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A Resistant Strain: Revealing the Online Grassroots Rise of the Antivaccination Movement

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An analysis of more than eight years of data from vaccination forums on mothering.com shows that the antivaccination movement is well-organized and widely dispersed, and that it emerged long before concerns about immunity were expressed. The findings are evidence of a formidable challenge to the social norms surrounding vaccination.

How effectively vaccines prevent the spread of infectious diseases depends on their widespread adoption, which in turn depends on how individuals regard them. Decades of investment in infrastructure aimed at educating and building public trust and making most vaccines affordable and universally available has laid a solid foundation for continued defense against diseases that vaccines can prevent. Despite this foundation, an antivaccination movement has emerged—not from validated scientific research, but as a product of larger trust issues with social norms.

The spread of antivaccination beliefs, in turn, has sparked a growing vaccination hesitancy among some parents.[1] Numerous factors have contributed to this trend, including how decision makers, particularly parents, process and react to media news; how knowledgeable they are about vaccines; how they communicate sentiments and information to one another (for example, through anecdotes); and their concerns about various stakeholders in the vaccination arena, such as government and medical institutions. These reactions and attitudes define the contours of the antivaccination movement.

To better understand the dynamics of trust issues—particularly how ideas emerge and people's attitudes stabilize—we studied more than eight years of vaccination forums on mothering.com, a website that has been active for more than a decade and is currently the online presence of a defunct print magazine focused on natural family living. We deliberately chose data from May 2003 to March 2012, the period during which the antivaccination movement took hold online, and used a suite of automated methods to capture collective data structures. Our dataset comprised vaccine-related posts, organized into threads consisting of initial posts and responses. Although posts regularly referred to individuals prominent in the antivaccination community, they also mentioned medical journals and government sites such as the

Probability — Active period (days)

Center for Disease Control and Prevention (CDC) and the National Institutes of Health (NIH). Indeed, medical journals and government sites were prominent in the more than 6,000 domains to which the posts cumulatively refer.

In collecting and mining this data, we aimed to answer two key questions:

› Were the decision makers in the antivaccination movement well-organized drivers of a grassroots effort or, as commonly perceived, was the movement spearheaded by a radical fringe group?
› Would it have been possible to track the emergence of parents' deliberations as the movement formed and shifted from discussion to action?

To answer these questions, we applied a topic-modeling approach to identify the main themes in the discussion forums. As parents making long-term decisions about their children, forum contributors displayed a high level of concern about vaccines, focusing on research and potential side effects. We found that the majority sentiment on this site is antivaccination, with 11 percent of the threads focusing on strategies for gaining religious or civic exemptions from vaccination.

We then studied contributors' interaction and sentiment-driven consensus networks and found that although contributors maintain distinct preferences for different topics within vaccination discussions, their interactions cross boundaries, allowing them to exchange information and influence one another. We also found evidence

for general consensus among contributors as a whole. Our automated analysis of sentiment enabled us to identify a specific contributor who initially intended to vaccinate her child, but ultimately decided against it on the basis of overwhelming negative reactions to her intent. Such results additionally confirm the notion that online sites such as mothering.com constitute a persistent discussion space for parents who strongly oppose vaccination. Moreover, although many have discounted the antivaccination movement as a fringe group, we found that the movement was a well-organized and widely dispersed online grassroots effort—driven in part by core contributors—that emerged long before researchers recognized its potential impact on herd immunity. Our findings have important implications for studies of what shapes opinion, such as how fake news circulates and how automated posting systems such as bots influence people's beliefs. The "Vaccination Decisions and Social Media" sidebar describes foundational work in more detail.

DATA CHARACTERISTICS

Forums on mothering.com include contributor-initiated threads consisting of initial posts and subsequent responses from others. Our dataset consists of 12,367 active contributors, representing 299,778 posts and responses in 26,942 threads about vaccination. In addition to active contributors, the forum draws those who read but do not post. In all, the threads received more than 16 million views, evidence that contributors to the site are highly aware information seekers.
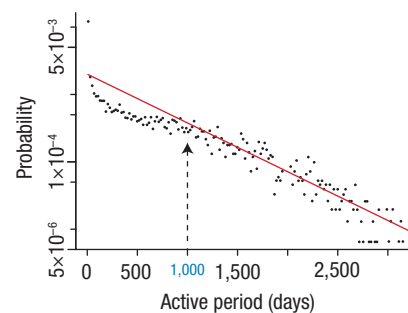
We did not consider geographic distribution because 50 percent of posters did not include any location information; of the half who did, 20 percent provided real locations, and the rest used fictitious names, such as Heaven and Shangri-La.

As is true of many online forums, temporal contributor activity is highly volatile with major spikes. The spiky nature usually indicates that message activity is induced by external events, such as news reports. In fact, 24 percent of the responses include a link to another webpage, and 18 percent of threads are initiated with a post that includes a link. Additionally, posts regularly refer to popular individuals prominent in the antivaccination community, such as Andrew Wakefield and Jenny McCarthy.

The timeline of those joining the site reveals that the forum experienced a peak in popularity between 2005 and 2007 and stabilized after 2009, with both the number of posts from established contributors and posts from new contributors showing no dramatic change.

Figure 1 shows the distribution of contributor-activity duration. The slope

VACCINATION DECISIONS AND SOCIAL MEDIA

Before semiautomatic mining and data analysis methods, the systematic study of vaccine discussions often relied on manual abstraction and analysis on very limited data.[1] Fully automated analysis, along with the escalation of social media as a communication channel, has changed the research landscape. One recent study explored ways to counteract strongly held antivaccination attitudes in online public health communications, with the most successful messages being those that emphasized the danger of communicable diseases.[2] A separate experiment that focused on social media found that spending 10 to 15 minutes accessing vaccine-critical websites increased the perception of vaccination risk and reduced the number of those who originally intended to vaccinate their children.[3]

BLOGS AND TWITTER

Although a growing number of researchers have concentrated on parental blogs—"mommy blogs"—[4] few studies have addressed discussion forums in which contributors who identify as parents discuss parenting-related issues. An analysis of parenting and health discussions on several platforms, including blogging sites and Twitter, shows that vaccination was addressed by 20 percent of the bloggers and 11 percent of the tweeters.[5] Twitter has also been explored in the broader context of influence, with one group showing the significant impact that automated posting systems, or *influence bots*, can have in these social media arenas.[6]

NARRATIVE EXTRACTION

At UCLA, researchers are investigating the deeper semantic structure of parent discussions about vaccinations on online forums informed by narrative theory,[7] automatically extracting the underlying narrative framework latent in posts about vaccination decision making. The study shows that parents sought exemptions as a means of protecting their children from the perceived vaccination threat. The generative narrative model derived aligns well with the broader phenomenon of fake news, which also presents misleading information as a compelling narrative. As others have observed, this alignment raises the all-too-real specter of automated bots flooding parenting conversations with posts engineered to fit the antivaccination narrative framework.[8]

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of the graph increases after 1,000 days (approximately 2.5 years), indicating that contributors stop being active at a higher rate after this period. In concert with our findings, this observation suggests that new parents discuss vaccination more within the first 2 to 3 years of having a child, the period during which most vaccines are administered.

OPINION DYNAMICS

Forum discussions covered a range of topics, which we derived by applying latent Dirichlet allocation (LDA) topic modeling on the text of threads. To train the models, we considered each thread to be a single document. We then compared the popularity of different topics within the forum. Using a nested Chinese restaurant process (nCRP),[2] we found 25 topics to be a suitable number for our dataset.

Topics and their significance

To generate meaningful human-understandable labels for every topic, we modified the topic weights to account for global term frequencies.
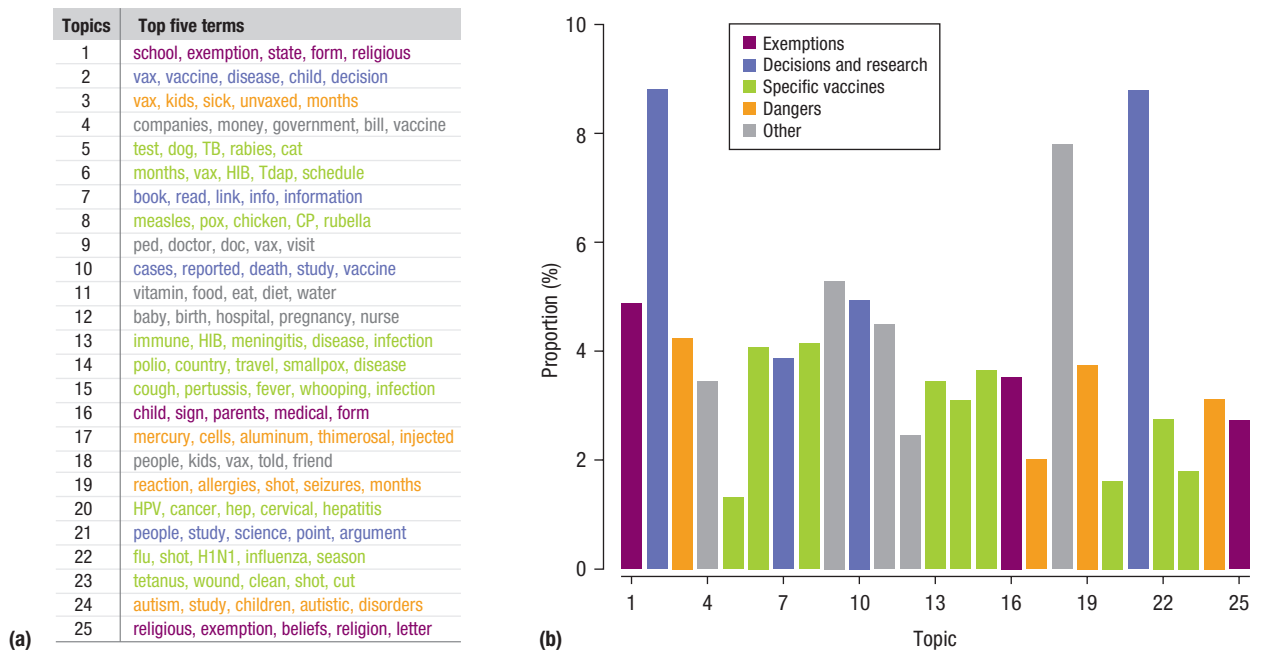
Topics	Top five terms
1	school, exemption, state, form, religious
2	vax, vaccine, disease, child, decision
3	vax, kids, sick, unvaxed, months
4	companies, money, government, bill, vaccine
5	test, dog, TB, rabies, cat
6	months, vax, HIB, Tdap, schedule
7	book, read, link, info, information
8	measles, pox, chicken, CP, rubella
9	ped, doctor, doc, vax, visit
10	cases, reported, death, study, vaccine
11	vitamin, food, eat, diet, water
12	baby, birth, hospital, pregnancy, nurse
13	immune, HIB, meningitis, disease, infection
14	polio, country, travel, smallpox, disease
15	cough, pertussis, fever, whooping, infection
16	child, sign, parents, medical, form
17	mercury, cells, aluminum, thimerosal, injected
18	people, kids, vax, told, friend
19	reaction, allergies, shot, seizures, months
20	HPV, cancer, hep, cervical, hepatitis
21	people, study, science, point, argument
22	flu, shot, H1N1, influenza, season
23	tetanus, wound, clean, shot, cut
24	autism, study, children, autistic, disorders
25	religious, exemption, beliefs, religion, letter

(a)   (b)

FIGURE 2. Results of topic-modeling thread data from mothering.com vaccination forums. (a) Topics with top five keywords colored according to categories. (b) Distribution across four distinct groups and an "other" category for topics not in those groups: overall, 27 percent of discussion focused on decisions and research, 13 percent on vaccines' dangers, 11 percent on exemptions, and 27 percent on specific vaccines. CP: chicken pox; Tdap: tetanus, diphtheria, and pertussis; HIB: haemophilus influenzae type B; H1N1: swine flu; Hep: hepatitis.

We define normalized word topic probability as

$$\beta'_{w,k} = \beta_{w,k}(\log \beta_{w,k} - \frac{1}{K}\sum_{k'} \log \beta_{w,k'}),$$

(1)

where $\beta_{w,k}$ denotes topic probability of a word w in a topic k, K represents the number of topics, and k' denotes all the topics from 1 to K. We then ranked the words according to $\beta'_{w,k}$ in each topic.

Figure 2a shows the five main keywords for each of the resulting 25 topics, which are distinct and can be grouped semantically into four coherent groups: exemptions, decisions and research, specific vaccines, and dangers. A fifth group, "Other," contains five topics that did not fit into any of the first four groups.

Despite views that contributors to this website hold antivaccination opinions because they lack education, our findings do not support this idea. Rather, decision making on vaccinations stem from sophisticated references to books, reports, research studies, and details of specific cases (topics 2, 7, 10, and 21). Topics 17, 18, and 24 concentrated on

vaccine dangers, with topic 24 focused on the alleged connection between vaccines and autism, and topic 17 discussing harmful chemicals associated with vaccinations. Our results also show that contributors actively seek and exchange information about how to avoid vaccinating their children. Forms, logistics, and strategies for gaining civic and religious exemptions from vaccination are evident in topics 1 (civic exemptions), 16 (medical forms), and 25 (religious exemptions), and are observed in many threads.

Strong mistrust of pharmaceutical companies was evident in topic 4, with "companies" being one of the top five terms. Specifically, contributors were suspicious about big pharma's profit motivation and its potential to influence the government's advocacy for vaccination. Finally, several topics are related to pediatric visits (topic 9), nursing and birth (topic 12), food (topic 11), and the exchange of experiences with friends (topic 18).

Although these results show that forums contain distinct topics, they do not reveal any topics' relative

prominence. Figure 2b shows the threads distributed over topics, with each bar representing the degree to which that topic is represented across threads. The topic with the highest share, or largest probability value, is the dominant topic for that thread. After computing the overall prominence of topics from the percentage of threads related to each topic, we found that 27 percent of threads focus on decision and research, and another 27 percent address specific vaccines. We also saw telltale indications of some foundational social-trust issues: 3.5 percent of the threads alluded to government, medical institutions, and drug companies, and air suspicions that these institutional actors might be acting in collusion to advocate for vaccination for profit or control. Finally, we noted considerable interest (13 percent) in exploring the dangers of vaccination and in seeking ways to get exemptions (11 percent).

These percentages corroborate the significance of contributors' antivaccination stance. Peaks and high posting activity on threads associated with
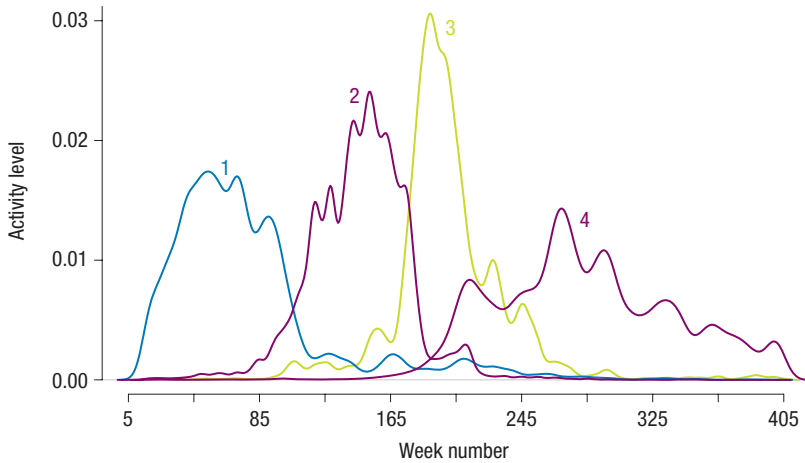
FIGURE 3. Temporal distribution for each of four interaction communities. The communities cannot be considered as distinct contributor groups because they are separated by largely disjoint temporal activities. Although contributors are actively engaged, most interact only broadly, not according to a shared interest. Peaks separated by about two years bolster the observation that groups with young same–age children are active and interacting most often with each other (see Figure 1). The y–axis represents the ratio of those who posted in a given week (x–axis) to the total number of posters in that community.

individual topics might relate to significant real-world disease outbreaks or media events, as evidenced by the timeline of posts. For example, when the US Food and Drug Administration (FDA) approved the use of Gardasil for vaccination against cervical cancer and genital warts in June 2006,[3] posts on vaccination safety and exemption-related topics increased dramatically.

Preferred topics

The posts revealed that contributors have distinct topic preferences. To derive a topic distribution, we computed the number of posts from each contributor in each topic. The Kullback–Leibler (KL) divergence between the overall topic distribution (see Figure 2b) and a particular contributor's topic distribution signifies the amount that the contributor diverges from the preferences of the contributors overall. The KL divergence measure for a particular contributor is

$$D_{\mathrm{KL}}(P \mid Q) = \sum_{i=1}^{25} p_i \ln \frac{p_i}{q_i} , \qquad (2)$$

where p_i is the probability that a given contributor will post on the ith topic, and q_i is the probability across all contributors (corpus wide) of posting on the ith topic. If a contributor posted on different topics in exact accordance with the overall topic distribution, then the KL divergence for that contributor would be close to zero. Similarly, if the contributor posted uniformly to all 25 topics, the KL divergence would be approximately 0.2. We found that neither extreme occurred; rather, contributors tended to diverge significantly from the overall topic distribution, indicating that they had distinct topic preferences.

The KL divergence results suggest that contributors might be clustering around their topics of interest. To investigate this idea, we implemented k-means clustering on the vectors for each contributor's topic distribution (the post's or response's association with the 25 topics). We found four clusters: cluster 1 concentrates on decision making, cluster 2 focuses on the flu, cluster 3 includes contributors who actively participated in various topics, and cluster 4 centers on exemptions from vaccination.

INTERACTION DYNAMICS

Clustering contributors into topic interest groups raises a question: Are contributors interacting only within their topic interest group, or does their interaction go beyond these interest boundaries? In other words, are opposing groups visiting this site or is the population mixed and homogenous?

Interaction network

To explore these questions, we used contributors' initial posts to form a weighted directed interaction network consisting of 12,367 nodes and 158,711 edges. A directed edge is drawn between contributors A and B if B replies to A's message in a thread, with an edge weight based on the number of times B responds to A. In any thread, B might also reply to the thread initiator's message or to another contributor, C, by quoting A's message.

We then applied an unsupervised modularity-maximization agglomerative community-detection algorithm[4] to the network. The algorithm, which automatically determines the number of communities, extracted groups in which contributors interact mainly among themselves. Results yielded four major communities with 2,087 nodes, 3,034 nodes, 1,633 nodes, and 5,343 nodes. At first glance, these might seem like distinct contributor groups, but as Figure 3 shows, contributors in the four communities occupy different regions in time. That is, within each time period, there is no distinct clustering based on initial post–response interaction patterns.

Consensus network

The results of community detection suggest that, at any time, a large number of active contributors interact broadly with one another, and this interaction crosses the boundaries

(a) **(b)**

FIGURE 4. Network graphs of the (a) fifth and (b) sixth communities in the consensus network. Unlike the other four communities, which had contributors with short time periods and varied interests, these two communities centered on a main contributor (center of the star) whose followers were active for almost the entire 8.75 years of our study. Such contributors are likely to be a force in shaping other contributors' opinions.

of distinct preferences for individual topics. Additionally, activity peaks in these communities are about one to two years apart. This phenomenon could be connected to the timing of the infant vaccine schedule, which recommends completing the first and largest set of these vaccines by 18 months. One hypothesis is that contributors with children younger than two years interact in threads about vaccination decisions until their children are past this age; as this initial group's conversations are winding down, a new group of parents who have newborns or are expecting them soon takes up the discussion, forming a subsequent community.

However, broad interaction among contributors could also be associated with two opposite hypotheses:

> Significant disagreement among contributors leads to increased debates and arguments.
> Continuous exchange of information leads to converging viewpoints or reinforces previously held agreements, resulting in a homogeneous community with a broad consensus.

To investigate whether interacting contributors have harmonious or conflicting attitudes, we used a lexicon-based algorithm[5] to analyze sentiment. If a response's sentiment agrees with the initial post's sentiment, we assigned +1 value to the interaction, conjecturing that the two have mutual dispositions about the subject of discussion. Otherwise, we assigned a –1 value. Similar to how we created the interaction network, we defined a consensus network in terms of contributor B responding to one of
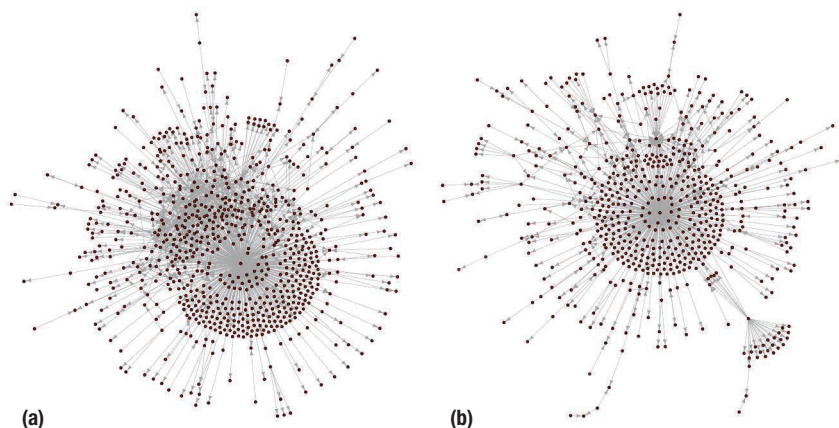
contributor A's posts with S_A being the sentiment of A's post and S_B the sentiment of B's response, where S_A and S_B are numerical values between –1 and +1. Because small sentiment values might not be accurate, we set a threshold of 0.2; if the absolute value of either S_A or S_B is less than 0.2, we set the exchange's value to 0. The weight of the edge from B to A is then the sum of the values of all the responses from B to A:

$$\text{weight(B, A)} = \sum_{\text{B to A responses}} \text{sign}(S_A \times S_B), \quad (3)$$

where sign is a function that returns +1 or –1 depending on whether the input is positive or negative.

We then examined the sum of the weights of all the outgoing edges from node B. A highly positive sum implies that contributor B has agreed with others in most replies; that is, B has a high *out-degree*. Alternatively, a contributor who receives a high level of agreement from others will have a high *in-degree*. Thus, the nodes' in-degree and out-degree indicate if contributors are mostly agreeing with others (high out-degree) or disagreeing with them (low out-degree) and if contributors have others mostly agreeing them (high in-degree) or disagreeing (low

in-degree) with them. We found that contributors with the lowest in-degree (most disagreed with) were either highly pro-vaccine or had posted links that were mostly pro-vaccine. Of the top two such contributors, the first poster was initially pro-vaccine but ended up deciding not to vaccinate—possibly affected by the overwhelming negative reaction to her initial intent—and the second contributor was a pro-vaccine pediatrician.

We also discovered that the most active posters had the highest in-degree (were most agreed with), suggesting that this forum is a fairly homogenous and consensus-driven community populated primarily by antivaccine contributors.

After running the same community-detection algorithm on the consensus network that we ran on the interaction network, but with only positive edges signaling sentiment agreement, we obtained six major communities with 1,232 nodes, 2,561 nodes, 1,413 nodes, 3,409 nodes, 783 nodes, and 602 nodes. As before, we used the time stamps of the messages posted within each community to determine the temporal distribution of each community's messages. The first four communities, which had the most messages, occupy much shorter time

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periods, relative to the fifth and sixth communities. As Figure 4 shows, each of these latter communities has a star-shaped network graph with most edges starting or ending at a single dominant contributor. These contributors are by far the community leaders with the most tenure.

With significant numbers of parents participating on various social media sites, the Internet provides an unprecedented opportunity to study how the antivaccination movement emerged and progressed. Although many have discounted antivaccination proponents as a fringe movement, by applying statistical analytical tools that capture strong collective structure, we found that the opposite is true: contributors are well-informed and were interacting long before anyone realized they could have an impact on herd immunity. Indeed, in light of the recent outbreaks of vaccine-preventable diseases,[6] there is reason to believe that this movement also has broad international appeal.

Vaccination adoption depends on a unique combination of issues that test some of the very fundamental contracts that bind a society. Even among educated and highly aware contributors, who represent the primary decision makers regarding vaccination choices for children, social trust issues play an overwhelming role. Ultimately, individuals must make decisions related to several basic risk–benefit and trust issues. Our research shows the feasibility of automatically discovering and quantifying versions and instantiations of many of these concerns on a large-scale social media dataset.

Our work underlines the ongoing need for a system to automatically detect the emergence of grassroots movements that could significantly affect public health. Mechanisms are required that can guide informed dialogue online, where various healthcare advocacy groups and civic institutions can be actively represented. Although federal, state, and local public health organizations carry out focused intervention programs aimed at increasing vaccine rates in low-adoption and high-risk groups, these programs are geographically local, community driven, and reflect several decades of tuning to fit brick-and-mortar support infrastructure. They are not designed for the online and social media world, which is better suited for awareness building and interventions, such as brand development and product promotions, as online advertising campaigns demonstrate only too well. Sophisticated analytical tools help in refining messages and increasing return on investment. Work such as ours can provide valuable support to public health advocacy groups as they adapt to the online world. A nation's

health might very well depend on such assistance. ▣

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