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ORIGINAL RESEARCH

Visual Analytics of Surveillance Data on Foodborne Vibriosis, United States, 1973–2010

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Abstract: Foodborne illnesses caused by microbial and chemical contaminants in food are a substantial health burden worldwide. In 2007, human vibriosis (non-cholera *Vibrio* infections) became a notifiable disease in the United States. In addition, *Vibrio* species are among the 31 major known pathogens transmitted through food in the United States. Diverse surveillance systems for foodborne pathogens also track outbreaks, illnesses, hospitalization and deaths due to non-cholera vibrios. Considering the recognition of vibriosis as a notifiable disease in the United States and the availability of diverse surveillance systems, there is a need for the development of easily deployed visualization and analysis approaches that can combine diverse data sources in an interactive manner. Current efforts to address this need are still limited. Visual analytics is an iterative process conducted via visual interfaces that involves collecting information, data preprocessing, knowledge representation, interaction, and decision making. We have utilized public domain outbreak and surveillance data sources covering 1973 to 2010, as well as visual analytics software to demonstrate integrated and interactive visualizations of data on foodborne outbreaks and surveillance of *Vibrio* species. Through the data visualization, we were able to identify unique patterns and/or novel relationships within and across datasets regarding (i) causative agent; (ii) foodborne outbreaks and illness per state; (iii) location of infection; (iv) vehicle (food) of infection; (v) anatomical site of isolation of *Vibrio* species; (vi) patients and complications of vibriosis; (vii) incidence of laboratory-confirmed vibriosis and *V. parahaemolyticus* outbreaks. The additional use of emerging visual analytics approaches for interaction with data on vibriosis, including non-foodborne related disease, can guide disease control and prevention as well as ongoing outbreak investigations.

Keywords: bioinformatics, data visualization, foodborne diseases, human-computer interaction, surveillance, *Vibrio* species, visual analytics

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Introduction

Foodborne illnesses caused by microbial and chemical contaminants in food are a substantial health burden worldwide.[1–6] The gram-negative *Vibrio* bacterial species, which are found worldwide in ecologically diverse marine and other aquatic organisms contribute to this burden especially through consumption of contaminated seafood.[1] The genus *Vibrio* belongs to the family *Vibrionaceae* and the class *Gammaproteobacteria*.[7] There are at least 78 known *Vibrio* species.[8] Most of them do not cause disease in humans. However, a small subset of species, notably *Vibrio cholerae, Vibrio parahaemolyticus,* and *Vibrio vulnificus*, cause the majority of human disease.[9] *Vibrio parahaemolyticus* and *V. vulnificus* are ubiquitous in salt waters. Specifically, *V. vulnificus* is mostly found in estuarine and *V. parahaemolyticus* is found both in marine and estuarine environments while *V. cholerae* non-O1 is ubiquitous in fresh and salt waters. *Vibrio* infections (vibriosis) can occur through the consumption of contaminated foods and water, or they can be associated with the exposure of skin to aquatic environments and marine animals.[10]

Annual surveillance data for contaminated food include numbers of outbreaks, illnesses, hospitalization and deaths.[11–13] In the United States, the Centers for Disease Control and Prevention (CDC) estimates that annually foodborne diseases are responsible for approximately 1,000 reported disease outbreaks, 48 million (about 1 in 6 persons) episodes of illnesses, 128,000 hospitalizations, and 3,000 deaths.[11] Since 1973, the CDC has maintained a collaborative surveillance program for collection and periodic reporting of data concerning the occurrence and causes of foodborne-disease outbreaks (FBDOs).[14] These multi-year and multi-state data on past foodborne outbreaks caused by bacteria (including *Vibrio* species), viruses/prions, protozoa, as well as chemicals, are available from the OutbreakNet Team website of the CDC.[15] Other food pathogen-related surveillance mechanisms that include *Vibrio* species conducted by the CDC include (i) the Foodborne Diseases Active Surveillance Network (FoodNet) initiated in 1996[16,17] and (ii) Cholera and Other *Vibrio* Illness Surveillance System (COVIS) initiated in 1988.[18] Furthermore, surveillance data on *Vibrio* species have also been published in the Mortality and Morbidity Weekly Report.[14,19] In 2007, vibriosis became a reportable disease in the United States.[20] Compared to 2006–2008, the 2010 incidence of laboratory-confirmed *Vibrio* infection (vibriosis) was significantly higher (39% increase; CI = 12%–72%).[11] Further, in 2009 the rates of human *Vibrio* infection were substantially higher compared to 1996–1998. The total cases reported for vibriosis (noncholera *Vibrio* species infections) in 2010, 2009, 2008, and 2007 were 848, 789, 588, 549 respectively.[15] Between 23 March and 13 April 2011, Florida recorded an outbreak of ten cases related to *V. cholerae* O75 after oyster consumption.[21]

Considering the significant increase in vibriosis in the United States, the recent observation of highly unusual oyster-borne toxigenic *V. cholerae* infections as well as the availability of diverse surveillance systems, there is a need for the development of easily deployed visual integration and analysis approaches that combine diverse data sources in an interactive manner. Current efforts to address this need are still limited or not freely accessible. We propose the use of emerging visual analytics approaches for interaction with data on vibriosis including non-foodborne cases (for example occupational exposure) to guide disease control and prevention. Visual analytics is an iterative process conducted via visual interfaces that involves collecting information, data preprocessing, knowledge representation, interaction, and decision making.[22,23] Visual analytics approaches have been applied to understanding spatiotemporal hotspots and syndromic surveillance.[24,25] Furthermore, recently a case for visual analytics for concentration of arsenic (a toxicant) in foods was made.[26]

The purpose of the reported research investigation was to demonstrate that visual analytics approaches could help to identify new relationships and unique patterns of foodborne vibriosis in the United States. Therefore, we identified relevant epidemiological surveillance datasets on foodborne vibriosis. We then used visual analytics tools to demonstrate data integration and interactive data visualization. To the best of our knowledge, this is the first report of the application of visual analytics to over 30 years of foodborne surveillance data on vibriosis in the United States.

Methods

The following four datasets on foodborne vibriosis were assembled: (i) Annual Listing of Foodborne Disease Outbreaks, United States (OutbreakNet);

(ii) the Cholera and Other *Vibrio* Illness Surveillance System (COVIS); (ii) the Foodborne Diseases Active Surveillance Network (FoodNet); and (iv) Epidemiological characteristics of *Vibrio parahaemolyticus* Infections in the United States, 1973–1998. Subsequently selected visual analytics tools were used to generate views of the datasets. Specific description of method for each dataset is described below.

Annual Listing of Foodborne Disease Outbreaks, United States (OutbreakNet)

The OutbreakNet dataset contains voluntarily reported foodborne disease outbreaks and illnesses by causative agent and food commodities in the United States. A foodborne disease outbreak occurs when two or more cases of a similar illness result from eating the same food.[3] The PDF files for 1990 through 1997 were downloaded from the CDC OutbreakNet website.[27] The data on *Vibrio* species were then obtained from each file. Data for 1998 through 2006 were downloaded from the CDC Foodborne Outbreak Online Database (FOOD).[28]

To facilitate data clustering and visual representations, the names of the etiologic agents reported were processed into 8 categories: (i) *Vibrio cholerae*; (ii) *Vibrio cholerae* O1; (iii) *Vibrio* other; (iv) *Vibrio parahaemolyticus*; (v) *Vibrio parahaemolyticus*; other; (vi) *Vibrio parahaemolyticus*; *Vibrio* other; (vii) *Vibrio* unknown and (viii) *Vibrio vulnificus*. Furthermore, based on a recent report[29] on produce-related foodborne illness, the categories developed from the names of the outbreak location categories were (i) Community Event; (ii) Community Event, Other; (iii) Food Service, (iv) Food Service; Community Event; (v) Home, Food Service; (vi) Food Service; Other, (vii) Home, (viii) Home/Community Event, (ix) Other and (x) Unknown.

The Cholera and Other *Vibrio* Illness Surveillance System (COVIS)

The Cholera and Other *Vibrio* Illness Surveillance System (COVIS) contains multi-year data (1997–2007) on human *Vibrio* illness in the United States.[18] The PDF files for 2002 to 2006 were downloaded from the CDC National Case Surveillance website.[30] The frequency of isolates of *Vibrio* species (excluding toxigenic *V. cholerae*) isolated from blood, stool, wound and other sites as well as the associated patients and complications (hospitalized or death) were obtained from the files. The data on illnesses were typically divided into patients from Gulf of Mexico Coast states (Alabama, Florida, Louisiana, Mississippi and Texas) and non-Gulf Coast of Mexico states. In the analysis presented here, we did not distinguish between these categories of states.

The Foodborne Diseases Active Surveillance Network (FoodNet)

The FoodNet[31] is a collaborative, active, population-based surveillance system from 10 states based on laboratory-confirmed infections caused by enteric pathogens commonly transmitted by food including *Vibrio* species.[16,17] The states cover more than 46 million people (15% of the US population) and include Connecticut, Georgia, Maryland, Minnesota, New Mexico, Oregon, Tennessee, and selected counties in California, Colorado, and New York. The incidence (Cases per 100,000) of vibriosis for each of the 10 states from 2004 to 2009 was obtained from 14 published data sets on FoodNet.[32–45] To compare age group incidence of foodborne vibriosis, the 2010 preliminary data on age group incidence for laboratory-confirmed selected bacteria and parasite in the 10 FoodNet sites were extracted from the 2010 FoodNet report.[11]

Epidemiological characteristics of *Vibrio parahaemolyticus* infections in the United States, 1973–1998

Daniels et al[46] compiled data on the epidemiology of sporadic infections and foodborne outbreaks caused by *V. parahaemolyticus* from data reported to the CDC, from state and local health departments. The data from Daniels et al[46] were converted into an electronic format suitable for visual analytics (Table 3 of publication). The unique aspect of this dataset is that in some reports it was possible to calculate the attack rate of the infection based on number of persons exposed and number of persons ill.

Results

Annual Listing of Foodborne Disease Outbreaks, United States (OutbreakNet)

The OutbreakNET dataset analyzed consisted of 101 outbreaks and 1,672 cases of foodborne illness linked to *Vibrio* species from 1990 to 2006 (Fig. 1).

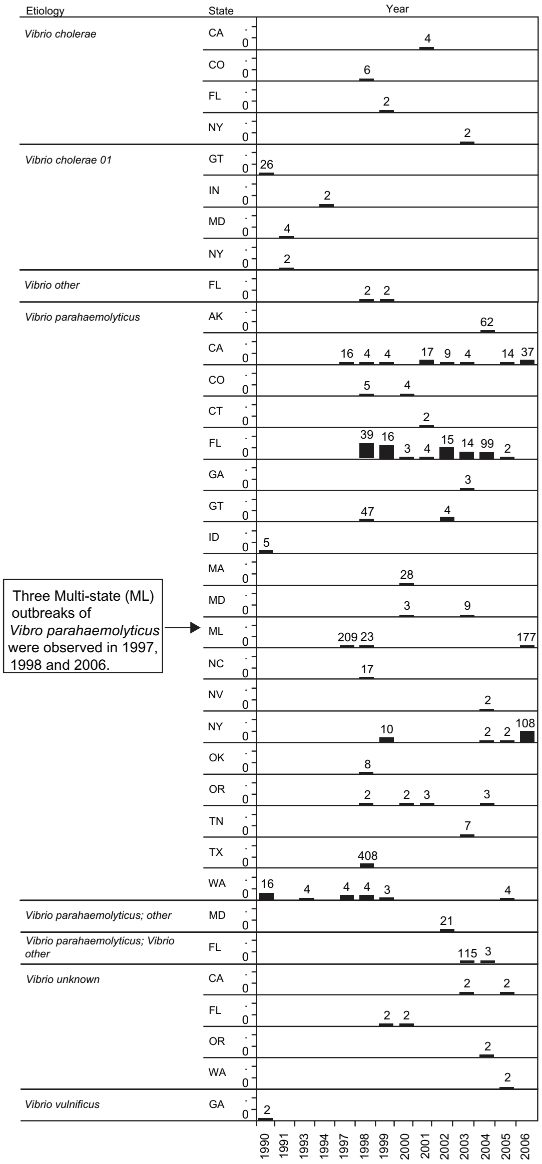


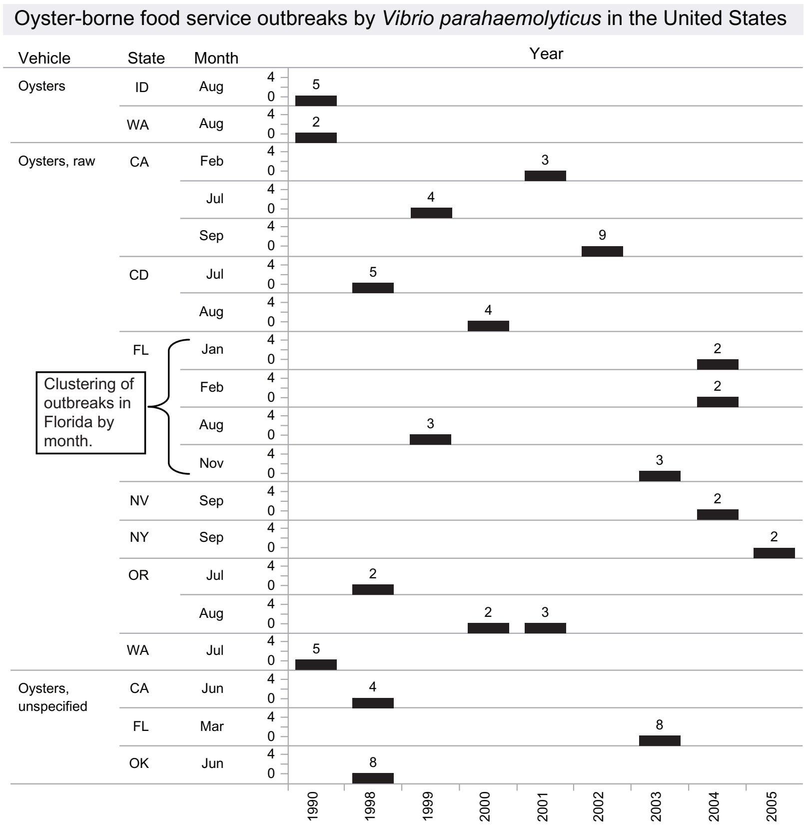
Figure 1. Foodborne vibriosis in the United States by etiologic agent (etiology field in OutbreakNET), state and year (1990 to 2006). A total of 19 states or territories reported foodborne vibriosis outbreaks. In addition, there were three multi-state (ML) outbreaks caused by *V. parahaemolyticus* in 1997, 1998 and 2006. The portion of the view with the data is annotated. Number over bars indicates number of ill persons. The data sources are (i) http://www.cdc.gov/outbreaknet/surveillance_data.html. (ii) http://www.cdc.gov/foodborneoutbreaks/. Visual analytics resource to interact with data by specifying etiologic agent, location of outbreak and month is available at http://public.tableausoftware.com/views/USA_FOODVIBRIO_1990TO2006/USA_Foodborne1990to2006.

Since consumption of raw or undercooked oysters is a risk factor for *V. parahaemolyticus* infection, we sought to determine oyster-borne outbreaks with *V. parahaemolyticus* as the causative agent. Figure 2 is a visual representation of the integration of data on causative agent, state, month, and year for outbreaks that occurred in a food service location and which were linked solely to consumption of raw oysters. The visualization helped us to among other findings (i) identify a single outbreak that led to at least 100 cases of illness (Table 1); (ii) determine that Georgia was the only state that reported *V. vulnificus* (2 cases); (iii) determined that in 1998, Guam Territory (GT) reported a total of 47 cases of *V. parahaemolyticus* infection associated with consumption of chicken.

The Cholera and Other *Vibrio* Illness Surveillance System (COVIS)

The views generated for the COVIS dataset (2002 to 2006) helped us to identify trends in the anatomic site isolations of *Vibrio* species. In the dataset analyzed, isolates were reported according to 13 categories including ten *Vibrio* species. Other categories were "Multiple Sites", "Species Unknown" and "Other". *Vibrio vulnificus* was most frequently isolated from blood and wound isolation sites peaking in 2003 and 2005 respectively (Fig. 3). Furthermore, *V. vulnificus* had a frequency of isolation approximately six times higher than any other *Vibrio* species analyzed for the blood isolation site. For isolates from stool specimens, it was noteworthy that *V. parahaemolyticus* was higher than any of the *Vibrio* species analyzed, peaking in 2006. The three *Vibrio* species that showed noteworthy frequencies for wound isolation site were *V. alginolyticus*, *V. parahaemolyticus*, and *V. vulnificus,* with the highest peak recorded in 2005 for all three species.

In terms of reported complications from vibriosis, *V. parahaemolyticus* and *V. vulnificus* had the highest frequencies relative to the other *Vibrio* species studied in all patients and complications (hospitalized and deaths) (Fig. 3). *Vibrio vulnificus* had the highest frequency for patient hospitalization and deaths compared with the other *Vibrio* species. Infections due to *V. vulnificus* resulted in approximately 30 deaths in 2002 and hospitalization of almost 100 individuals in 2005. Furthermore, *V. parahaemolyticus* infection led to the highest numbers of patients ranging from approximately 200 patients in 2002 to approximately 400 patients in 2006. The comparison of the shapes of the line graphs in the boxes of Figure 3 could reveal novel insights on reporting features. For example, the shape of the line graph for patients with *V. parahaemolyticus* infection (see Column 3, Row 1 in Patients and Complications chart) is similar to stool site of *V. parahaemolyticus* isolation (see Column 3,



Month	State	Vehicle	Year	Ill
Jul	WA	Oysters, raw	1990	5
Jul	CO	Oysters, raw	1998	5
Jul	OR	Oysters, raw	1998	2
Jul	CA	Oysters, raw	1999	4
Aug	FL	Oysters, raw	1999	3
Aug	CO	Oysters, raw	2000	4
Aug	OR	Oysters, raw	2000	2
Feb	CA	Oysters, raw	2001	3
Aug	OR	Oysters, raw	2001	3
Sep	CA	Oysters, raw	2002	9
Nov	FL	Oysters, raw	2003	3
Jan	FL	Oysters, raw	2004	2
Feb	FL	Oysters, raw	2004	2
Sep	NV	Oysters, raw	2004	2
Sep	NY	Oysters, raw	2005	2

Figure 2. Visualization of oyster-borne food service outbreaks of *V. parahaemolyticus* infections integrated by state, month and year. The height of bars indicates number of outbreaks. Outbreaks in Florida are annotated to illustrate data clustering. Number over bars indicates number of ill persons. Dataset on outbreaks caused by raw oysters appended to the bottom of the visualization. Visual analytics resource to interact with data is available at http://public.tableausoftware.com/views/USA_FOODVIBRIO_1990TO2006/V_para_Oyster_borne_FoodService.

Table 1. Highlights for foodborne outbreaks attributed to *Vibrio* species, United States (1990–2006).

State	Year	Pathogen	Number of illness
Texas (TX)	1998	*V. parahaemolyticus*	408
Multistate (ML)	1997	*V. parahaemolyticus*	209
Florida (FL)	2003	*V. parahaemolyticus* and other *Vibrio* species	115
Multistate (ML)	2006	*V. parahaemolyticus*	177
New York	2006	*V. parahaemolyticus*	108

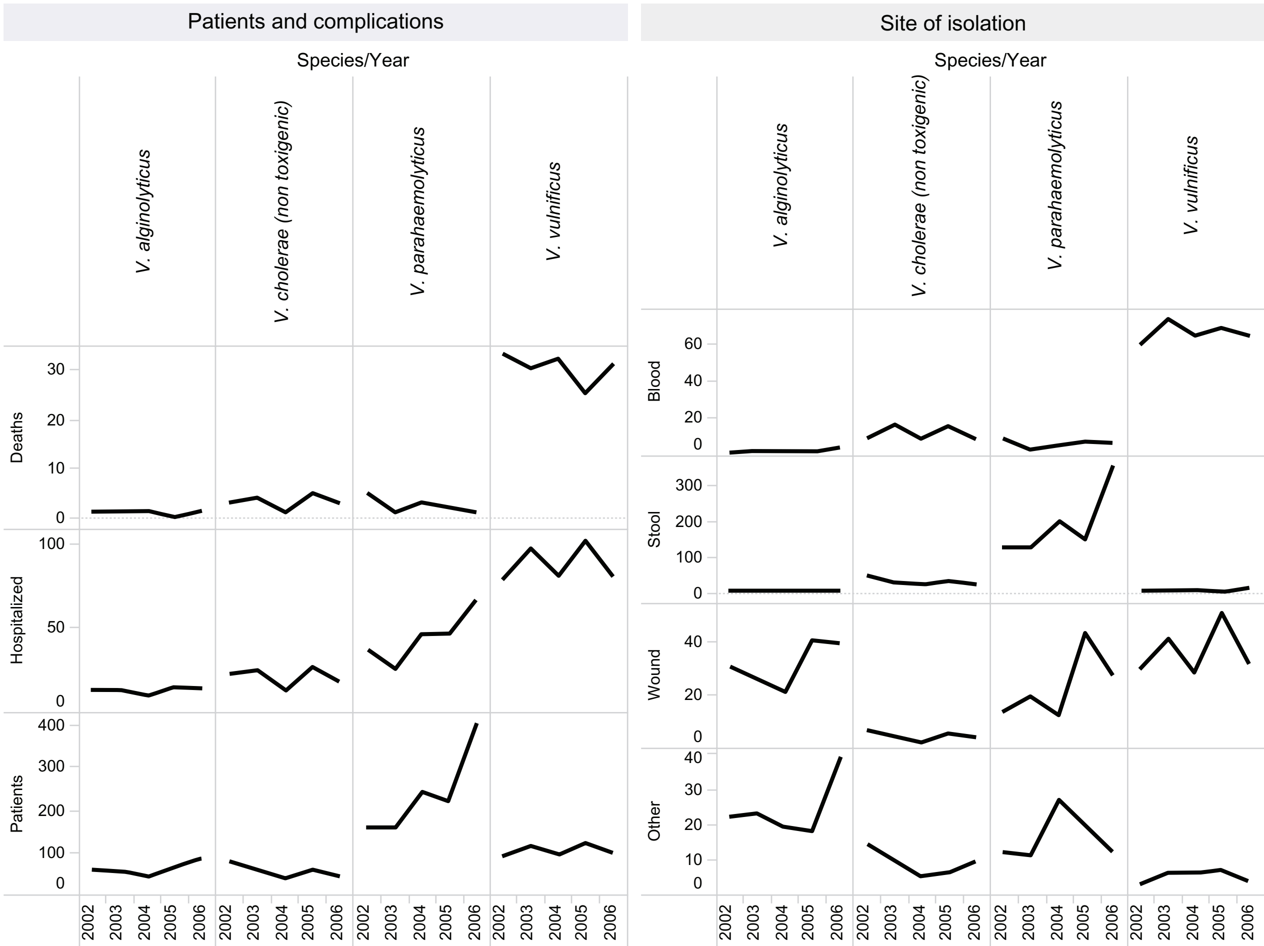


Figure 3. Vibriosis in United States: Patterns of patients, complications and site of isolation of *Vibrio* species, 2002 to 2009. The comparison of the shapes of the line graphs in the boxes could reveal novel insights on reporting features. For example, the shape of the line graph for patients with *Vibrio parahaemolyticus* infection (see Column 3, Row 1 in Patients and Complications chart) is similar to stool site of *V. parahaemolyticus* isolation (see Column 3, Row 2 in Site of Isolation chart). Row 1 (Patients) is the bottom row while Column 1 (*V. alginolyticus*) is the left-most column. Visual analytics resources to interact with data is available at http://public.tableausoftware.com/views/USA_vibrio_isolates_2003to2006/Patient_Complication; http://public.tableausoftware.com/views/USA_vibrio_isolates_2003to2006/Site_Isolation.

Row 2 in Site of Isolation chart). In both reporting features, cases were approximately the same in 2002 and 2003, followed by an increase in 2004, a decrease in 2005, and then an increase in 2006. Data used to generate Figure 3 can be downloaded from website addresses provided along with the figure legend.

The Foodborne Diseases Active Surveillance Network (FoodNet)

The incidence of vibriosis available from FoodNet for 2004 to 2009 is presented in Table 2 and visualized in Figure 4. The weight of the line is proportional to the incidence (per 100,000 cases). A comparison of the incidence per state for the six years revealed that Connecticut had the highest incidence of 0.77 per 100,000 cases in 2009. Furthermore, the visual representation revealed that, in addition to Connecticut, Oregon in 2009 reported incidence values higher than previous years. The highest incidence for the period was 1.15 per 100,000 cases, which occurred in California in 2006.

Preliminary data on the 2010 incidence of laboratory-confirmed bacterial and parasitic infection cases, by age group and pathogen, were published by FoodNet in 2011. A view of Table 2 of the FoodNet article is presented in Figure 5. This view allowed us to produce a non-redundant list of incidence values and then identify pathogens that have identical incidence values to *Vibrio* species. The incidence of infection reported for *Vibrio* species from FoodNet sites in 2010 ranged from 0 (age group < 5) to 0.8 (age group ≥ 60). The highest incidence was in the $\geq$60 years age group.

Table 2. Incidence of foodborne vibriosis in 10 states in the United States, 2004–2009.*

Year	CA	CO	CT	GA	MD	MN	NM	NY	OR	TN	Overall
2009	0.60	0.33	0.77	0.28	0.53	0.17	0.05	0.26	0.47	0.13	0.35
2008	0.65	0.15	0.40	0.20	0.59	0.15	0.10	0.19	0.32	0.16	0.29
2007	0.37	0.15	0.46	0.25	0.45	0.15	0.00	0.21	0.22	0.05	0.24
2006	1.15	0.12	0.54	0.28	0.59	0.08	0.10	0.28	0.27	0.15	0.34
2005	0.69	0.31	0.34	0.24	0.49	0.12	0.05	0.19	0.25	0.08	0.27
2004	0.81	0.44	0.29	0.28	0.51	0.06	0.16	0.02	0.25	0.15	0.28

Notes: *Incidence is per 100,000 cases. Data were compiled from publications from the FoodNet surveillance program.

Further, foodborne illnesses caused by *Vibrio* and *Yersinia* had identical incidence (0.2) for the age group 10 to 19 years.

Epidemiological characteristics of *Vibrio parahaemolyticus* infections in United States, 1973–1998

A total of 40 outbreaks of *V. parahaemolyticus* infections in the United States were compiled for the period 1973–1998 (Tables 3 and 4). Data were available for 14 years of the possible 26 years. We used Parallel Sets software for categorical data visualization[47] to compare the epidemiological characteristics of *V. parahaemolyticus* infection outbreaks with the food vehicle reported as "Shrimp" or "Raw oyster" (Fig. 6). The horizontal bars in the visualization show the absolute frequency of how often each category occurred. The top horizontal bar shows the months when the

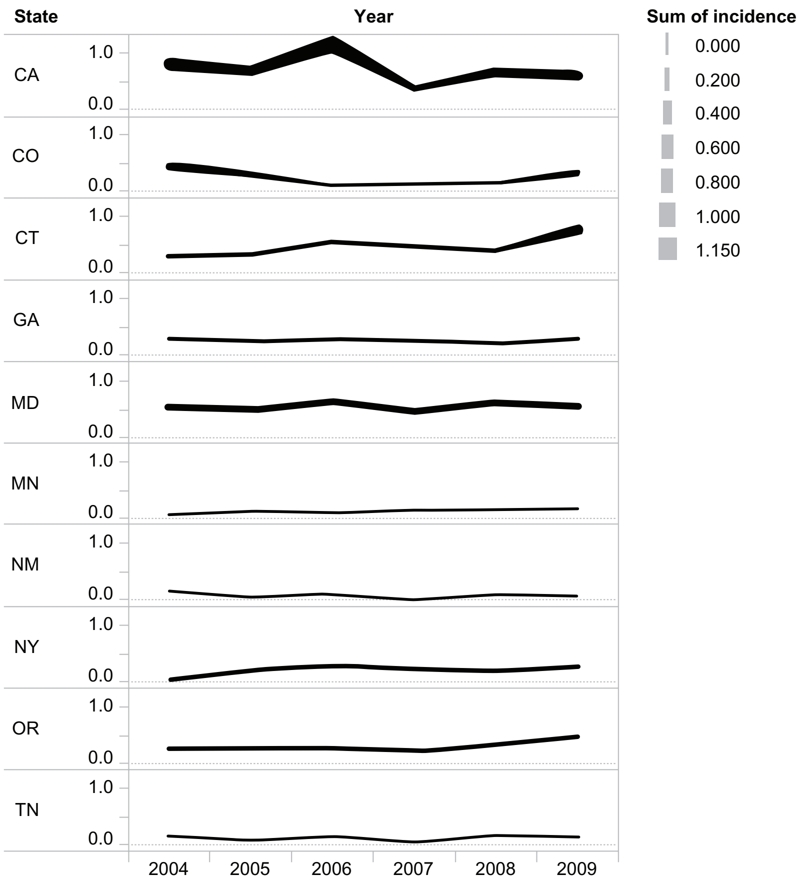


Figure 4. Visualization of incidence of vibriosis from 10 States in the United States, 2004 to 2009. The size of the line indicates the incidence. Visual analytics resource to interact with data is available at http://public.tableausoftware.com/views/FoodNetIncidence2004to2009_1/FoodNet_Vibrio_Incidence_2004to2009.

Incidence (cases per 100,000 population) of laboratory−confirmed bacterial an
parasitic infection cases, by age group and pathogen−Preliminary Data from
Foodborne Diseases Active Surveillance Network, United States, 2010
http:// www.cdc.gov/mmwr/preview/mmwrhtml/mm6022a5.htm

		Age Group				
Incidence	**Pathogen**	<5	<5–9	10–19	20–59	=>60
0	Cyclospora	■	■			
	Vibrio	■				
0.02	Cyclospora			■		
0.03	Listeria		■			
0.05	Listeria			■		
0.1	Cyclospora				■	■
	Listeria				■	
0.2	Vibrio			■		
	Yersinia			■	■	
0.3	Listeria	■				
	Vibrio		■			
0.4	Vibrio				■	
	Yersinia		■			■
0.5	STEC non-O157				■	■
	STEC O157				■	
0.7	STEC O157					■
0.8	Vibrio					■
1.1	Listeria					■
	Shigella					■
	STEC non-O157		■			
	STEC O157			■		
1.3	STEC non-O157			■		
1.9	Yersinia	■				
2.2	Shigella			■		
2.5	Cryptosporidium			■		■
	Shigella				■	
	STEC O157		■			
2.6	Cryptosporidium				■	
2.7	Cryptosporidium		■			
3.3	STEC O157	■				
5	STEC non-O157	■				
5.1	Cryptosporidium	■				
10.1	Campylobacter			■		
10.6	Campylobacter		■			
11.7	Shigella		■			
12.2	Salmonella				■	
12.3	Salmonella			■		
13.3	Campylobacter				■	
13.9	Campylobacter					■
16.4	Shigella	■				
17	Salmonella					■
21.4	Salmonella		■			
24.4	Campylobacter	■				
69.5	Salmonella	■				

Figure 5. Incidence (cases per 100,000 population) in United States of laboratory-confirmed bacterial and parasitic infection cases, by age group and pathogen, 2010. The source of the data is the Foodborne Disease Active Surveillance Network, United States, 2010 (http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6022a5.htm). Visual analytics resource to interact with data available at http://public.tableausoftware.com/views/foodnet2010/incidence.

outbreaks occurred. The visualization revealed that July had the highest frequency of outbreaks. Between the dimension bars are ribbons that connect categories and split up. This illustrates how combinations of categories are distributed and how a particular subset, for example, Month of July (Jul), can be further subdivided into vehicle (in this example, shrimp and raw oyster). It also illustrates that the vehicle (food) for the pathogen in WA (Washington) and OR (Oregon) was raw oysters while in GU (Guam) it was shrimp. The third horizontal

Table 3. Epidemiological characteristics of *Vibrio parahaemolyticus* infection outbreaks in the United States (1973–1987).*

Year	Month	State or territory	Vehicle	No. of persons exposed	No. of persons ill	Attack rate (%)
1973	February	California	Shellfish	4	2	50
1975	July	Louisiana	Boiled shrimp	700	100	14
1975	November	Guam	Octopus	590	122	21
1977	December	Virgin Islands	Seafood salad	1059	98	9
1977	October	Guam	Shrimp	400	20	5
1978	June	Louisiana	Boiled shrimp	122	82	67
1978	May	Guam	Shellfish	350	10	3
1978	June	Guam	Shellfish	8	8	100
1978	August	Guam	Shellfish	8	4	50
1979	February	Guam	Shrimp	40	3	8
1979	February	Guam	Shrimp	30	11	37
1980	October	Arizona	Shrimp	5	4	80
1980	April	Florida	Raw oysters	2	2	100
1980	July	Guam	Shrimp	5	3	60
1980	August	Guam	Shrimp	3	3	100
1981	February	Arizona	Seafood dinner	2	2	100
1981	February	Rhode Island	Shellfish	223	11	5
1982	August	Massachusetts	Raw clams	51	26	51
1982	July	New York	Steamed clams	300	10	3
1982	July	New York	Raw clams	3	3	100
1986	September	Washington	Shrimp	3	2	67
1987	July	Washington	Raw oysters	4	4	100
1987	September	Washington	Raw oysters	5	5	100

***Source:** Daniels et al.[46] Reproduced with permission to illustrate the use of visual analytics software on the data.

Table 4. Epidemiological characteristics of *Vibrio parahaemolyticus* infection outbreaks in the United States (1990–1998).*

Year	Month	State or territory	Vehicle	No. of persons exposed	No. of persons ill	Attack rate (%)
1990	August	Idaho	Oysters	Unknown	5	
1990	July	Washington	Raw oysters	Unknown	5	
1990	July	Washington	Raw oysters	12	9	75
1990	August	Washington	Raw oysters	9	2	22
1993	May	Washington	Unknown	Unknown	4	
1997	May	Washington	Raw oysters	Unknown	56	
1997	July	Oregon	Raw oysters	Unknown	13	
1997	June	California	Raw oysters	Unknown	11	
1997	September	California	Shark's fin/crabmeat	44	16	36
1998	January	Guam	Cross-contamination with seafood	150	47	31
1998	May	Florida	Steamed lobsters/shrimp	8	6	75
1998	June	Texas	Raw oysters	Unknown	296	
1998	June	North Carolina	Boiled shrimp	19	17	89
1998	June	Florida	Crabs	15	13	87
1998	June	California	Raw oysters, steamed shrimp	Unknown	4	
1998	July	New York, New Jersey, Connecticut	Raw oysters, clams	Unknown	23	
1998	July	Washington	Oysters	Unknown	2	

***Source:** Daniels et al.[46] Reproduced with permission to illustrate the use of visual analytics software on the data.

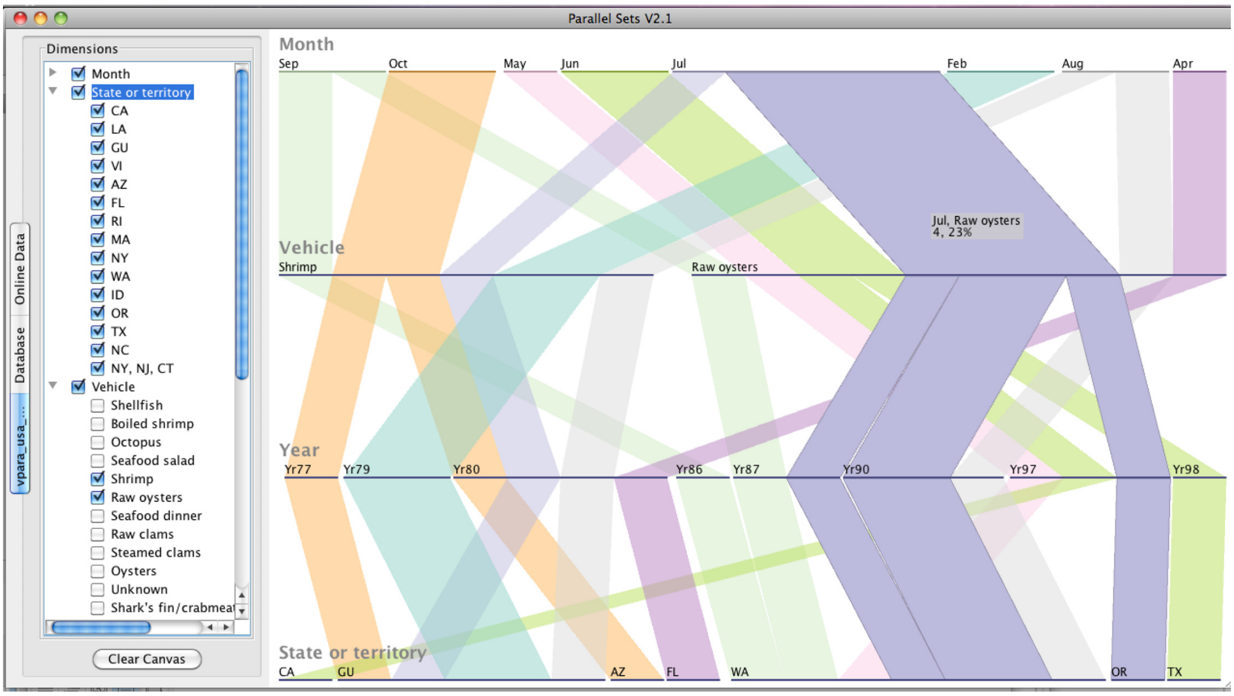


Figure 6. Interaction with data on epidemiologic characteristics of *Vibrio parahaemolyticus* infection outbreaks caused by shrimp and raw oysters in United States (1973–1998). This Parallel Sets visualization is for the rows with vehicle of pathogen labeled as "Shrimp" and "Raw oysters" (Table 4). A commonality observed from a visualization of the data was that in the month of July, outbreaks occurred in Guam (GU) in 1980, Washington in 1987 and 1990; and Oregon 1997. Additionally, one outbreak with "Shrimp" as vehicle occurred in GU in 1977 and in Arizona in 1980. See text for interpretation of data visualization.

bar represents the Year of outbreak and shows that two raw oyster-borne outbreaks in WA took place in 1990 and one outbreak took place in 1987. In the case of shrimp, the commonalities observed is that in October for both 1977 and 1980 outbreak with shrimp as vehicle occurred in Guam and Arizona.

Websites for interactive visual analytics of foodborne vibriosis surveillance data

Table 5 presents the dataset, sources of dataset, and links to web-based visualization. These views are designed to enable users interact with the dataset as well as to download raw or processed data for re-use. The surveillance data visualized were OutbreakNET, COVIS, and FoodNet.

Discussion

There are increasing efforts to develop visual analytics software that facilitates discussion between user and disease surveillance data for environmental and public health policy formulation, resource allocation, and decision making.[48–50] In this report, we have used a combination of data extraction and data visualization software to illustrate the integration and interactive visualization of surveillance data on foodborne vibriosis in the United States. The three datasets (OutbreakNet, COVIS and FoodNet) were individually processed in the Tableau Software[51,52] and the results of analysis were published on websites (Table 5). The websites permit download of datasets and further exploration of the data based on filters available on the website. In addition, Parallel Sets,[47] a visual analytics software for categorical data, was used to analyze epidemiological characteristics of *V. parahaemolyticus* infection outbreaks.

Through the data visualization it was possible to identify unique patterns and/or novel relationships within and across datasets regarding (i) causative agent, (ii) foodborne outbreaks and illness per state, (iii) location of infection, (iv) vehicle (food) of infection, anatomical site of isolation of *Vibrio* species, (v) patients and complications of vibriosis, (vi) incidence of laboratory-confirmed vibriosis, and *V. parahaemolyticus* outbreaks.

In the dataset analyzed for 1990 to 2006, *Vibrio parahaemolyticus* was the major cause of outbreaks (including multistate outbreaks) of foodborne vibriosis (Fig. 1, Table 1). *Vibrio parahaemolyticus* is

Table 5. Websites for interactive visual analytics of foodborne vibriosis surveillance data.

Dataset, sources of dataset and link to web-based visualization*
OutbreakNET—Foodborne vibriosis in the United States (1990 to 2006) (Fig. 1a).
Sources: (i) http://www.cdc.gov/outbreaknet/surveillance_data.html (ii) http://wwwn.cdc.gov/foodborneoutbreaks/
http://public.tableausoftware.com/views/USA_FOODVIBRIO_1990TO2006/USA_Foodborne1990to2006
OutbreakNET—Oyster-borne food service outbreaks of *Vibrio parahaemolyticus* infections integrated by state, month and year (Fig. 1b).
Sources: (i) http://cdc.gov/outbreaknet/surveillance_data.html (ii) http://wwwn.cdc.gov/foodborneoutbreaks/
http://public.tableausoftware.com/views/USA_FOODVIBRIO_1990TO2006/V_para_Oyster_borne_FoodService
COVIS—Patients and Complications
http://public.tableausoftware.com/views/USA_vibrio_isolates_2003to2006/Patient_Complication
COVIS—Site of Isolation
http://public.tableausoftware.com/views/USA_vibrio_isolates_2003to2006/Site_Isolation
FoodNet—Incidence of vibriosis from 10 States in the United States, 2004–2009.
Source: http://www.cdc.gov/foodnet/
http://public.tableausoftware.com/views/FoodNetIncidence2004to2009_1/FoodNet_Vibrio_Incidence_2004to2009
FoodNet—Incidence of laboratory-confirmed bacterial and parasitic infection cases, by age group and pathogen—Preliminary Data from 10 States in the United States, 210.
http://public.tableausoftware.com/views/foodnet2010/incidence

Note: *OutbreakNET: Annual Listing of Foodborne Disease Outbreaks, United States; COVIS: The Cholera and Other *Vibrio* Illness Surveillance System; FoodNet: The Foodborne Diseases Active Surveillance Network.

recognized globally as a major cause of foodborne gastroenteritis associated with seafood consumption with a higher incidence in Japan and East Asian countries.[53] Three major types of clinical illnesses cause by *V. parahaemolyticus* are gastroenteritis, wound infections, and septicemia. Recent classifications of *V. parahaemolyticus* have been made based on the presence of particular genes, some of which correlate with pathogenicity. For general species delineation, the thermolabile hemolysin (*tlh*) gene is used. *Vibrio parahaemolyticus* strains are considered "pathogenic" if the thermostable direct hemolysin *(tdh*) and/or TDH-related hemolysin (*trh*) genes are present. Pathogenicity of *V. parahaemolyticus* is associated with beta-hemolysis, adherence factors, various enzymes, and the products of the *tdh, trh,* and *ure* genes.[54]

Gastroenteritis caused by *V. parahaemolyticus* is almost exclusively associated with seafood consumed raw or inadequately cooked or contaminated after cooking. We have used the visualization in Figure 1 to identify outbreaks resulting in at least 100 cases (Table 1) to prioritize retrieval of additional information including journal articles and reports from states on foodborne outbreaks. We discuss those publications to further identify localized information that may have promoted the transmission of the *Vibrio* species.

The July to August 1997 multistate outbreak of culture-confirmed *V. parahaemolyticus* had 209 cases and was associated with eating raw oysters harvested from California, Oregon, and Washington in the United States and from British Columbia (BC) in Canada.[55] The largest *V. parahaemolyticus* oyster-borne outbreak (caused by single clone of O3:K6) was in 1998 with over 400 cases associated with oysters harvested from Galveston Bay, TX.[56] The exact number of cases in Texas was 296 (Table 4) with 120 other cases reported from 12 other states (California, Florida, Georgia, Oklahoma, Tennessee, Colorado, Virginia, Alabama, Kentucky, Massachusetts, New Jersey, and Missouri).[56] This number of cases was not classified as a multistate outbreak because OutbreakNET defines a multistate outbreak as one in which exposures occurred in more than one state, while an outbreak affecting residents of more than one state due to exposures in a single state is considered to be a single-state outbreak.

In 2003, an outbreak of *V. parahaemolyticus* in Florida resulted in 115 infected persons (Fig. 1). We obtained additional information on the outbreak through the 2003 Food and Waterborne Illness Surveillance and Investigation Annual Report, Florida.[57] The outbreak was due consumption of Seafood Newburg prepared by a caterer in Pinellas County.[57,58] The 2006 *V. parahaemolyticus* infection outbreaks in New York resulted in 108 cases (Fig. 1) with three outbreaks reported in New York City.[59] Further, there were 3 confirmed and 2 suspected *V. parahaemolyticus* related outbreaks in 2006, compared with only 1 confirmed outbreak and 1 suspected outbreak in the previous five years. This trend is captured in Figure 1 (see NY row for *V. parahaemolyticus*). The outbreak in New York was linked to the multistate outbreak in Oregon, Washington, and British Columbia.[60–62] Between 2004 and 2009, the FoodNet determined that the incidence of foodborne vibriosis in a California population of 3.21 million was highest in 2006 at 1.15 per 100,000 cases (Table 2 and Fig. 4). Additionally in 2006, OutbreakNET reported two *V. parahaemolyticus* infection outbreaks of 10 and 27 cases in California (Fig. 1).

Subtyping of selected *V. parahaemolyticus* isolates in the 2006 outbreaks identified serotype O4:K12 as the causative serotype. In 1997, isolates from serotype O4:K12 were one of the serotypes that caused outbreaks in the Pacific Northwest.[55] The draft genome sequence of a *V. parahaemolyticus* serotype O4:K12 strain has recently been announced.[63] The availability of genomic sequences of diverse *Vibrio* species ushers a new era for genome-based surveillance of foodborne vibriosis.

Vibrio vulnificus infection can cause septicemia in a person with an open wound who has been in close contact with waters infected with *V. vulnificus*.[64] Further, there are two key features of *V. vulnificus* pathogenesis: (1) extreme destruction of host tissues and (2) the rapid proliferation of the bacteria in the host. The most important virulence factor for *V. vulnificus* is its capsular polysaccharide (CPS), which assists the species in avoiding phagocytosis by host defense cells and complement. *Vibrio vulnificus* carries one of the highest mortality rates of any bacterial pathogen and is the leading cause of reported death in the United States related to seafood consumption.[65] The hospitalization rate and case-fatality rate for *V. vulnificus* infection have been reported as 0.910 and 0.390, respectively.[66] These high hospitalization and mortality rates are illustrated in the integrated view of the patterns of patients, complications, and sites of isolation of *Vibrio* species (Fig. 3). Blood and wound are the predominant isolation sources of *V. vulnificus*, consistent with known pathogenic characteristics of the bacteria.[65,66] Most cases of *V. vulnificus* infection are found in males whose immune system is suppressed or who have underlying diseases with concomitant elevated serum iron levels, primarily liver cirrhosis secondary to alcoholism.[67] The age group with highest incidence of *Vibrio* infections according to the 2010 FoodNet data was 60 years or over (captured in Fig. 5). The virulence factors of *V. vulnificus* are still poorly characterized. However, the increasing use of genomic and genetic analysis in conjunction with detailed animal models is shedding new light into the pathogenesis of *V. vulnificus* disease.[68]

Using Tables 4 and 5, we have illustrated integrated visualization of categorical data (year, month, state or territory and food vehicle) associated with *V. parahaemolyticus* outbreaks from 1973 to 1998. Public and environmental health data are often collected in categories requiring statistical methods to model and find associations between categorical variables.[69,70] Interactive exploratory analysis via visual interfaces to identify partitions in a dataset can prevent missing information on noteworthy associations between variables.[71] A total of 17 pathogen vehicle types were present in the dataset (Fig. 6) including "Raw Oysters" and "Shrimp". In both oysters and shrimps, *V. parahaemolyticus* is part of their natural bacterial flora.[72,73] Consumption of raw oysters is a recognized risk factor for foodborne vibriosis caused by *V. parahaemolyticus* and *V. vulnificus*.[74–76] Visual analytic methods such as geovisual analytics storytelling[77,78] that integrates multidimensional data including spatial and temporal data could help enhance the education of producers and consumers of seafood on foodborne vibriosis. In particular, public health advisories as well as annual reports on vibriosis outbreaks when presented in the context of spatial and temporal events can be supplement to advisories and reports disseminated via electronic and print versions.

Foodborne vibriosis surveillance data for United States from 1973 to 2010 were analyzed in this research. *Vibrio* species are among the 31 major known pathogens transmitted through food in the United States.[13] There are also concerns in Europe and other parts of the world of the increasing numbers of illness by non-cholera *Vibrio* that may be linked to rising temperature of the oceans.[79–83] The increasing incidence of non-cholera vibrios linked to global climate change may lead to worldwide surveillance system to document data on temporal and spatial incidence of non-cholera *Vibrio* infections.[82] Further, new estimates of the burden of foodborne pathogens based on better data sources and methods are now available through the CDC.[12,13,84] These recently published datasets as well as future global surveillance data present opportunities for the application of visual analytics methods to gain actionable insights from foodborne disease surveillance data.

Conclusion

In this research article, we have demonstrated the use of visual analytics techniques to facilitate user discourse with datasets on foodborne vibriosis in the United States. The additional use of emerging visual analytics approaches for interaction with data on vibriosis, including non-foodborne (ie, occupational exposure), can guide disease control and prevention as well as during outbreaks by identifying commonalities.

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