# Design and Usage of an Ozone Mapping App

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## ABSTRACT

With the proliferation of environmental sensor networks, real-time, quantitative, and localized pollutant information has become available for a few big cities. Several mobile apps have been developed to bring this information to the user 24/7. In contradistinction to conventional weather reporting systems that provide a qualitative and static description of pollutant levels for an entire metropolitan area, these new apps dynamically relay quantitative pollutant measurements at high spatial resolution. No design methodology has been rationalized for pollutant apps thus far. And, although such apps have potential impact to public health, their actual user base and usage have not been investigated. We have fielded an ozone mapping app for the Houston area. Ozone is a harmful environmental pollutant developing under certain conditions in major metropolitan centers. We use this as a case study to put forward a design philosophy for pollution apps in general. We also analyze the app's user portrait and her/his interaction patterns. The results of our study can inform the development and marketing of similar apps in this burgeoning field.

## Categories and Subject Descriptors

H.5.m [**Information Interfaces and Presentation**]: Miscellaneous; J.3 [**Computer Applications**]: Life and Medical Sciences—*Health*

## General Terms

Design, Experimentation, Human Factors, Measurement

## Keywords

Pollution, pollution apps, app design, pollution visualization, air quality monitoring, ozone, user studies


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## 1. INTRODUCTION

Reporting of environmental pollution levels has been mostly qualitative. For example, 'Ozone Alert - avoid outdoor activities', accompanied by a warning symbol is a typical message in weather bulletins. The recent installation of environmental sensor networks in metropolitan areas, however, has made feasible the acquisition of real-time quantitative pollutant information across space [1][6]. Such detailed and live information can help people to plan their localized outdoor activities with greater freedom. Relevant smartphone apps have appeared in the App Store and the Android Market, rendering this information ubiquitous.

How to represent this newly minted data in order to facilitate communication and user interaction is an open question. Issues of pollution are politically charged. Local agencies and advocacy groups (the guardians of environmental data), often come with their own ideological preconceptions masqueraded as design proposals. Poorly conceived and often conflicting interfaces undercut the usefulness and potential of these applications. The problem is exacerbated by the small display factor in mobile devices. Things look especially bleak if one considers the future integration of the various environmental reports in a composite mapping interface. Adopting competing design philosophies, such integrated maps would pose usability challenges.

Here we present an iPhone app for reporting the spatiotemporal evolution of ozone plumes in the Houston metropolitan area, where a distributed network of environmental sensors has been installed. A unique feature of this app is the interpolation among sensor stations, which yields a continuous measurement plane superimposed on the corresponding geospatial map. Other apps provide quantitative ozone information for the closest sensor station [2][11] or a broader area [10][8], leaving the user to guess the current ozone level in her/his exact location. On the other end of the spectrum, mobile ozone sensor systems inform the user of ozone levels in her/his exact location but no further [5][12].

Please note that apps relaying ozone measurements from the closest tower may introduce a significant error, providing a disservice to the user. Consider the following illustrative example: Assume the ozone sensors have been laid out in a square grid with edge X, where X is typically several miles. Moreover, assume that the user walks outdoors in an area closest to sensor [2,2] and inside an ozone plume that spreads from her/his locale all the way to sensors [1,1], [1,2], and [2,1] (Fig. 1). The plume, however, stops short of sensor [2,2], which shows 'all clear'. Unfortunately, this is the sensor that would provide the measurement to the user, based on the shortest distance criterion. By contrast, a weighted measurement from all neighboring sensors would provide a significantly higher ozone value, appropriately alerting the user.

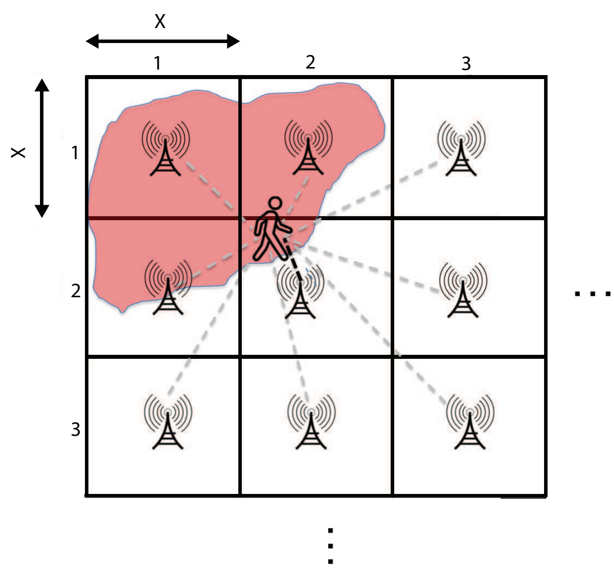


Figure 1: Illustrative example of significant error, if the value of the closest ozone sensor is used instead of an interpolated value among all the neighboring ozone sensors. The red area indicates the ozone plume.

Our app's high spatial resolution over an extended region is a harbinger of things to come; it poses both a design opportunity and a challenge, about which we comment in this paper. In fact, we reported in [13] our initial design deliberations and the perceptions of potential users, prior to the app's release in the App Store. In this paper we report the results of a usability study on actual users, following the app's release in the App Store, which brings closure to the design issue. We also report the collection and analysis of user profiles and usage patterns. This is important information that is likely to improve the development and marketing strategies for such apps in the future.

## 2. BACKGROUND

Ozone in high concentrations is a harmful pollutant and physical activity is highly discouraged in its presence [4]. The Environmental Protection Agency's (EPA) standard is 75 parts per billion (ppb) [7]; beyond that, ozone levels are unhealthy, first for sensitive groups, and above 95 ppb for everybody. Sensitive groups include people who suffer from asthma and other respiratory ailments.

In the presence of sunlight, chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC) create ground level ozone. Emissions from industrial facilities and motor vehicle exhaust are the major sources of NOx and VOC. Hence, ozone pollution is produced in certain parts of a metropolitan area and then it is transported by the prevailing winds [9] - aka ozone cloud.

The purpose of our *OzoneMap* app [3] is to communicate the ozone movement for the last two hours. Presently, the app can do this for Houston only, but soon it will expand to include additional cities. Forty (40) ozone sensors, distributed across an area of 7,665 square miles in greater Houston, send measurements to our server every 5 min. These measurements are interpolated, forming a smooth 2D matrix that maps to the geographic region under monitoring. Sequencing of these matrices for the last 2 hours forms a 3D matrix, which captures the ozone's spatiotemporal evolution. If the matrices' values are color mapped, then an animation can be formed depicting the recent movement of ozone clouds.

Please note a number of characteristic factors that define the transitional and critical character of the *OzoneMap* and other similar apps:

1. It is unlikely that such apps will remain stand-alone for very long. Ozone clouds constitute man-made weather and naturally belong to weather apps. Real-time ozone mapping can also be linked to physical activity apps (walking, running, and biking), as this information mostly concerns users who are physically active outdoors.

2. These apps provide information for specific metropolitan areas with acute ozone problems and a sensor network in place (e.g., Houston). As the infrastructure is being developed in other metropolitan areas, such information will become commonplace for cities across the United States and beyond.

3. There is currently emphasis on ozone, but information about other environmental pollutants (e.g., particulates) is coming online as well.

4. These apps are not directly predictive. They let the user know how the ozone cloud has been developing the last couple of hours, leaving her/him to guess what is going to happen next. Hence, information clarity is especially important.

## 3. APPLICATION DESIGN

We adopted a bare bones app design borrowing familiar user interface elements from other weather apps. The targeted user is a person who is physically active outdoors (e.g., walker) and may or may not belong to the sensitive group. S/he needs a fast answer to a simple question: 'Should I do it right now or not?' Hence, by definition the app does not warranty long user visits, where extensive options and features might have been useful. In fact, we expect the average visit to last a few seconds.

The app's opening screen is the map of the user's surrounding region (as determined by the phone's GPS reading), with a default pin at her/his position communicating the current ozone level (Fig. 2 and 3). The user may add more pins by tapping any specific point on the map. At the bottom of the screen the user can tap on the play icon to visualize the ozone cloud movement the last two hours. At the top of the screen there is a color index that helps the user to interpret the health impact of the evolving ozone clouds. The user can select the type of map (standard, satellite, or

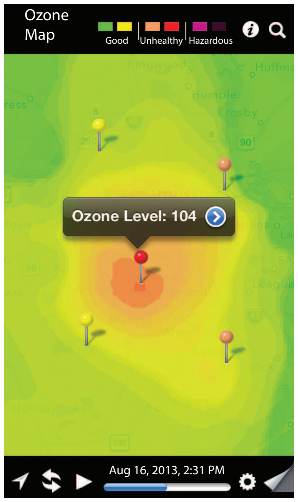


Figure 2: Flag style skin, where healthy, marginal, and unhealthy levels of ozone are represented by solid colors.

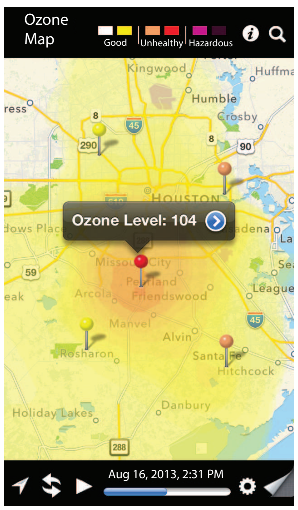


Figure 3: Radar style skin, where only marginal and unhealthy levels of ozone are represented by transparent colors.

hybrid) and can search for a specific address to refocus the displayed map - both typical features in map applications.

The map covers $\sim$ 90% of the application's real estate and thus, the superimposed color annotation for ozone levels greatly affects the way the user perceives information and interacts with it. Hence, the ozone color mapping scheme is the major interface issue at stake.

Two schools of thought formed within the project team across stakeholder lines (environmental scientists and advocacy groups versus interface designers) regarding color mapping:

**Flag Style:** Keep the legacy color mapping favored by environmental agencies and groups, where green represents safe levels of ozone, yellow represents marginal levels, and hues of red represent unsafe levels (Fig. 2).

**Radar Style:** Replace the green color with clear coat and enhance the transparency of the other colors (Fig. 3).

The main argument for the *flag style* thesis was conformity to the established standard of reporting environmental events - every event (safe or unsafe) needs to be vividly flagged. An event that is not flagged may be open to misinterpretation and subsequent litigation. The *radar style* thesis was based on a design philosophy that brings to bear the appropriate metaphors in order to improve usability and ensure scalability. Ozone and other pollutants constitute man-made weather elements. For natural weather, a number of well-established visualization schemes exist to depict important phenomena captured in high spatiotemporal resolution with modern sensor technology. Hence, if for each pollutant we determine the natural weather analogue, then we can borrow the respective visualization scheme, capitalizing upon successful (and truly relevant) prior research and practice.

The natural analogue to ozone clouds is storm clouds. We reached this conclusion through systematic comparison of the key characteristics between the two phenomena. The ozone clouds, much like the storm clouds, are locally produced and are transported by the winds. This means that they are characterized by relatively sharp borders (inside vs. outside the phenomenon) and are usually on the move. Also, the ozone clouds, much like the storm clouds, are not the norm; most of the time there are neither storms nor high ozone levels in a locality. Finally, storm clouds can be tracked with high spatiotemporal resolution by radar; ozone clouds can also be tracked with high spatiotemporal resolution via interpolation of sensor network values.

There are two fundamental differences between the *flag* and *radar style* designs: (a) The former fails to account for technological change and uses the wrong metaphor for ozone visualization. (b) The latter reckons with technological change and through a systematic process selects the correct metaphor. Indeed, the legacy color annotation scheme for ozone levels was conceived in an era that only static, scalar information was available for a metropolitan area (e.g., normal ozone levels for Houston on October 24, 2002). In this case a single color flag for an entire region, which was valid for a day or more, was highly appropriate. There was no need to superimpose this uniform information on a map - it was typically accompanying a textual description as a side flag.

The wrong analogue can adversely impact usability, while the correct analogue can greatly facilitate it. Under the *flag style* visualization scheme the geo map will be covered all the time with solid colors, reducing legibility. Given the intended use of this technology in guiding runners and bikers who make heavy use of map information, the *radar style* visualization appears a better choice.

Interestingly, we opted to incorporate both color mapping schemes in the Settings interface as options, randomizing the default upon the app's download. The interactive help page of the app clearly explained the two color maps and the user was free to change the default option any time s/he pleased. By following this strategy we wanted to test the following hypothesis: Given several options, the persistent user will gravitate on his/her own towards the option that best suits her/him. Hence, competing design schemes can be simultaneously accommodated in an app and left to naturally flourish or perish.

## 4. RESULTS

Two important goals of this research were to: (a) draw the portrait of the OzoneMap user and (b) capture the app's usage patterns. To fulfill these goals we collected online data from August 1 to September 13, 2013 per an approved protocol by the Institutional Review Board of the University of Houston. This is the period of the year with the most frequent ozone alerts in the Houston area. Upon first launch, each user was assigned a unique id and was requested to provide information about his/her age, gender, outdoor activity (if any), and whether s/he had any breathing problems or not (Table 1). For the outdoor activity, the questionnaire was giving the user the option to choose between physically active outdoors and non-active outdoors. If the user were physically active outdoors s/he needed to specify details of her/his preferred physical activities by checking accordingly the following boxes: Walking ($\mathcal{W}$) AND/OR Biking ($\mathcal{B}$) AND/OR Hiking($\mathcal{H}$) AND/OR Soccer ($\mathcal{S}$) AND/OR Other ($\mathcal{O}$). After this point, the application would send a timestamped log of user interactions to our server; these included logins and change of color map preferences.

Table 1: Questionnaire delivered upon user registration.

| # | Question | Value |
|---|---|---|
| Q1 | Gender | Female OR Male |
| Q2 | Age | Numeric |
| Q3 | Outdoor Activities? | $\mathcal{W}\|\mathcal{B}\|\mathcal{H}\|\mathcal{S}\|\mathcal{O}$ OR None |
| Q4 | Breathing Problems? | Yes OR No |

### 4.1 User Portrait

To facilitate a meaningful data analysis, we categorized the users according to the intensity with which they used the application - a variable we termed User Persistence (UP). Table 2 shows the UP breakdown. UP0 represents the 'curious' category - users who downloaded the application, checked it once and never opened it again. UP1 represents the bulk of the user base - people who downloaded the application and used it a few times. UP2 represents the committed category of users who used the app nearly half of the time during the performance period - it is a sizable minority. UP3 and UP4 represent the core of fanatics who used the app nearly every day. We define as fleeting users the union of UP0 and UP1 ($\mathcal{F}$=UP0 ∪ UP1) and as persistent users the union of UP2, UP3, and UP4 ($\mathcal{P}$ = UP2 ∪ UP3 ∪ UP4).

Table 2: Definition of User Persistence

| UP | Criteria | # users |
|---|---|---|
| 0 | days $\leq 1$ | 114 |
| 1 | $1 <$ days logged $\leq 10$ | 240 |
| 2 | $10 <$ days logged $\leq 20$ | 53 |
| 3 | $20 <$ days logged $\leq 30$ | 10 |
| 4 | $30 <$days logged | 10 |

Over 90% of the users stated that were physically active outdoors in one or more activities and about 27% of the users had breathing problems. Based on the possible combinations between these two attributes we partitioned the user base into four groups: **BA**: Users with Breathing problems and physically Active outdoors. $\mathbf{BN_A}$: Users with Breathing problems and physically Non-Active outdoors. $\mathbf{N_BN_A}$: Users with No Breathing problems and physically Non-Active outdoors. $\mathbf{N_BA}$: Users with No Breathing problems and physically Active outdoors. Fig. 4 shows the distribution of these categories for different UP levels. The percentage of the **BA** category increases as the UP level increases.

Figure 5 shows the age distribution for different UP levels. We defined as Adolescents individuals less than 18 years old, Young Adults between 18 and 34, Early Middle Age between 34 and 45, and Late Middle Age and Older above 45. It is clear that the most persistent users $\mathcal{P}$ were overwhelmingly middle age adults, while teenager users were in small numbers and only in the fleeting categories $\mathcal{F}$. Our analysis also revealed that the percentage of females steadily increased in the most persistent user categories (Fig. 6), closing the gap between the two genders.

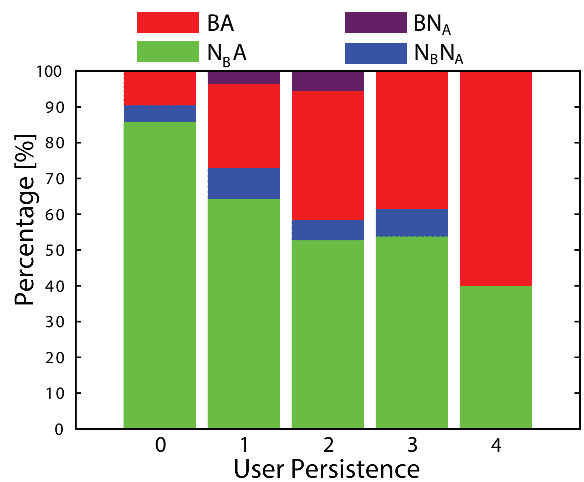


Figure 4: User Persistency and distribution of physically active/non-active individuals with/without breathing problems.

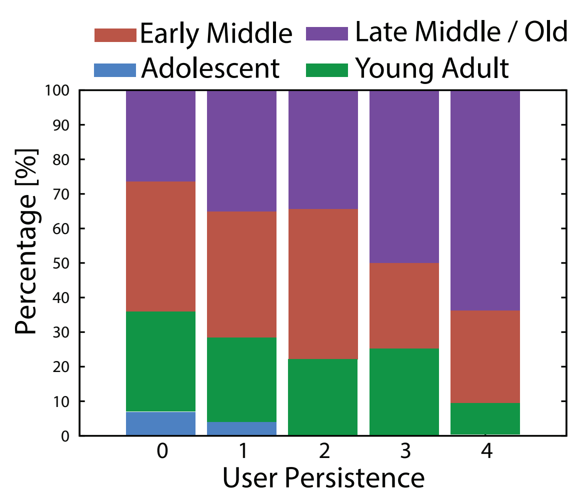


Figure 5: User Persistency and age distribution.

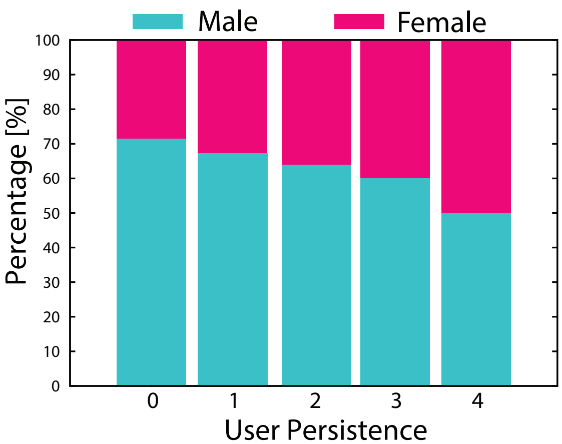


Figure 6: User Persistency and gender distribution.

## 4.2 App Usage

Figure 7a shows that the randomizer was assigning the default colormap with nearly equal probability between the two visualization schemes. At the end of the observation period (Fig. 7b), however, nearly all the persistent users $\mathcal{P}$ had switched to the *radar style* visualization (p<0.001, two sample hypothesis testing for population proportion), while there was no significant change for the fleeting users $\mathcal{F}$ (p=0.227, two sample hypothesis testing for population proportion).

Figure 8 shows that the logins peaked early in the morning, late in the afternoon, and around lunch time. These times coincide with the time people perform outdoor exercises prior to going to work and after getting off work, respectively, as well as the midday break when some people walk to their favorite restaurant. This correlates well with the survey results, according to which the overwhelming majority of the users are physically active outdoors. Figure 9 shows that during the performance period total logins peaked the days with high ozone levels in the Houston area. Indeed, the cross-correlation between the Login and Mean Ozone Level signals is strong (r=0.778, p<0.001 - cross correlation of lag 0 between the two time series).

Collectively, the data from Fig. 4, Fig. 8, and Fig. 9 suggest the likely mode of usage for this app. The users were most probably informed about a generic ozone alert from the weather channel, because OzoneMap does not issue such alerts. Then, they logged in the OzoneMap app to obtain real-time ozone cloud development in their locality, prior to engaging in outdoor exercises or excursions.

# 5. DISCUSSION

In this research we addressed three questions for pollutant apps using a case study: (a) design methodology; (b) user base; and, (c) usage patterns of such apps. The essence of our design methodology is to consider pollution as man-made weather and find its natural weather analogue, in terms of key feature resemblance (speed of movement and persistency) and assuming equivalent sensing resolution. This reduction enables the adoption of appropriate, well researched, and familiar visualization schemes for newly minted pollution information. With this method, we found that tracking ozone clouds in real-time resembles tracking storm clouds in real-time and thus, we brought to bear the familiar *radar style* visualization.

The rationale for these classic weather visualizations can be abstracted along the following lines: A highly dynamic phenomenon moves fast and does not persist for long, requiring real-time map consultation and an approach easy on colors. A rather static phenomenon moves slow (if at all) and persists for long time; a general impression is acceptable and often preferable, suggesting an approach heavy on colors.

As a matter of process, the designer of a future composite pollution map would need to form two tables: one table with well known weather phenomena and their characteristics; the other table with well known pollutants and their characteristics. Visualization schemes for the pollutants in the second table can be determined by matching them with analogue weather phenomena in the first table.

According to this approach, most air pollutants (e.g., particulates and ozone) would fall under the storm analogue, because they are transported by the prevailing winds and

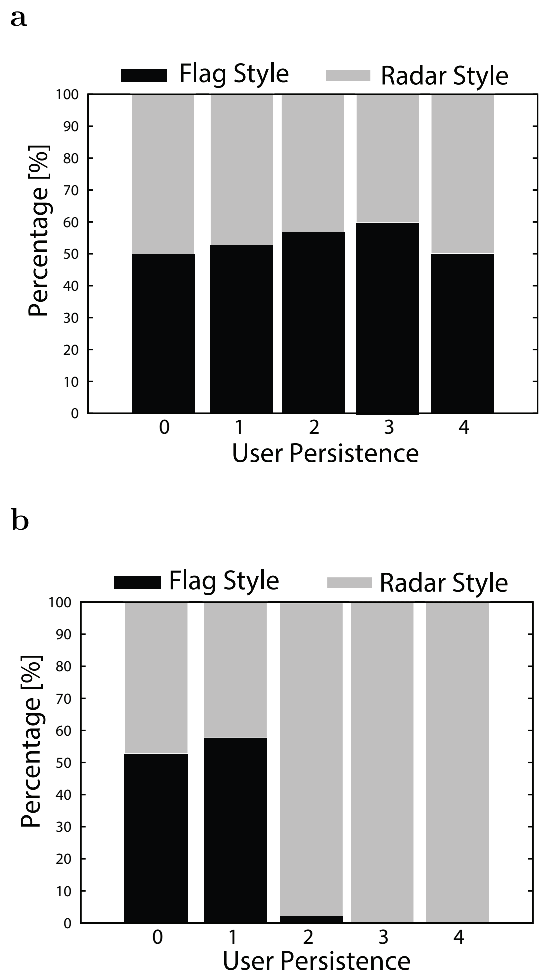


Figure 7: Evolution of users' color mapping preferences per the persistency levels exhibited during the observation period. **a.** Assignment of color mapping scheme upon user registration. **b.** Settlement of color mapping scheme at the end of the observation period.

thus, they are highly dynamic. By contrast, in the case of mapping ground pollutants, the situation is much more static. The user does not necessarily need to consult the map in real-time, because the time scale of ground pollution is long. Hence, for ground pollutants a visualization closer to flag style would make sense, much like the case with ground freeze maps.

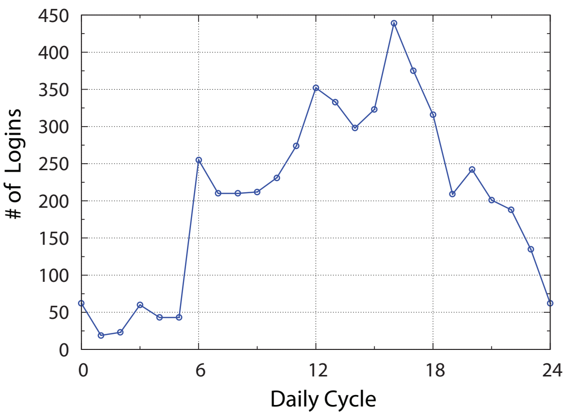


Figure 8: Cumulative daily cycle usage of OzoneMap for the observation period.

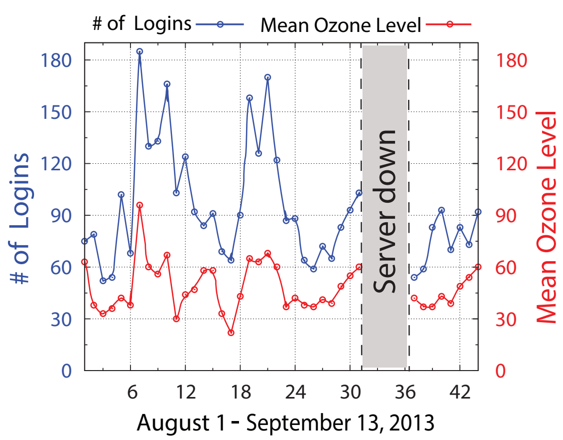


Figure 9: OzoneMap usage vs. recorded mean ozone levels per day during the observation period.

Our design efforts focused on the visualization scheme, because it is clearly the most important issue at hand: real-time pollutant apps are annotated geo-maps. Ozone is the first pollutant that has been incorporated in such real-time apps.

In issues with political overtones, such as pollution, various stakeholders have differing and strong opinions about the specifications of the apps. Having a rational and scalable design methodology for pollutant apps that is widely adopted will stem the proliferation of conflicting 'ideological' designs.

In this context, it is interesting that when the persistent users of pollution apps are given the choice between a design based on the 'analogue' method and a design based on other considerations, they naturally gravitate to the 'analogue' design (Fig. 7).

Regarding the user base of the OzoneMap app, our hypothesis and hope were that it would be used by people who are active outdoors and/or have breathing problems, because these are the people who need this information the most. Based on the survey results this appears to be the case in general. However, the survey also revealed that the users are overwhelmingly middle-aged. There is absence of adolescents and only a small percentage of young adults in the persistent user categories $\mathcal{F}$. This is disconcerting, because we know that these ages are especially active outdoors and include individuals with breathing problems as well.

The OzoneMap app was promoted in a conventional way: there was a press release, which was picked up by local and national news outlets (Houston Chronicle, USA Today, NBC News, and others). Perhaps an additional marketing focus on social media would have had a stronger impact on younger ages - a message that researchers and agencies should keep in mind.

In terms of usage, the server records revealed that by and large the users were logging in the application either early in the morning, or late in the afternoon, or around the lunch break. Based on the users' profiles (over 90% physically active outdoors), it is likely that the morning and afternoon logins were related to their daily exercise before and/or after work. This provides an additional incentive for incorporation of real-time pollutant information in physical activity apps (walking, running, and biking apps) - a goal that drives our ongoing efforts.

## 6. ACKNOWLEDGMENTS

This work was funded by a grant from the Houston Endowment - a philanthropic foundation dedicated to improve the life for the people of greater Houston. Any opinions, findings, and conclusions or recommendations in this material are those of the authors and do not reflect the view of the funding agencies.

## 7. REFERENCES


[1] J. Abraham and A. Comrie. Real-time ozone mapping using a regression-interpolation hybrid approach, applied to Tucson, Arizona. *Environmental Pollution*, 125:369–383, 2003.

[2] Branecky Application Development and Design LLC. Oklahoma Ozone app. `itunes.apple.com/us/app/oklahoma-ozone/id515838340?mt=8`, Updated Jan 11, 2013.

[3] Computational Physiology Lab, Univ. of Houston. OzoneMap app. `itunes.apple.com/us/app/ozonemap/id579938656?mt=8`, Updated Sept 16, 2013.

[4] R. Delvin, J. Raub, and L. Folinsbee. Health effects of ozone. *Science & Medicine*, 4(3):8–17, 1997.

[5] S. Devarakonda, P. Sevusu, H. Liu, R. Liu, L. Iftode, and B. Nath. Real-time air quality monitoring through mobile sensing in metropolitan areas. In *Proceedings of the 2nd ACM SIGKDD International Workshop on Urban Computing*, page 15. ACM, 2013.

[6] J. Diem. A critical examination of ozone mapping from a spatial-scale perspective. *Journal of the Air & Waste Management Association*, 54(8):914–925, 2004.

[7] Environmental Protection Agency. Federal Register Volume 73, Number 60. www.gpo.gov, Thursday, March 27, 2008.

[8] Environmental Protection Agency. EPA AIRNow app. itunes.apple.com/us/app/epa-airnow/id467653238?mt=8, Updated Oct 11, 2011.

[9] J. F. Meagher, E. B. Cowling, F. C. Fehsenfeld, and W. J. Parkhurst. Ozone formation and transport in southeastern United States: Overview of the SOS Nashville/Middle Tennessee ozone study. *Journal of Geophysical Research: Atmospheres (1984–2012)*, 103(D17):22213–22223, 1998.

[10] MN Pollution Control Agency. Minnesota Air app. itunes.apple.com/us/app/minnesota-air/id648582702?mt=8, Released May 18, 2013.

[11] Mobeezio, Inc. Air Quality Pro app. itunes.apple.com/us/app/air-quality-pro/id477522970?mt=8, Updated Jun 12, 2013.

[12] N. Nikzad, N. Verma, C. Ziftci, E. Bales, N. Quick, P. Zappi, K. Patrick, S. Dasgupta, I. Krueger, T. Š. Rosing, et al. CitiSense: Improving geospatial environmental assessment of air quality using a wireless personal exposure monitoring system. In *Proceedings of the Conference on Wireless Health*, page 11. ACM, 2012.

[13] I. Uyanik, D. Price, P. Tsiamyrtzis, and I. Pavlidis. Interfacing real-time ozone information. In *Proceedings of the 1st ACM SIGSPATIAL International Workshop on MapInteraction*, pages 20–23. ACM, 2013.

**NOTE**

## Report of Referee 1

**** Comments to the Authors: Detailed comments to the authors*

*In the introduction the authors describe the difference between their spatial interpolation technique and other approaches pollution apps have used in the past. It would be helpful and interesting if they would calculate the relative improvement provided by their approach. Using their own data base of closest tower ratings and exact location ozone readings, would it be possible to work out what users would have seen with older approaches and then compare the relative improvement provided by the app developed here?*

**R1C1: We have included an illustrative example (Fig. 1) to address the point raised by the reviewer, writing on pages 1-2:**

**'Please note that apps relaying ozone measurements from the closest tower may introduce a significant error, providing a disservice to the user. Consider the following illustrative example: Assume the ozone sensors have been laid out in a square grid with edge X, where X is typically several miles. Moreover, assume that the user walks outdoors in an area closest to sensor [2,2] and inside an ozone plume that spreads from her/his locale all the way to sensors [1,1], [1,2], and [2,1] (Fig. 1). The plume, however, stops short of sensor [2,2], which shows 'all clear'. Unfortunately, this is the sensor that would provide the measurement to the user, based on the shortest distance criterion. By contrast, a weighted measurement from all neighboring sensors would provide a significantly higher ozone value, appropriately alerting the user.'**

## Report of Referee 2

**** Weaknesses: What are the main weaknesses of this paper? [1-3 sentences]*

*- It would have been nice to define 'ozone cloud' sooner, up front.*

**R2C1: We have added the definition of ozone cloud early in the Background section, writing on page 2 of the revised manuscript:**

**'In the presence of sunlight, chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC) create ground level ozone. Emissions from industrial facilities and motor vehicle exhaust are the major sources of NOx and VOC. Hence, ozone pollution is produced in certain parts of a metropolitan area and then it is transported by the prevailing winds [9] - aka ozone cloud.'**

*- Fig 6a,b is a little confusing - what exactly do the categories 0-4 on UP refer to during the 'registration' phase of 6a - I would think that this is a very short period of time, less than a day, but you have UP=4 which indicates 'every day use'. How many days were the two periods in (a) and (b) of Fig 6?*

**R2C2: To further clarify this point, we have reworded the caption of Fig. 6, which has become Fig. 7 in the revised manuscript:**

**'Evolution of users' color mapping preferences per the persistency levels exhibited during the observation period. a. Assignment of color mapping scheme upon user registration. b. Settlement of color mapping scheme at the end of the observation period.'**

## Report of Referee 3

**** Weaknesses: What are the main weaknesses of this paper? [1-3 sentences]*

*The paper has a lot of information in a small amount of space. Many topics surrounding app usage are covered, but each is covered in very little depth.*

**R3C1: The reviewer overall is quite positive. We do not see a point specific enough to be properly addressed and hence, we take no action in this case.**

## Report of Referee 4

**** Weaknesses: What are the main weaknesses of this paper? [1-3 sentences]*

*The visualization presented is not novel and arguably the obvious choice. Users will need to see the map to plan well. The flag visualization covers the map, making it much more difficult to do so.*

*The design process presented is not really a process. It is a philosophy that seems difficult to apply outside of this paper. When should I use this process? What are the steps I should take to use it?*

**R4C1: We do not claim that our design method can be used in any domain. We claim, however, that our method can be used in any pollutant (not just Ozone) visualization. The key step in this design process is to determine the characteristics of the pollutant and try to relate them to the characteristics of a well known weather phenomenon, assuming the pollutant and weather tracking technology are on par. The main characteristics of interest are two: speed of transport and persistence (time scale). A highly dynamic phenomenon moves fast and does not persist for long, requiring real-time map consultation and an approach easy on colors. A rather**

**static phenomenon moves slow (if at all) and persists for long time; a general impression is acceptable and often preferable, suggesting an approach heavy on colors. The visualizations established for classic weather phenomena can be abstracted along these lines.**

**We convincingly likened Ozone clouds to storm phenomena and opted for a radar style visualization (analogue method), which the users favored. Most other air pollutants likely fall under this analogue category, because they are transported by the prevailing winds and thus, they are highly dynamic. For example, particulate clouds can also be visualized radar style, but with a different colormap to distinguish them from ozone clouds. And, since snow is also made out of solid particles, applying to particulate clouds the color mapping used in snow storms would be apt.**

**By contrast, in the case of mapping ground pollutants, the situation is much more static. The user does not necessarily need to consult the map in real-time, because the time scale of ground pollution is long. Hence, for ground pollutants a visualization closer to flag style would make sense, much like the case with freeze maps.**

**In summary, the designer of a future composite pollution map would need to form two tables: one table with well known weather phenomena and their characteristics; the other table with well known pollutants and their characteristics. Visualization schemes for the pollutants in the second table can be determined by matching them with analogue weather phenomena in the first table.**

**The Discussion section in the revised paper has been enriched accordingly to address the point raised by the reviewer.**

******* *Comments to the Authors: Detailed comments to the authors*

*Please specify the statistical tests used.*

**R4C2: To analyze the evolution of users' color mapping preferences per the persistency levels exhibited during the observation period (Fig. 7), we used two sample hypothesis testing for population proportion. To analyze the relationship between the Login and Mean Ozone Level signals (Fig. 9) we used cross correlation of lag 0 between the two time series. Explicit descriptions of the statistical tests were added in the App Usage section on page 5 of the revised manuscript.**