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## GIScience 2021 Short Paper Proceedings

### Title

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### Permalink

<https://escholarship.org/uc/item/5016t2k9>

### Authors

Noi, Evgeny  
Rudolph, Alexander  
Dodge, Somayeh

### Publication Date

2021-09-01


### DOI

10.25436/E2WC7B

Peer reviewed

# 1 A novel method for mapping spatiotemporal 2 structure of mobility patterns during the 3 COVID-19 pandemic

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5 **Evgeny Noi**<sup>1</sup> 

6 Department of Geography, UC Santa Barbara  
7 noi@ucsb.edu

8 **Alexander Rudolph**

9 Department of Statistics and Applied Probability, UC Santa Barbara  
10 arudolph@umail.ucsb.edu

11 **Somayeh Dodge** 

12 Department of Geography, UC Santa Barbara  
13 sdodge@ucsb.edu

## 14 — Abstract —

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15 Many classic exploratory data analysis tools in quantitative geography, designed to measure global  
16 and local spatial autocorrelation (e.g. Moran's  $I$  statistic), have become standard in modern GIS  
17 software. However, there has been little development in amending these tools for visualization and  
18 analysis of patterns captured in spatiotemporal data. We design and implement a new open-source  
19 Python library, VASA, that simplifies analytical pipelines in assessing spatiotemporal structure of  
20 data and enables enhanced visual display of the patterns. Using daily county-level social distancing  
21 metrics during 2020 obtained from two different sources (SafeGraph and Cuebiq), we demonstrate  
22 the functionality of the developed tool for a swift exploratory spatial data analysis and comparison  
23 of trends over larger administrative units.

## 27 **1** Introduction

28 Many political, social, and economic processes are geographical in nature and are, therefore,  
29 subject to first order non-stationary effects (spatial heterogeneity) and second order stationary  
30 effects (spatial autocorrelation), which may be scale-specific [8]. These effects invalidate  
31 two assumptions of classic inferential (confirmatory) statistics, namely independence and  
32 identical distribution, making usage of traditional statistical tools problematic. In classical  
33 statistical modeling, these violations may lead to instability in parameter estimation and  
34 biasedness. To account for these spatial effects, different methods from spatial statistics  
35 were devised, including tools for exploratory spatial data analysis, such as local indicators of  
36 spatial association (LISA) [3]. ESDA, an extension of conventional exploratory data analysis  
37 (EDA), combines various graphic and numerical statistical techniques designed to generate  
38 hypothesis and detect spatial patterns in data.

39 Currently, there are many software implementations designed to gauge spatial associations  
40 in areal data [7]. Recent progress in computational methods and advances in locational

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<sup>1</sup> Corresponding author

## 2 Mapping spatiotemporal structure of mobility

41 data acquisition technologies have made calculation of local multivariate spatial association  
42 [4, 5] and spatio-temporal pattern mining [10, 9] more manageable. However, the graphic  
43 display for many of the outlined tools has not changed within the last 10 years and is not  
44 ideally suited for spatial-temporal analysis on multivariate data sets. In fact, many current  
45 research investigations rely on static two-dimensional choropleth maps, space-time cubes,  
46 and Moran’s scatter plots. In this study, we develop three visualization techniques that  
47 help identify spatiotemporal structure of the data. These techniques which are developed  
48 as a Python package are based on conventional LISA and are ideally suited for analysis of  
49 spatiotemporal areal data. The developed Python package, named VASA, will be accessible  
50 at <https://github.com/move-ucsb/VASA>. To demonstrate the applicability of the designed  
51 visualizations, the variability in spatiotemporal structure of human mobility patterns during  
52 COVID-19 pandemic in the United States is assessed.

### 53 2 Methods

54 VASA offers three novel multivariate visualizations: A *stacked recency and consistency map*,  
55 a *line-path scatter plot*, and a *categorical strip (dot) plot*. All three techniques use LISA as  
56 the base and utilize local Moran’s  $I$  and permuted  $p$ -values. The techniques are best suited  
57 for analysis of areal data at two levels of analysis: the object-level and the summary-level.  
58 The object-level of analysis receives the data at the finest available scale (e.g. county, census  
59 blocks, etc.), whereas the summary-level (e.g. state) refers to the less granular spatial  
60 units that contain object-level units. The stacked recency and consistency map allows to  
61 ascertain the spatiotemporal structure of data at both object- and summary-level. The  
62 categorical strip plot allows for comparison of trends at the summary-level. The line-path  
63 visualization is better suited for a fine-detail analysis of individual object-level trajectories  
64 within a specified summary-level. The developed visualizations can be made interactive and  
65 web-based, allowing user interaction to enhance user exploration performance<sup>2</sup>.

#### ■ Algorithm 1 Recency and consistency mapping algorithm.

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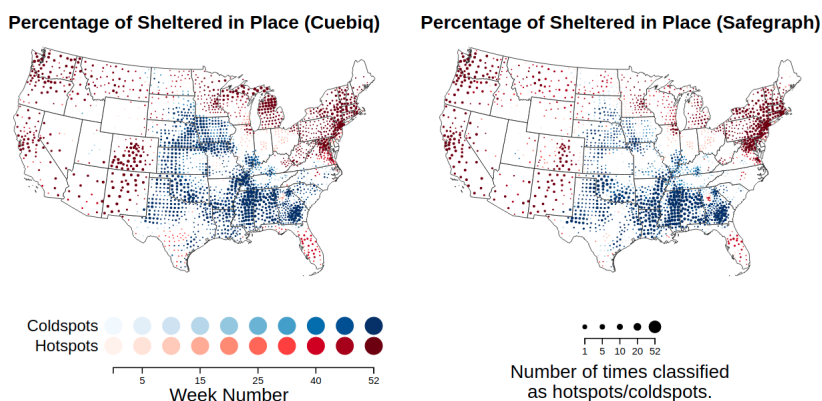
```
set spatial (e.g. county) and temporal (e.g. week) unit for aggregation;  
for each aggregate spatial ( $i$ ) and temporal unit ( $j$ ) do  
    calculate local Moran’s  $I$  ( $I_{ij}$ ) and permuted  $p$ -value;  
    recode statistically significant values ( $\alpha = 0.05$ ) of  $I_{ij}$  according to Moran’s  
    scatterplot quadrants (i.e. hotspots and coldspots);  
    calculate cumulative sum of classifications for coldspots ( $S_c$ ) and hotspots ( $S_h$ );  
    retain the week number the county was classified as either coldspot ( $W_c$ ) or  
    hotspot ( $W_h$ );  
end  
map county polygons to centroids and display as a marker;  
map retained hotspots to red color and coldspots to blue color;  
map the cumulative sums ( $S_c, S_h$ ) to the size of the marker;  
map retained week numbers ( $W_c, W_h$ ) to the intensity of marker color;
```

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<sup>2</sup> See <https://move-ucsb.github.io/covid19-mobility-vis/> for some examples.

## 2.1 RECO: the stacked recency and consistency map

The stacked recency and consistency map (RECO) improves traditional graphic representation of local Moran's  $I$  using several visual variables (e.g. color hue and value, shape, size, texture, transparency) [6] to better illustrate spatial and temporal structure of data. The mapping algorithm is described in Algorithm 1. An example of the generated RECO map is illustrated in Figure 1, and explained later in the Case Study section. Note that the RECO map is a snapshot and static representation of the accumulative patterns up to the last data frame. To represent changes over time dynamically, the RECO can be animated for various timelines.



**Figure 1** The stacked recency and consistency map of mobility. The color represents hotspots (red) and coldspots (blue). The hue denotes the week number, and not the intensity of hotspot/coldspot. For cases when the county was a hotspot/coldspot for more than one week, the hue intensity denotes the hue for the most recent week. The size of the marker corresponds to the number of weeks the county was classified as either a hotspot/coldspot.

**Algorithm 2** The line-path scatter plot algorithm.

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```

set spatial (e.g. county) and temporal (e.g. week) unit for aggregation;
for each aggregate spatial ( $i$ ) and temporal unit ( $j$ ) do
    calculate local Moran's  $I$  ( $I_{ij}$ ) and permuted  $p$ -value;
    recode statistically significant values ( $\alpha = 0.05$ ) of  $I_{ij}$  according to Moran's
    scatterplot quadrants (i.e. hotspots and coldspots);
    calculate cumulative sum of classifications for coldspots ( $S_c$ ) and hotspots ( $S_h$ );
    retain the week number the county was classified as either coldspot ( $W_c$ ) or
    hotspot ( $W_h$ );
end
plot the cumulative sums ( $S_c, S_h$ ) against the week number;
map retained hotspots to red color and coldspots to blue color;
mark the cumulative sum on the last week number of classification with a circle;

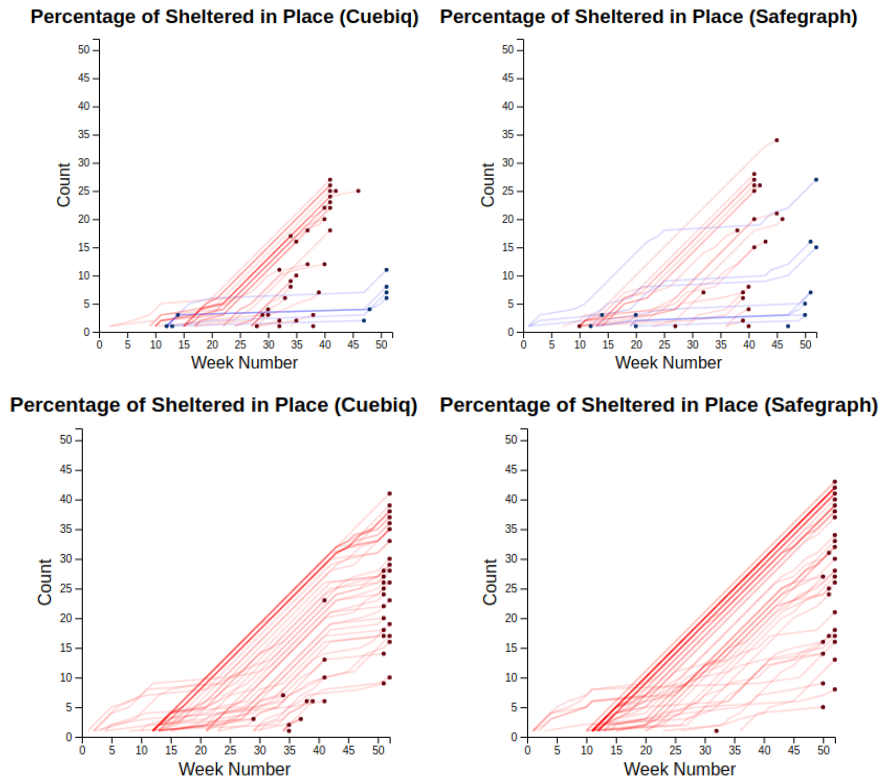
```

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## 2.2 Line-path scatter plots

To provide an analyst with a better view of trends for individual counties (or, potentially, any other spatial units) the line-path scatter plots (Algorithm 2) is developed. This visualization

4 Mapping spatiotemporal structure of mobility

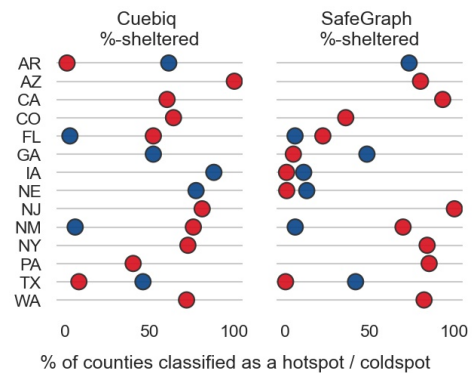


■ **Figure 2** Line-path of social distancing metrics for counties in Florida (top row) and counties in California (bottom row). Each line traces the cumulative number of times a county is identified as a hotspot or coldspot.

77 uses a line for each county to represent the cumulative number of times it has been identified  
 78 as a hotspot or coldspot. Compared to RECO, this representation has the advantage of  
 79 being able to show county behavior over time (e.g. at each week), instead of just the final  
 80 time point. Figure 2 illustrates an example of the line-path scatter plot (see Case Study).

81 **2.3 The categorical strip (dot) plot**

82 The primary purpose of the categorical strip plot is to combine the LISA clusters with  
 83 a categorical locational variable, such as  
 84 U.S. states. Unlike RECO, this visualization  
 85 provides an aggregate aspatial view of  
 86 the data to ease the comparison between  
 87 different variables or data sources. The al-  
 88 gorithm that creates visualization is detailed  
 89 in Algorithm 3. An example of the categor-  
 90 ical strip (dot) plot is provided in Figure 3,  
 91 and further explained in Case Study.  
 92



■ **Figure 3** Strip (dot) categorical plot for mobility metrics.

■ **Algorithm 3** Categorical strip (dot) plot algorithm.

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```

set spatial (e.g. county) and temporal (e.g. week) unit for aggregation;
for each aggregate spatial (i) and temporal unit (j) do
    calculate local Moran's I ( $I_{ij}$ ) and permuted p-value;
    recode statistically significant values ( $\alpha = 0.05$ ) of  $I_{ij}$  according to Moran's
    scatterplot quadrants (i.e. hotspots and coldspots);
    calculate cumulative percentage of classifications for coldspots ( $P_c$ ) and hotspots
    ( $P_h$ );
end
aggregate cumulative percentage ( $P_c, P_h$ ) at the state level into  $P_{sc}, P_{sh}$ ;
map aggregated percentages ( $P_{sc}, P_{sh}$ ) on the x-axis;
map states on the y-axis;
map retained hotspots to red color and coldspots to blue color;

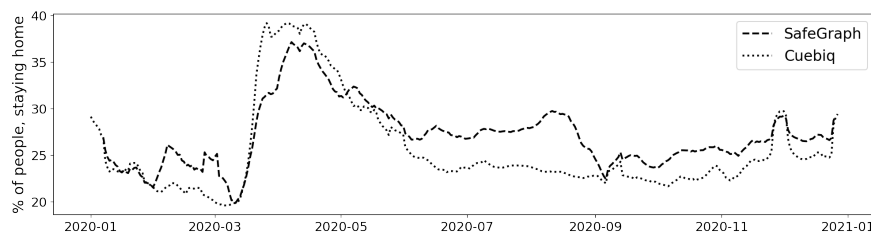
```

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93 **3 Case study: investigating**  
 94 **spatiotemporal structure of mobility during COVID-19 pandemic**

95 **3.1 Data**

96 In order to demonstrate the applicability of the developed visualization techniques, two social  
 97 distancing mobility metrics are used. These indices include *% sheltered in place, weekly rolling*  
 98 *average*<sup>3</sup> obtained from Cuebiq and *% sheltered, weekly average* obtained from SafeGraph.  
 99 The choice of these two sources is intentional: Cuebiq [1] provides data by subscription, while  
 100 SafeGraph [2] provides data free of charge through an open data consortium. Both data  
 101 sources are widely used in COVID-19 related research. More importantly, they provide a full  
 102 coverage across the U.S. and throughout 2020 which make them easily comparable. The data  
 103 are collected daily<sup>4</sup> at the county level for all of the United States for a total of 12 months of  
 104 observation in 2020. Figure 4 below plots the time series of 7-days rolling national average  
 105 for the observation period. Both metrics illustrate sharp increase in the percentage of people  
 106 staying home at the start of the pandemic and initiation of governmental cordoning policies  
 107 in March 2020, followed by a steady decline over the summer. However, some differences are  
 108 observed in the captured patterns using these indices.



■ **Figure 4** Mobility metrics from Cuebiq and SafeGraph used for demonstration purposes

<sup>3</sup> *% sheltered* indicator measures the percentage of population, staying at home, where the location of *home* is identified computationally based on proprietary algorithms of Cuebiq and SafeGraph.

<sup>4</sup> We aggregate data by week to make computations more manageable for demonstration purposes.

109 **3.2 Experimental results**

110 Figure 1 illustrates the recency and consistency map of the produced spatial clusters, assessed  
 111 via LISA. In this figure, Cuebiq is depicted on the left and SafeGraph is plotted on the right.  
 112 Cluster ‘recency’ (i.e. how recent a cluster appeared towards the end of 2020) is mapped to  
 113 the color gradient. That is, the hotspots/coldspots occurring in the beginning of 2020 are  
 114 denoted in lighter shades of red/blue. Conversely, more recent clusters are visualized in darker  
 115 shades. Cluster consistency (i.e. how frequently a cluster appeared throughout 2020), defined  
 116 as the number of weeks the county was consistently ranked as either a hotspot or coldspot,  
 117 is mapped to the centroid marker size. That is, the higher consistency values correspond to  
 118 proportionally larger marker sizes. While the location of coldspots in both sources is centered  
 119 in the South for both data sets, with the core in Northern Texas, Mississippi, Alabama,  
 120 Louisiana and Georgia, a higher cluster consistency (i.e. bigger markers) is observed in  
 121 Cuebiq data for Nebraska, Iowa and Kansas. The location of hotspots is similar in the  
 122 Northeastern states, Great Lakes region, and in Western United States for both data sources,  
 123 but the recency and consistency is higher (i.e. darker and bigger markers) for Cuebiq data in  
 124 Wisconsin and Michigan. In both sources, the states with some of the least recent hotspots  
 125 are situated in Indiana and Ohio. It is necessary to remark that here, the hotspots represent  
 126 a lower mobility in the area (higher percentage of sheltered-in-place population).

127 Figure 2 illustrates individual trajectories for counties in Florida and California. These  
 128 two states are selected for illustration purposes because they had different non-pharmaceutical  
 129 policies. Top row shows the spatiotemporal paths of counties in Florida. As we can see,  
 130 there are counties that remained hotspots (higher percentage staying home) and coldspots  
 131 (lower percentage of people staying home) during the observation period. Both SafeGraph  
 132 and Cuebiq show consistent hotspot behavior for counties starting from week 10 to week 40,  
 133 when the governor opened the Florida’s economy. On the other hand, only a few counties  
 134 were consistent coldspots. California (bottom row Figure 2) is a completely different story:  
 135 none of the counties were classified as coldspots, and a lot more counties were consistent  
 136 hotspots starting from week 10, when the stay-at-home order was issued. These group of  
 137 counties remained consistent until the end of 2020, which can be seen from the slope of the  
 138 lines, where the slope of 1 indicates that the county was classified as either a hotspot or a  
 139 coldspot each week for each particular segment.

140 Figure 3 illustrates the resulting summaries as a series of scatter plots, where each state  
 141 is marked on the y-axis, and there is a separate column for each data source<sup>5</sup>). The location  
 142 of each marker on the horizontal axis denotes the percentage of coldspots/hotspots (from the  
 143 total number of counties within a state). The blue markers indicate coldspots and the red  
 144 markers indicate hotspots. It is not uncommon for some states to include counties of both  
 145 cluster types. In such cases, two markers (blue and red) per line are visualized. The primary  
 146 goal of this visualization is to summarize and communicate the differences in spatial structure  
 147 across various mobility indices or data sources for different states. The visualization can be  
 148 read vertically and horizontally. Vertically, it allows to assess the overall split between the  
 149 hotspots and coldspots, and to identify the states which are primarily hotspots, coldspots or  
 150 a combination of both. Horizontally, it allows a comparison in three dimensions: state-level,  
 151 source-level, and indicator-level.

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<sup>5</sup> For demonstration purposes and due to limitation on the size of the submission only a subset of states is selected

## 4 Conclusion

This paper demonstrated the applicability of three developed visualization techniques for assessing spatiotemporal structure of mobility during COVID-19. When combined, these techniques provide an effective visual analytic tool to identify micro and macro patterns in data at different scales by identifying consistent spatial clusters with statistically significant observed spatial dependence. By adding a temporal component, the presented mapping techniques will help identify primary interest areas for further more detailed and fine-grained analysis. Furthermore, these tools provide enough flexibility to switch between the level of detail and efficiently track individual trajectories of various administrative units. These package can be further extended to allow aggregation and analysis of various geographic processes on irregular lattice. In the course of the next few months, user studies will be conducted to improve the interface and assess the effectiveness of the tool.

## 5 Acknowledgements

The authors gratefully acknowledge the support from the National Science Foundation Award BCS # 2043202 “CAREER: Modeling Movement and Behavior Responses to Environmental Disruptions”.

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