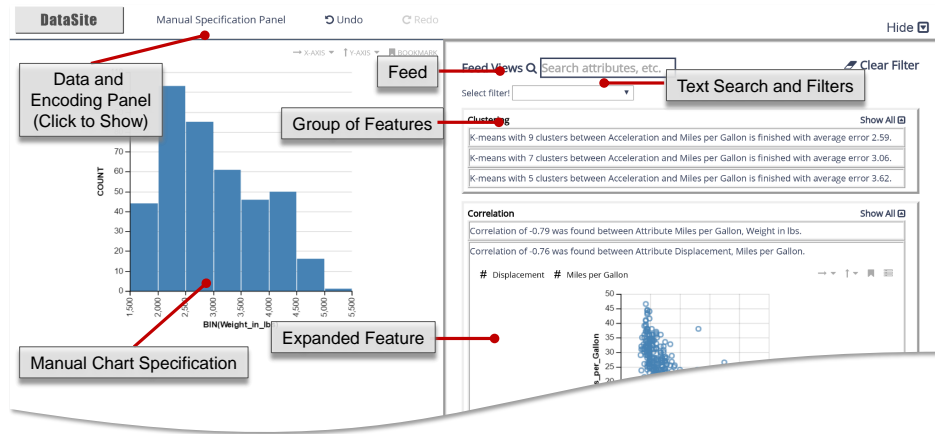


# DataSite: Proactive Visual Data Exploration with Computation of Insight-based Recommendations

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**Figure 1:** DataSite is a proactive visual analysis system that allows the analyst to explore data on the web-based client using a standard visualization interface (data, encoding, and manual chart specification panel), while a server-side component automatically selects and executes relevant computations without prompting. Features gleaned from these analyses are surfaced and updated dynamically in a Feed View (right) on the client, similar to posts in a social media feed.

## Abstract

Effective data analysis ideally requires the analyst to have high expertise as well as high knowledge of the data. Even with such familiarity, manually pursuing all potential hypotheses and exploring all possible views is impractical. We present DataSite, a proactive visual analytics system where the burden of selecting and executing appropriate computations is shared by an automatic server-side computation engine. Salient features identified by these automatic background processes are surfaced as notifications in a feed view, akin to posts in a social media feed. DataSite effectively turns data analysis into a conversation between analyst and computer, thereby reducing the cognitive load and domain knowledge requirements. We validate the system with a user study comparing it to a recent visualization recommendation system, yielding significant improvement particularly for complex analyses that existing analytics systems do not support well.

## CCS Concepts

•Human-centered computing → Visual analytics; Empirical studies in visualization;

## 1. Introduction

Data exploration using visual analytics is often characterized as a partnership between analyst and computer, with each partner providing unique and complementary capabilities [BZS\*16, TC05]. In practice, however, most current visual analytics systems put the

analyst in the driver's seat to guide the analysis. This one-sided arrangement falls short when the analyst does not know how to best transform or visualize the data, or is simply overwhelmed due to the sheer scale of the dataset or the limited time available for analysis. A true partnership would share control between the two partners—analyst and computer—in a way that leverages their

respective strengths. Such a *proactive approach* to data analysis would automatically select and execute appropriate computations to inform the analyst's sensemaking process.

In this paper, we present DATASITE, a proactive visual analytics system where the user analyzes and visualizes the data while a computation engine simultaneously selects and executes appropriate automatic analyses on the data in the background (Figure 1). By continuously running all conceivable computations on all combinations of data dimensions, ranked in order of perceived utility for the specific data, DataSite uses brute force to relieve the burden from the analyst of having to know all these analyses. Any potentially interesting trends unearthed by the computation engine are propagated as status notifications on a *feed view*, akin to posts on a social media feed such as Twitter or Facebook. We designed this feed view to support different stages of exploration. Status updates are continuously and dynamically added to the feed as they become available during the exploration. To provide a quick overview, they are presented with a brief description that can be sorted, filtered, and queried. To get more details on an individual response without committing to the active path of exploration, we allow the analyst to expand an update to see details in natural language as well as an interactive thumbnail of a representative visualization. Finally, the user can select an update to bring it to the manual specification panel, allowing for manual exploration.

Our web-based implementation of DataSite consists of an interactive web client interface for multidimensional data exploration as well as a server-side computation engine with a plugin system where new components can be integrated. The client interface is a shelf-based visualization design environment similar to Tableau (and based on Polestar [Pol17] implementation). The server-side computation engine currently features common multidimensional components such as clustering, regression, correlation, dimension reduction, and inferential statistics, but can be further expanded depending on the type of data being loaded into DataSite. Each computational plugin implements a standardized interface for enumerating and ranking supported algorithms, running an analysis, and returning one or several status updates to the feed view. Computational tasks are run in a multithreaded, non-blocking fashion on the server, and use rudimentary scheduling based on their perceived utility for the specific data.

To demonstrate the utility of the system, we present results from two user studies involving exploratory analysis of unknown data, one that compared DataSite to a Tableau-like visualization system (PoleStar [Pol17]), and one that compared it to a partial-specification visualization recommendation system (Voyager 2 [WQM\*17]). Using DataSite's feed, our participants derived richer, more complex, and subjectively insightful findings compared to when using PoleStar, or even Voyager 2's recommendation feed. This supports our hypothesis that a true proactive analytics platform such as DataSite can improve coverage and increase complexity of insights compared to reactive or partial-specification approaches. Beyond the DataSite system, our approach can be applied to other exploratory analysis tools to promote richer exploratory analysis, even for non-experts, analysts pressed for time, or analysts unfamiliar with a dataset before exploration.

## 2. Background

DataSite extends the literature on exploratory visual analysis and visualization recommendation to better aid analysts with data exploration in a proactive manner. Here we discuss the state-of-the-art research and inspirations for DataSite.

### 2.1. Exploratory Visual Analysis

Exploratory data analysis (EDA) [KMSZ06, Tuk77] is the canonical user scenario for visualization. The key characteristic for EDA is that the analyst is not initially familiar with the dataset, and may also be unclear about the goals of the exploration. The exploratory process involves browsing the data to get an overall understanding, deriving questions from the data, and finally looking for answers.

Efficient data exploration often relies on visual interfaces [Tuk77]. *Dynamic queries* [Shn94] is an interaction technique for such interfaces, where users formulate visual queries as a combination of filters. Writ large, *faceted browsing* allows for creating queries on specific dimensions of the data [YSLH03].

### 2.2. Visual Specification

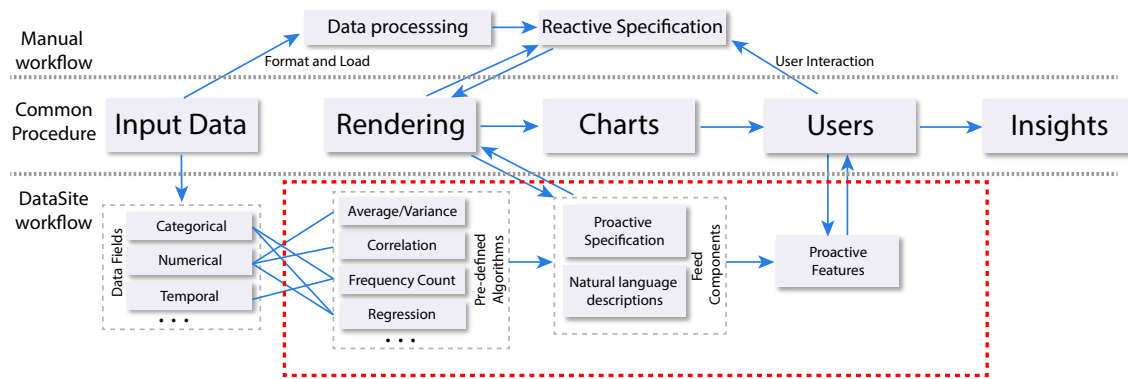
Specifying visual representations is one of the key challenges in visualization. Research efforts here span the spectrum from programming languages to point-and-click interfaces. Visualization toolkits such as D3 [BOH11] represent one side of this spectrum, and gives unprecedented control over the visualization, but at the cost of significant programming expertise and development time. High-level visual grammars, such as Grammar of Graphics [Wil06], ggplot2 [Wic16], and Vega-Lite [SRHH16], abstract away implementation details, but may still have a high barrier of entry and steep learning curve due to the need for visual design knowledge.

A recent development in visual specification has been the introduction of interactive visual design environments such as Lyra [SH14], iVoLVER [MNV16], and iVisDesigner [RHY14]. These require no programming expertise, and are thus positioned at the very other end of the spectrum from visualization toolkits and grammars. However, interactive view specification can be clumsy and inefficient at times, and may still be plagued by technical challenges due to the intricacies of visualization design.

Shelf-based visualization environments such as Polaris [STH02], Tableau [Tab17], and PoleStar [Pol17] fall in the middle of the spectrum. Common among these is their ability to allow the user to drag and drop data dimensions, metadata, and measures to specific "shelves," each one representing a visual channel such as axis, shape, scale, color, etc. This point-and-click approach to visual specification is flexible enough to construct a wide range of visualizations, but not so complex so as to become technical, such as Lyra, iVoLVER, and iVisDesigner. In DataSite, we employ a variant of a shelf-based visualization environment for this very reason.

### 2.3. Visualization Recommendation

The idea behind visualization recommendation is to use recommendation engines [HKTR04] to suggest relevant views to the user, thus reducing the cognitive load. While this idea has seen a resurgence



**Figure 2:** The structure and workflow of the DataSite visual analysis system. The manual and proactive (DataSite) visualization workflow have shared common procedures in the middle. Components within the red rectangle are the key parts of DataSite: proactive computational modules that can run through various data fields, visualization, and natural language descriptions. These together offer suggested features in the feed.

in the visualization community in recent years, it is by no means a new idea. Mackinlay [Mac86] first proposed automatic visualization design based on input data in 1986. His work combines expressiveness and effectiveness criteria inspired by Bertin [Ber83] and Cleveland et al. [CM84] to recommend suitable visualizations. Tableau's Show Me system [MHS07] provided a practical and commercial implementation of these ideas.

Many similar approaches to automatic visual specification exist. Sage [RKM94] extends Mackinlay's work to enhance user-directed design by completing and retrieving partial specifications based on their appearance and data contents. The rank-by-feature framework [SS05] sorts scatterplot, boxplots, and histograms in a hierarchical clustering explorer to understand and find important features in multidimensional datasets. SeeDB [VMPP14] generates a wide range of visualizations, and define which ones would be interesting by deviation and scale. Perry's [PHKA13] and Van den Elzen's [vdEW13] work attack the problem that generates multiple visualizations shown with small thumbnails.

Recommendation engines have been used to great effect for visualization in the last few years. Voyager [WMA\*16] generates a large number of visualizations and organizes them by relevance on a large, scrolling canvas. Visualization by demonstration [SKBE17] lets the user demonstrate incremental changes to a visualization, and then gives recommendations on transformations. Zenvisage [SKL\*16] automatically identifies and recommends interesting visualizations to the user depending on what they are looking for. Recently, Voyager 2 [WQM\*17] builds on Voyager, but supports wildcards in the specification and provides additional partial view suggestions. "Top-K insights" [THY\*17] provides theory for generating insights, which is the main motivation of our paper. All of these ideas were formative in our work on DataSite, but our approach takes this a step further by focusing on continuous computation from a library of automatic algorithms, with findings propagated to the user in a dynamically updating feed.

## 2.4. Proactive Computation alongside Visualization

The idea of proactive visual analytics discussed in our paper builds on the idea to opportunistically run computations in anticipation of user needs, which is observed in Novias [NNL\*12], Treeversity [GBCPS11], and Analyza [DMN\*17] (*Explore* in Google Sheet). Novias identifies visual elements of evolving features and provides multiple views in an interactive environment. Treeversity provides a list of outliers in textual form, which identifies changes in the data automatically. The most similar research to DataSite is Analyza, which provides auto-computed features in natural language. In contrast, DataSite aims to push proactive computation to depth and complexity rather than just simple overall statistics in the dataset. Furthermore, DataSite pushes features to a feed view that is akin to social media feeds users are already accustomed to.

## 3. Design Rationale: Proactive Analytics

The core philosophy for proactive analytics is the following:

*Human thinking is expensive, whereas computational resources are (generally) cheap.*

Following this philosophy, a proactive approach to visual analytics should automatically run computations in the background and present its features to the analyst in an endeavor to reduce the analyst's cognitive effort during the sensemaking process. In essence, the solution is to use the brute force computational power of the computer to help balance out the equation between the human analyst and the computer tool. This leverages the respective strengths of each partner while complementing their weaknesses:

- Human analyst: The human operator driving the analysis.
  - *Strengths:* creativity, intuition, experience, deduction.
  - *Weaknesses:* limited short-term memory, computational power, knowledge, and perception.
- Computer analytics tool: The tool facilitating the analysis.
  - *Strengths:* significant memory and computational power; large library of algorithmic techniques.

- *Weaknesses*: no creativity, intuition, or deductive reasoning.

Based on these ideas, we derive the following design guidelines for our (and future) proactive visual analytics tools:

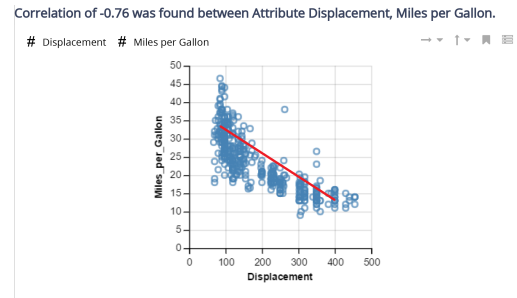
- D1 Offload computation from analyst to machine.** The analytical tool should be designed so as to offload as much as possible of the analysis from the user. Given our core philosophy, this means that the tool should never be idle in reactive mode waiting for the user to act. Instead, it should always be running tasks in the background, and start another task as soon as one finishes.
- D2 Present automated features incrementally with minimal interruption to the analyst.** Automatic features derived by the background computational processes must be propagated to the user, but the presentation of these features should be designed so as not to interrupt the user's cognitive processes needlessly. These features should be accumulated in a feed where they can be easily surveyed and viewed at the user's own initiative rather than in a blocking manner that requires action.
- D3 Reduce the knowledge barrier of human thinking.** Data analytics is a nascent discipline with rapidly evolving methods, many requiring the data to support specific assumptions or exhibit certain properties, so it is often difficult even for expert-level analysts to stay abreast of current practice [BE18]. This is another situation where timely proactive support can save analyst effort by investing CPU time: the tool can simply run every conceivable analytical method from a large library of methods (ordered by perceived utility) and only present interesting trends.
- D4 Eliminate “cold-start” through exposing potentially relevant features of the data early during exploration.** A challenge related to the knowledge barrier is the so-called “cold-start problem” [SPUP02]; the fact that, when beginning analysis on a new dataset, it can be challenging to know how to get started because the data can be overwhelming and difficult to get a handle on. Again, this can be mitigated by not choosing but simply performing **all** applicable analyses from a library of such methods.

#### 4. The DataSite System

The DataSite system consists of (1) a user interface for proactive visual analytics containing components for visualization authoring along with a dynamically updated feed view, and (2) a proactive computation engine continuously running background modules on a target dataset (D1). The user interface (Figure 1) runs on a modern web browser and consists of a manual visualization view coupled with a *feed view*. In particular, the feed view accumulates features as status updates (D2) consisting of a textual description and a representative interactive visualization. Working in concert, the feed view reduces the knowledge barrier (D3) by continuously displaying trends from the proactive computation engine. The feed also provides a starting point, eliminating the cold start problem (D4).

##### 4.1. Visualization Interface

The DataSite interface comprises a data schema panel, an encoding panel, a manual chart specification view, and a feed view (Figure 1). The data schema, encoding, and chart specification views together compose a basic shelf-based visualization system that the analyst can employ to explore the data in a conventional way, potentially



**Figure 3:** Example of features in the feed: a brief textual description (“Correlation metric between Miles per Gallon and Displacement attributes in a Cars dataset.”) with a corresponding auto-generated chart (scatterplot for these two specific attributes). A red line which shows the computed correlation trend between two attributes is also shown.

disregarding the proactive analysis entirely. The dynamically updated feed view is the key interface-level contribution of DataSite, and accumulates features generated by the computation engine. To give ample space for the analyst's navigation through the interface components, the feed is placed on the right of the manual specification view, and data and encoding panel can be hidden.

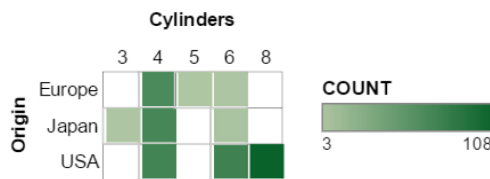
The feed view is inspired by social media feeds, where events posted by participants appear in a dynamically updating list. A *data feature* in the feed is a notification from a computation engine. Once a feature finished computing, it will be dynamically updated to the feed. The feed view can be searched and filtered, sorted by the computational measure, the time it was produced, or in simple alphabetical order, and grouped by their type. Each feature is initially represented as a textual description explaining the underlying computation task. Users can expand a feature to see more of the text as well as an associated chart for the data attributes processed by the underlying computation (Figure 3), or collapse it when needed. Here, we describe the textual description and charts within the feed view. One thing to note is that in the paper we use “data attributes” and “data fields” interchangeably, representing attributes in the dataset.

- **Textual description:** Text that describes a feature presented on the feed view in a proactive manner. For example, for the Pearson correlation coefficients [Pea95] between *Weights in lbs* and *Miles per Gallon* in cars dataset [HV81], the textual description is: “Correlation of 0.5 was found between attributes *Weights in lbs* and *Miles per Gallon*.” This active description gives the analyst the sense that the computer is their collaborator in helping them explore the data. To avoid overloading the feed with an excessive number of features, we combine related trends and illustrate them with a single chart (e.g., min/max are combined, described as a range, and shown on a bar chart, see Fig. 5).
- **Charts:** Manual view specification yields full control to the analysts, but may cause high cognitive load. To avoid this, DataSite shows the most efficient encodings for each chart corresponding to tasks from a computational module according to the existing metrics [Ber83, CM84, Mac86]. For instance, with two categorical attributes, DataSite renders a heatmap (Figure 4) with the



intersecting frequency counts marked in color. Similar to the approach in previous research [BZS\*16, WMA\*16], charts can be moved to the main view panel by clicking a *specify the chart* icon on the top right. Furthermore, charts highlight aspects of the underlying computation as visual cues for the user: for example, charts generated from the clustering computation will highlight the clusters within the chart in color.

At the same time, analysts can post an important view in the manual chart visualization window, saving that view as a post in the feed. The feed view keeps track of these user-generated posts as a separate category. This is the same as bookmarking charts, and in the future we plan to make the feed a collaborative space, where either human or computer post features to allow sharing of findings. Charts are lazily rendered when clicked, thus reducing the page load significantly.



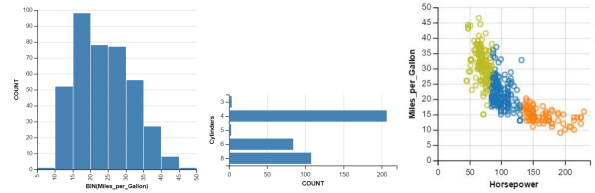
**Figure 4:** Representative chart (heatmap) automatically generated for co-occurrence frequency counts of two categorical data fields (origin country and number of cylinders) in a Cars dataset. Darker color indicates more counts in that category combination; in this example, eight-cylinder cars from the USA.

## 4.2. Computation Engine

The DataSite computation engine begins analyzing a dataset as soon as it is loaded. The engine consists of multiple computational modules (easily extended as plugins); Table 1 shows a sample. A single module can yield several tasks; for example, a simple Pearson correlation module would create a task for each combination of numerical attributes, but not for categorical attributes.

A scheduler analyzes the data and runs computations in a specific order; see the next section for details on scheduling analysis. The computation engine is multi-threaded using a computational thread pool, executing each computation in the scheduled order. For each finished task, the computational module will generate a status update that will be pushed to the visualization interface. As soon as a computational thread is freed up, the scheduler will recycle the thread for a new task. In this way, the engine is never blocked by complex, long-running tasks. Furthermore, each computation module executes independently, so a single module failure does not affect the overall system. For example, if one module fails executing due to errors or invalid data, it won't return results, while other modules still executes without interruptions.

By virtue of this modular architecture, DataSite can be easily extended with new computation modules. The current implementation provides statistical analysis, clustering (3, 5, 7 clusters), and regression modules. Figure 5 shows sample charts created in the feed view for some computation modules.



**Figure 5:** Chart types for different computational modules used in DataSite. From left: histogram bar (mean/variance), histogram line (min/max), and scatterplot (clusters in 2D).

## 4.3. Scheduling Automatic Analysis

The scheduler is a core component in the computation engine. It passes the dataset through its entire library of loaded computational modules, receiving an estimate of the computational complexity and relevance from each module based on the meta-data—number of attributes, types, and dataset size. Furthermore, the scheduler also encodes typical analytical practice by focusing on main effects and trends in the dataset, and then turn to specific combinations of dimensions of the data. All of the metrics are then used by the scheduler to determine which modules to run, and in which order to run them. It may also reschedule jobs in response to results returned from another module; for example, to run post-hoc analysis in response to a significant result from an analysis of variance test. In addition, the scheduler may choose to launch long-lasting analyses—such as multidimensional scaling or cluster analysis—early, knowing that these results will take a while to return.

In the future, we anticipate letting the user guide the computation order, either implicitly (by analyzing which data the user is interacting with), or explicitly (by providing specific interactions to guide the computation). This would enable customizing the DataSite scheduler to the analytical practice of a specific user while retaining the overall hybrid model.

## 4.4. Implementation

DataSite is based on a client/server architecture. The client side is developed using AngularJS,<sup>†</sup> a JavaScript-based web application framework. The visualization functionality in the DataSite client is based on the PoleStar interface (available as open source) [Pol17], which is built on top of Vega-Lite [SRHH16].

We implemented the computational engine using Node.js,<sup>‡</sup> a non-blocking server-side JavaScript framework. Datasets of interest can be uploaded by the user on the client interface, and sent to the server. The server processes them using the engine and proactively sends the finished features to the feed view. This structure enables managing a wide array of input data formats, and scales to large datasets. In essence, the server does all the heavy lifting: loading data, maintaining the connections to clients, executing computational modules, and updating features.

<sup>†</sup> <https://angularjs.org/>

<sup>‡</sup> <https://nodejs.org/>

Modules	Data Formats	#Attr.	Chart	Descriptions
Mean/variance	numerical	1	hist. (Fig. 5)	Attribute A has mean of X with variance of Y.
Min/max (range)	numerical	1	hist. line	Range (min, max) was found in attribute A.
Freq. counts	categorical	1	aggr. (Fig. 5)	X was the most/least frequent sub-category in attribute A.
Freq. counts (comb.)	categorical	2	heatmap (Fig. 4)	Most frequent combination was found between X in attribute A, and Y in attribute B.
Correlation	numerical	2	scatterplot	Correlation of A was found between attribute X and attribute Y.
Clustering	numerical	2	scat. (Fig. 5)	Kmeans with $N$ clusters between $X$ and $Y$ has average error $E$ .
Regression	numerical	2	regression line	Linear Regression between $X$ and $Y$ has estimate error of $E$ .

**Table 1:** Example computational modules with corresponding data and chart types. We have currently used algorithms working with one or two data attributes in our computation engine. Brief textual descriptions for each module are also listed.

## 5. Evaluation Overview

DataSite creates a new method for visual exploration through a mixture of manual and automated visualization specifications driven by proactive computations. For this reason, we are interested in understanding whether the exploratory analysis with DataSite supports bootstrap understanding and broad coverage of the data. We are also curious about knowing how/why the feed helps, and how it changes the analyst's approach in finding features. To answer these questions, we conducted two user studies: (1) comparing with a manual visualization specification tool, PoleStar, focusing on data field coverage; and (2) comparing with a visualization recommendation system, Voyager 2 [WQM\*17], focusing on data exploration to compare the effects of adding a *Feed* (in DataSite) versus *Related Views* (in Voyager 2). In other words, Study 1 aims to understand the fundamental utility of the feed view itself, while Study 2 expands this to understanding DataSite's proactive analytics workflow compared to a recent visual recommendation system.

### 5.1. Dataset

To enable comparisons of our results with PoleStar and Voyager 2, we reused the same datasets for our studies. One is a collection of films ("movies") containing 3,178 records and 15 data fields, including 7 categorical, 1 temporal, and 8 quantitative attributes. The other dataset contains records of FAA wildlife airplane strikes ("birdstrikes"), which contains 10,000 records and 14 data fields, with 9 categorical, 1 temporal, and 4 quantitative attributes. These two datasets have similar complexity (w.r.t. number of attributes), and are easy to understand.

### 5.2. Study Design and Procedure

In both user studies, we used 2 tools with 2 datasets (one dataset on each tool interface). Participants in both studies started with an assigned tool and dataset, and then moved to the second interface. To deal with learning effects, we counterbalanced the order of tools and datasets—half of our subjects used PoleStar/Voyager 2 first and the other half used DataSite first (similarly with the dataset).

Each participant began a session by completing a short demographic survey and was then introduced to the first interface assigned. The participants were first shown the interface and a tutorial on how to use the tool with an automobile dataset [RD83] for

training purposes. For DataSite, they were also shown the feed view and its associated operations. The participant was then allowed to train using the interface with the automobile dataset, and were encouraged to ask questions about the dataset and tools until they indicated that they were ready to proceed.

The experimenter then briefly introduced the participant to the experimental dataset and asked him/her to explore the dataset "as much as possible" (open-ended) within a given time of 20 minutes. They were asked to speak out aloud their thinking process and insights. We did not ask the participants to have specific questions to answer during the session, as this may bias them in exploration and limit their focus to specific subsets rather than the whole dataset. After completing a session with the first tool, the participants repeated the same procedure for the second tool and dataset. After completing the tasks for both tools, they were asked to complete a questionnaire with Likert-scale ratings on the efficiency and usefulness of each tool as well as the participant's rationale for their ratings. Participants were also encouraged to verbalize their motivations and comment on each tool. Each session lasted 60 minutes.

All the sessions were held in a laboratory setting in a university campus. Both tools ran on Google Chrome web browser on a Windows 10 laptop with a 14-inch display. The experimenter observed each session and took notes. Participant's interactions with the tool were logged into files, including application events. The audio of the session was also recorded for further analysis.

## 6. User Study 1: Comparison with PoleStar

In this study, we compare DataSite with a Tableau-style visual analysis tool (PoleStar). As described earlier, this study was motivated by a fundamental question: what happens when you incorporate a feed view into a conventional visualization tool. We therefore studied the data field coverage during open-ended visual exploration influenced by the Feed in DataSite against Polestar (a baseline interface without the Feed view). Note that apart from the Feed view, the DataSite interface resembles the PoleStar interface. Our hypotheses were: (1) DataSite would have higher data field coverage and more charts viewed, (2) DataSite would allow exploration of complex charts with multiple encodings (capturing multiple attributes), and support faster understanding of the data.

### 6.1. Participants

We recruited 16 paid participants (7 female, 9 male) from the general student population at our university. Participants were 18 to 35 years of age, with some prior data analysis and visualization experience. All of them had experience with data analysis and visualization tools: All (16) had used Excel, 10 had used Tableau, 7 Python/matplotlib, 7 R/ggplot, and 3 had used other analytics tools. No participant had previously seen or analyzed the datasets used in our study. They had not heard of or used DataSite or PoleStar, though some found PoleStar to be similar to Tableau.

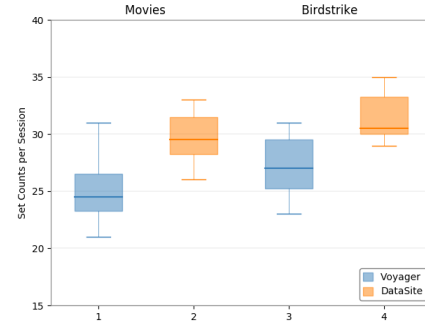
### 6.2. Results and Observations

As mentioned in the evaluation overview, participants' interaction logs and notes taken by experimenter were collected during the study. We used the linear mixed-effects model [BLST13, GHM13] for our analysis of the collected data. We modeled the participants and datasets as random effects with intercept terms (per-dataset and per-participant bias), and regarded different tools and the order of tool usage as fixed effects. This setting accounts for the variance of tools and datasets with individual subject's performance during the study. We used likelihood-ratio tests to compare the full model with other models to evaluate the significance of difference.

To assess the broad coverage of data fields, we consider the number of unique data field sets. Users may have been exposed to a large number of visualization charts, while the unique field sets shown and interacted with are conservative and reasonable measures of overall dataset coverage. Based on this, there is a significant improvement of data attribute coverage with DataSite (30% increase compared to PoleStar:  $\chi^2(1) = 19.26, p < 0.005$ ). Participants interacted with more charts, both from the feed as well as by modifying encodings from the charts present within the feed. This confirms the first hypothesis.

There are more multi-attribute charts (encoding two or more data attributes) that participants viewed and interacted with using DataSite than PoleStar ( $\chi^2(1) = 10.31, p < 0.005$ ). This is expected since DataSite provides pre-computed features, while participants had to manually create all visualization charts themselves in PoleStar. 75% participants have seen at least 50% more data fields in DataSite. Participants also found twice the number of charts using DataSite that are informative and worth "speaking out" ( $\chi^2(1) = 7.82, p < 0.005$ ). 10 participants have created more than 3 advanced charts with the help of feed (and "spoke out" about them): they started with charts from feed and added more data fields as encodings to the charts. This suggests that the DataSite system through its Feed view leads to the users viewing more number of charts that are beneficial from their perspective. It also indicates that DataSite encourages the user to reach complex (multi-attribute) charts during visual exploration, confirming our second hypothesis.

Participants showed great interest in the features within the feed view. Most of them spent at least 25% of time on exploring the feed itself. All participants felt that the feed is useful for analysis and provides guidance of "where to look" in the data. They rated DataSite higher than PoleStar in terms of efficiency (Likert scale, 1 to 5, mean: 4.67 vs 3.40) and comprehensiveness (mean: 4.20 vs. 3.21). All participants rated the usefulness of the feed 3 or higher.



**Figure 6:** Box plot showing the distributions of number of unique fields that users interacted with for per tool and dataset. DataSite has slightly larger number of unique field sets in both cases.

## 7. User Study 2: Comparison with Voyager 2

The results from the first study were promising and they answer our fundamental questions about the utility of the DataSite feed view. In Study 2, we compared DataSite with Voyager 2, a modern visualization recommendation system. The goal was to observe differences and further understand the utility of the feed in DataSite compared to the Related Views and *wildcards* in Voyager 2. Our hypotheses are: (1) DataSite will provide comparable if not more data field coverage owing to its rigorous computation engine; and (2) DataSite will better guide the user's exploration towards faster and comprehensive understanding in the given time.

### 7.1. Participants

We recruited 12 participants (8 female) from our university. All had similar demographics (between 18 and 35 years of age) and data analysis experience as before: all participants (12) had used Excel, 8 Tableau, 6 Python/matplotlib, 1 with R/ggplot. They had not heard of DataSite or Voyager 2, or seen the datasets involved.

### 7.2. Results: Quantitative

We used the same linear mixed-effect model for statistical analysis in Study 2 similar to Study 1.

#### 7.2.1. Data Field Coverage

We first looked into the participants' performance separately for both datasets (movies and birdstrikes), and compared the effects of visualization tools. We consider the number of unique field sets that users have shown and examined, respectively (similar to the previous study). In Figure 6, we see that for movies and birdstrikes datasets, the number of unique field sets that users interacted with (hovered mouse for more than three seconds) is similar: DataSite has 5 and 4 more unique field sets respectively in the birdstrike dataset (median: 30 in DataSite vs. 25 in Voyager 2) and movies dataset (median: 31 in DataSite vs. 27 in Voyager 2). Overall, DataSite promotes slightly more data field coverage in total (mean: 30 and 26), mainly because the feed contains an exhaustive list of features across computational modules.

In regard to the number of unique field sets that have been shown (the user may look through the charts without interaction) to the users, DataSite users (mean 43, s.d. 19.7) were shown fewer charts than Voyager 2 (mean 54, s.d. 13.5). The reason may be that Voyager 2 shows charts by default, while DataSite needs user interaction to expand the features in the feed to see the charts. As for the number of charts that participants spoke out aloud during the study, the tools have a significant difference ( $\chi^2(1) = 7.34$ ,  $p < 0.05$ ): DataSite (mean 14.53, s.d. 2.04) gave participants 30% more charts to “speak out” about, compared to Voyager 2 (mean 11.63, s.d. 2.32). In other words, participants found more charts to be informative and worth talking about using DataSite. Among all the “speak out” charts, an average of 35% are directly from the feed. Other “speak out” charts in DataSite are either moved from the feed to the main view and then edited, or manually created. This indicates that the feed view contributes to more data field coverage and more charts that analysts find useful and worth pointing out.

When using DataSite, all participants viewed and interacted with charts in the feed. Most of them (11 of 12) spent more than 30% percent of time exploring the feed. Two participants even used the feed as the main interface for exploring the datasets. Beyond this, two participants interacted with more than 70% of total charts, and 75% of their “speak out” charts were directly from the feed.

### 7.2.2. Text Search and Filter Usage

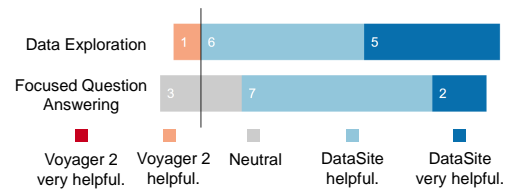
We analyzed the usage of filters and text search bar. We were interested in observing whether filters and text search can aid them in searching for desired features within the feed view, and whether it is efficient and easy to use compared to *Related Views* and *Wildcards* in Voyager 2. All participants have used the drop-down filters at least 5 times, and 9 of 12 tried text search. 8 of 12 of them said that the filters and the text search were useful for quick search of the feed during the study session. 7 of 12 had used the combinations of text search and filter. Three participants found *wildcards* in Voyager 2 to be not very intuitive. They used wildcards fewer times during the exploration, which matches the results from Wongsuphasawat et al. [WQM\*17]. In comparison, filters and search options not only contribute to fast data exploration, but also improve the efficiency of drilling down into features during proactive visual analytics. We believe that this is one of the advantages of providing descriptions for the features shown in the feed view.

### 7.2.3. User Ratings

We collected user’s feedback and ratings for tools in the post-study survey. For each tool, participants were asked to evaluate the tools based on the efficiency, enjoyability, and ease of use, on Likert scale ratings from 1 (least) to 5 (most). The participants rated DataSite ( $\mu = 4.32$ ,  $\sigma = 0.67$ ,  $p = 0.14$ ) higher than Voyager 2 ( $\mu = 3.92$ ,  $\sigma = 0.67$ ) regarding the efficiency. For enjoyability and ease of use, the ratings are comparable: enjoyability (DataSite:  $\mu = 4.33$ ,  $\sigma = 0.65$ ; Voyager 2:  $\mu = 4.08$ ,  $\sigma = 0.67$ ), ease of use (DataSite:  $\mu = 3.92$ ,  $\sigma = 0.85$ ; Voyager 2:  $\mu = 4$ ,  $\sigma = 0.60$ ). When asked about the comprehensiveness of their explorations of the dataset (DataSite:  $\mu = 4.42$ ,  $\sigma = 0.87$ ; Voyager 2:  $\mu = 3.75$ ,  $\sigma = 0.51$ ,  $p = 0.013$ ), 7/12 users rated DataSite higher and 4/12 rated both tools with the highest (5) score. Two participants gave lower ratings for DataSite

compared to Voyager 2 and mentioned that it is because they felt in Voyager 2 it was easier to browse multiple charts while in DataSite they had to explicitly click. Overall, DataSite was seen to be more efficient and presenting a more comprehensive coverage of the data fields with respect to visual exploration than Voyager 2, while maintaining the similar level of enjoyability and ease of use.

Users also responded very positively when asked whether features in the feed provide guidance in their data analysis: 50% chose 5 and the rest chose a 4 rating. When it comes to comparison (Fig. 7) between two tools on a 5-level symmetric scale (with range  $[-2, 2]$ ), most participants (11 of 12) preferred DataSite ( $\mu = 1.25$ ,  $\sigma = 0.87$ ) to be most useful or useful for data exploration. Beyond this, participants were asked about their preferences between the two tools for focused question answering (as questioned by Wongsuphasawat et al. [WQM\*17]). 7 of 12 users preferred DataSite, and 4 were neutral with no preference, with 1 preferring Voyager 2 (rated -1). This is a little surprising since DataSite was primarily designed for visual exploration (and not question answering).



**Figure 7:** User preference in terms of visualization tools for open-ended exploration and focused question answering. DataSite received higher preference in both; 11 of 12 participants prefer DataSite for data exploration, and 9 of 12 prefer DataSite for focused question answering.

## 7.3. Results: Qualitative

To better understand the results from the statistical analysis, the participant ratings, and how DataSite helped participants explore the datasets, we present our observations below.

### 7.3.1. When the Participants used the Feed

The 12 participants were divided evenly to have different orders of the tools (DataSite first or Voyager 2 first). Four out of six who used Voyager 2 first, examined the feed (first interacted with the feed) in the beginning of their analysis with DataSite. For those exposed to DataSite first, 5 of 6 did the same. The rest started their manipulation first with manual specifications. It is worth noting that when the participants did not have any idea of how to construct interesting charts to get insights, they (8 of 12) switched to the feed for charts and inspirations (during the middle 10 minutes). 10 of 12 scanned through the feed at least once in the last 5 minutes of the session. 9 of 12 participants returned to the feed at least 3 times during the study. All of them specified at least 3 charts from the feed into the main view. This suggests that the feed can help analyst in multiple phases of exploration.



### 7.3.2. In-depth Data Exploration

Users usually create charts in manual specification tools with less than three attributes for encodings to limit the information encoded to a perceivable level. 7 of 12 participants found more advanced charts (3 or more data fields/attributes, the same below) that they “spoke out” in DataSite than Voyager 2 (at least 20% more). They mentioned that the summary in feed provides descriptive analysis, while charts alone in Voyager 2 may need more time to understand. It is worth noting that one participant used feed as the only interface for data exploration without additional manual specifications, and none did the same in Voyager 2. She explained that the feed provides a systematic approach towards analyzing the dataset, while she had difficulty understanding *Related Views* in Voyager 2.

# Interactions	Simp. Stats	Corr	Freq	Clust	Regr
mean	2.25	4.38	4.31	3.54	3.26
std. dev.	1.25	2.5	3.46	1.02	1.57

**Table 2:** Mean and standard deviation of participant interactions with computational results. Participants interacted with advanced features more (e.g., correlations, frequency counts, clustering, etc), while few features regarding simple statistics (min/max and mean/variance) were examined.

### 7.3.3. “Speak out” Charts in the Feed

The number of “speak out” charts that users verbally referred to during the study revealed interesting aspects for data analysis by general users. Table 2 gives mean and variance of features in different categories that the participants “speak out” about. Participants were more interested in plots of multiple numerical fields and categorical fields, rather than a single numerical field. Specifically, they merely viewed the charts in range/mean/variance modules (average number of charts are around 1), and from our observations, they skimmed through the natural language descriptions but did not click to see the charts. This implies that simple statistics are not interesting enough for analysts to examine, or the text descriptions alone are sufficient to understand.

For complex computations (correlation and clustering), charts are viewed more by expanding their textual description in the Feed. This is because there are usually no intuitive attribute combinations to creating informative charts with data fields (participants had to rely on random combinations or based on their general understanding). After seeing the charts in the feed, they all agreed that those charts were more informative than the ones they created by manual specification. This motivates us to choose other suitable modules to make the feed more fascinating and user friendly to explore.

### 7.3.4. Inspirations from the Feed

The feed view provides recommendations for visual data exploration from an analytical perspective. The features suggest certain combinations that yield effective visualizations. All the participants manually specified similar charts (w.r.t. encodings) after they had seen the charts within the feed, especially heatmaps representing frequency combination of two categorical fields. More than 80% (10 of 12) of the participants mentioned that the feed gave them

some ideas of which features and encodings can be used to make the chart more informative. On the other hand, *Related Views* in Voyager 2 show visualization recommendations to users that can be easily browsed, but participants thought of them just as related charts rather than specific analytical insights. They browsed through *Related Views* a lot but had never considered about how and why the specific chart was suggested. Also, 2 participants felt that the descriptions sometimes were not very easy to understand.

### 7.4. Participant Feedback

In this section, we list comments, suggestions, and feedback from the free text comments in the post-study survey and audio recording transcripts. For example, participants described that DataSite helped visual data exploration process: “*The feed helps gear you in the right direction, especially if you are new to a dataset. It tells you something notable that is worth looking into.*” As for comparisons to Voyager 2, “*DataSite is more specific because it gives you the options with various kinds of results. The feed is very helpful in data analysis.*” One participant even remarked that “[DataSite] will be very useful for day-to-day usage, especially for advanced data analysis, and can be used in industrial applications.”

Overall, the feed view was lauded, with one participant noting that “*the feed in DataSite provides a good starting point to visualize data if you don’t have any idea about the dataset.*” However, participants also provided suggestions on how to improve the feed. Said one participant, “*it would be better to make feed more user friendly, such as drag-and-drop to move charts into the main view.*” The feed was also perceived to be daunting, or as one participant put it: “*the feed is very useful, but sometimes it has a lot of results and can be a little overwhelming.*” Another participant said that “*in DataSite it is a bit difficult for me to understand the results in the feed, while Voyager 2 provides intuitive charts.*” One participant suggested that “*it would be interesting if there were guided tips that can help when I’m stuck in a chart, such as ‘try changing x and y axis’ when the axis label is difficult to read.*”

## 8. Discussion

Our results show that the feed interface in DataSite expedites the process of data exploration both in breadth and depth: participant preference for both open-ended as well as focused exploration was favorable to our tool. Below we explain these results in depth, and then discuss some of the limitations of our work.

### 8.1. Explaining the Results

Compared with the study results in Voyager 2, DataSite has a comparable unique field set coverage. The reason why DataSite does not improve the coverage significantly is that Voyager 2 shows all the charts by default, while DataSite only shows charts on demand when participants click on the descriptions. In other words, DataSite requires participants to actively examine the charts in the feed rather than merely browsing them in Voyager 2’s *Related Views*. Most participants preferred DataSite for data exploration, and rated the feed very useful to aid data analysis and provide trends and guidance of creating meaningful visualization. It is worth noting

that DataSite also yielded higher ratings in focused exploration. While DataSite is not designed primarily for targeted exploration, the study reveals a potential effect on that. This also motivates us to consider what and how a targeted data analysis system should adjust, and what evaluations can be done to achieve that purpose.

One observation from our evaluation studies is that simple statistics (average, range, variance, etc) did not interest participants much. A comprehensive evaluation of what features would be more interesting to the analysts is needed. The salient features lower barrier for bootstrapping exploration. However, too many features may distract user's interest, which have to be balanced carefully. While Voyager 2 also provides efficient visualization recommendations, results from our evaluation indicate that participants felt that the feed was more targeted and worth analyzing. Three participants noted that while they were going through Voyager's related views, they sometimes forgot what they had seen using manual view specifications. We speculate that DataSite explicitly labels the features using a textual description facilitates more targeted analysis.

It is worth noting that DataSite exhaustively applies computations to all the possible data fields (and combinations). While this enhances data coverage, not all modules and corresponding charts represent a clear insight. For example, categorical attributes such as "name" may have thousands of entries, and it is very difficult to find salient trends via such a chart. While DataSite ranks features by their significance, a more precise saliency measure is needed. The challenge is how to measure the efficiency of analytical features from a human perspective, and how to unify the metrics across various types of computations. This requires comprehensively measuring the efficiency for each visualization. This is further complicated by the fact that different analysts may have different perspectives, or the same analyst may have different perspectives depending on the question in the study. For the automobile dataset, buyers may wish to see which car is more economic and safer (higher fuel mileage and fewer accident records), while sellers may be interested in popularity (higher profits and larger number of sales). These contexts should also be considered for customization and personalization of features. Automatic guided tooltips, suggested by one participant, would be one way to achieve this.

## 8.2. Limitations

Our goal with DataSite is to take computational guidance to its logical extreme, building on the current trend of recommendation engines for visualization. However, this kind of automatic analysis approach is fraught with challenges, including eroding an analysts' independent thought process (as discussed by Wongsuphasawat et al. [WQM\*17]), automating key decisions that would benefit from analyst insight, and even HARKing [Ker] (hypothesizing after results are known) and p-hacking [SS66] (extensively mining a dataset in search of significant findings). We do not claim that DataSite's mixed-initiative method is the optimal method for balancing the analytic burden between analyst and computer, only that it is one instance in the design space that shows promise.

However, while DataSite automates some of the analytical process, it does not aim to replace the analyst. Data analysis is best performed with an analyst in the loop, and DataSite ensures the analyst is always in control. From our evaluation, the average number

of insights from different data sources are 8 manually created, 11 from the feed, and 7 from the feed with modifications. This observation shows that participants generated almost the same number of insights from feed (automatic) and manually created.

Another valid point of criticism is that computational power is not always cheap; some algorithms are simply not tractable to be run for an entire dataset in an exhaustive manner. This means that DataSite's scheduling algorithm requires fine tuning; pure brute force, as somewhat provocatively stated earlier in this paper, is not a universal solution. Our current implementation can scale up to tens of thousands of entries in the dataset, which is comparable to many existing visualization tools [WQM\*17, YEB17]. In particular, our evaluations involve datasets with 10,000 (bird strikes) and 3,000 (movies) items. Still, while there is potential for a more scalable system, it is beyond the scope of this paper.

## 9. Conclusion and Future Work

We have presented DataSite, a visual analytics system that integrates automatic computation with manual visualization exploration. DataSite introduces the feed, a list of dynamically updated notifications arising from a server-side computation engine that continually runs suitable analyses on the dataset. The feed stimulates the analyst's sensemaking through brief descriptions of computational modules along with corresponding charts. Filters and text search bar enable quick scan and fast data exploration. Two controlled user studies evaluate the approach compared to PoleStar and Voyager 2, respectively, and show that significant performance improvements over the manual view specification tool (PoleStar) in both breadth and depth for data coverage, as well as useful guidance in exploration. It also provides more meaningful charts and features to analysts over Voyager 2, while maintaining similar enjoyability and ease of usage. The results are promising and indicate that the system promotes data analysis in all stages of exploration.

DataSite can be seen as a canonical visual analytics system in that it blends automatic computations with manual visual exploration, thus establishing a true partnership between the analyst and the computer. We regard it as the first step towards a fully proactive visualization system involving a human in the loop. Of course, many improvements can be made towards a more efficient system; after all, while CPU resources are cheap, they are not free. One potential future research topic is guiding recommendations based on the analyst's interest, past interactions, and even their personality. For example, consider a DataSite-like system that would respond to an analyst drilling deep into a part of a sales dataset over time to proactively compute future sales projections for that part of the data in an effort to anticipate future questions the analyst may have. Other ideas may include mining the analyst's click stream, browsing and analysis history, and even social media profiles to determine how to best guide the proactive computation. Finally, we could also use interaction to dynamically update the ranking of features in the feed, e.g., prioritize features for data fields selected by the user.

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