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Capture & Analysis of Active Reading Behaviors for Interactive Articles on the Web

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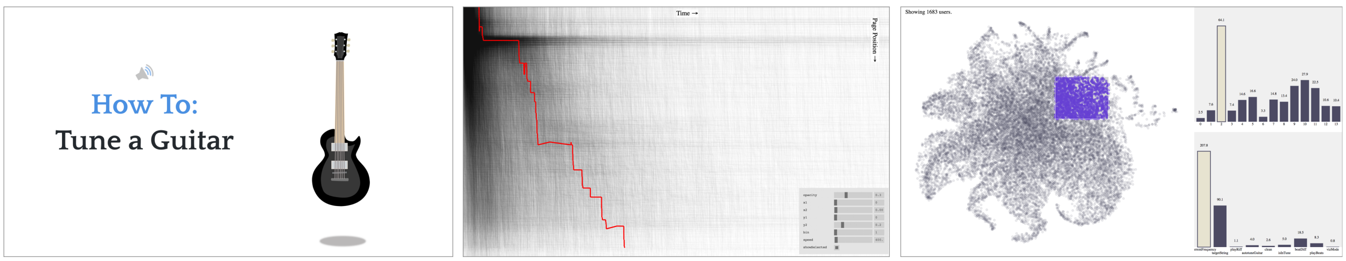

Figure 1: *An online interactive article* How To: Tune A Guitar *(left) and visualizations of collected reader activity data.* HopScroll *(center) visualizes reader progress over time, revealing reading patterns and fixation points.* Readuction *(right) uses dimensionality reduction of reader feature vectors to enable nuanced segment analysis; linked views show timing and event information for selected points. Along with these tools we present Idyll language extensions for automating the collection of detailed log data, and discuss reading patterns discovered.*

Abstract

Journalists, educators, and technical writers are increasingly publishing interactive content on the web. However, popular analytics tools provide only coarse information about how readers interact with individual pages, and laboratory studies often fail to capture the variability of a real-world audience. We contribute extensions to the Idyll markup language to automate the detailed instrumentation of interactive articles and corresponding visual analysis tools for inspecting reader behavior at both micro- and macro-levels. We present three case studies of interactive articles that were instrumented, posted online, and promoted via social media to reach broad audiences, and share data from over 50,000 reader sessions. We demonstrate the use of our tools to characterize article-specific interaction patterns, compare behavior across desktop and mobile devices, and reveal reading patterns common across articles. Our contributed findings, tools, and corpus of behavioral data can help advance and inform more comprehensive studies of narrative visualization.

1. Introduction

The *interactive article* is a form of web content increasing in popularity. Newspapers publish interactive graphics and visualizations in addition to more traditional articles. Educators and technical communicators enrich text with multimedia in an effort to further engage their readers. These interactive pieces often resonate with a wide audience [GB18] and may more effectively communicate complex topics [May02]. Publishers understand that interactive articles can bring both acclaim and a broad readership [HR15]. However, due to time constraints and a lack of tooling, these articles are seldom analyzed to see if their interactive features are effective at engaging readers and delivering the desired message. Interactive articles suffer from the additional issue that there are no clearly defined metrics or evaluation methods to measure their effectiveness.

Visualization practitioners have debated whether interactive components are effective and worth the significant effort and expense necessary to create them [Tse16, Bau17, Ais18]. Researchers have called for more data to be collected on these articles, in a more realistic context than the laboratory [KM13]. To advance more comprehensive and realistic studies of narrative visualization use, we contribute capture and analysis tools for reader sessions of interactive articles. We first present extensions to the Idyll markup language that automate the detailed instrumentation of interactive articles. The logger captures browser metadata, scroll position, and time-series data of mutations to Idyll's article state model, which tightly corresponds to article feature usage.

We next present visual analysis tools to enable exploration of collected reader data. *HopScroll* plots user scroll positions over

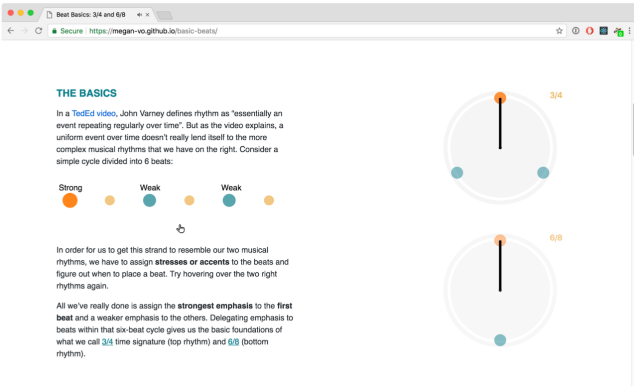

Figure 2: Beat Basics *was produced by an undergraduate computer science student. She designed it to teach curious readers the basics of rhythmic time signatures in music.*

time to reveal a diversity of reading behaviors. In addition to an aggregate overview, HopScroll shows individual user sessions in an animated fashion akin to *Hypothetical Outcome Plots* [HRA15]. *Readuction* uses dimensionality reduction to visually cluster related feature vectors automatically derived from event logs. Coordinated plots show associated timing and event data for selected points, enabling nuanced segment analysis of reader behavior. Both tools support *micro / macro readings* [Tuf90], enabling simultaneous consideration of aggregate patterns and individual behaviors.

We apply our tools in three case studies of interactive articles. We follow the articles through their entire life cycle: from inception through design, publication, and evaluation. Each was written to appeal to a specific audience, and instrumented to record reader interaction logs. These articles were visited more than 50,000 times by readers across the world. We report aggregate usage statistics, compare behavior across mobile and desktop devices, and demonstrate the use of our tools to characterize both article-specific interaction patterns and cross-article reading patterns. Additionally, we show how the collected data can be operationalized and measured against content-specific metrics developed by the articles' authors. We conclude with a discussion of findings, implications, and avenues for future research in this area. By publicly sharing our tools and corpus of reader data, we hope to encourage the collection and study of reader behavior at scale in real-world contexts.

2. Background & Related Work

Our work is motivated by calls from researchers in the data visualization, journalism, and educational communities for further inquiry into the effectiveness of dynamic content. In conducting our analysis we build on a large body of work on the analysis of webpage usage, and the instrumentation of software applications more generally. We scope our work to consider content specifically that is published online to an anonymous readership with whom the author has no direct communication. We use the phrase *interactive article* to encompass several types of web content. In general these articles are characterized by interleaved text and interactive widgets – often utilizing animations, data visualizations, or simulations – and guide a reader through a primarily linear narrative. This scoping is in contrast to the use of *interactive fiction* by media critics to describe non-linear, branching text [Zie89], and *interactive non-fiction* which has been used to refer to similar techniques applied in a journalistic context [SZ11]. *Explorable Explanations* [Vic11] are one notable type of interactive article that promote active reading and inquiry into the details of a topic. This type of article is becoming increasingly prevalent on the web [exp18]. Explorable explanations share design techniques with interactive articles published by news outlets, however they have not been widely studied.

The use of narration alongside graphics has been broadly studied by education researchers. Mayer [May02] aggregates principles of multimedia learning that can inform designers of interactive educational content. In a classroom setting the effectiveness of educational content might be assessed via tests or quizzes given directly to students. However, in contrast to a classroom or MOOC setting, we are interested in content published to broad audiences who are not externally motivated, for example, by being enrolled in a class. As such, while the design principles are related, the methods by which materials are evaluated should vary.

2.1. Usage Logging and Analysis

There is a rich history of research on capturing and visualizing usage of applications in general [KTPG*02, HMSA08, MGF13] and specifically on web sites [HC02, PSF04]. Commercial and open source tools like Google Analytics [goo18], Chartbeat [cha18], and Matomo [mat18] are commonly used to collect basic statistics of web page visitation. These services record visitor counts and time spent on pages, in addition to profiling how users flow from page to page. Google Analytics offers web administrators the ability to deploy surveys to website visitors as a means of assessing the quality of page content. In this work we focus on capture and analysis methods that do not require additional page content or input from readers. Other services like Heap [hea18] focus on tracking behavioral events such as button clicks. Visualization researchers have presented systems for analysis of event logs [DL17] and clickstreams [LWD*17]. For example, CoreFlow [LKD*17] is a tool for extracting and visualizing branching patterns in event sequences.

Quantifying user engagement beyond simple measures like page views and time spent on task is difficult. Attfield et al. [AKLP11] propose different facets of user engagement: focused attention, positive affect, aesthetics, endurability, novelty, richness & control, reputation, trust & expectation, and user context. The data that we have collected can be used to assess engagement through aesthetics and richness & control. Rodden et al. [RHF10] contribute a generic framework (HEART) for measuring user experience of web applications. These models are not fully applicable to the study of interactive articles. For example, an article about gun violence [CCFB16] may induce negative affect in readers, but still effectively communicate a message. Metrics like retention may not apply to individual articles if there is no need for visitors to return after they have read and learned from the presented content. Some applications opt to tailor metrics and visualizations to their specific domain rather than relying on a general framework. For example, LectureScape [KGC*14] visualizes how viewers interact with educational videos and Porta [MG18] profiles tutoring software. These projects demonstrate that tailoring metrics to a specific domain can lead to more effective analytics platforms. In ad-

dition to our domain-specific logging and analysis tools, we work with domain experts to derive quantitative content-specific metrics to assess particular aspects of article design.

2.2. Journalism and Narrative Visualization

Visualization researchers have studied the techniques used in interactive and data-driven stories published by news outlets. In 2010, Segel & Heer [SH10] articulated a design space of narrative visualization. This design space has been further refined [SLRS16] to reflect modern practice. Researchers have noted several opportunities for further research in this space, including evaluating the effectiveness of data-driven storytelling techniques [LRIC15]. Along these lines, McKenna et al. [MHRL*17] report on the effects of design choices on reader engagement in a controlled study. However, Kosara & Mackinlay [KM13] write that studies will need to be performed outside of a traditional laboratory setting in order to "get stories in front of the types of people who are also the audience for news media." Amini et al. [RHDC18] explicate the criteria, methods, and metrics that may be used when evaluating data driven stories. They, too, suggest that case studies may be necessary in order to better understand how tools and stories perform in the wild. In this research, we conduct evaluation of interactive articles published in an uncontrolled setting. Boy et al. [BDF15] present a case study examining the effect of the presence of narrative text on users' engagement with visualizations in the wild. Boy et al. use semantic operations to operationalize log data by mapping it onto a generalized vocabulary of user actions. While this work is similar to ours in its collection of usage data from public web pages, we focus on capture and analysis of reader behavior with the article as a whole, rather than a specific visualization.

Other projects contribute models and tools for narrative visualization. Walny et al. [WHP*18] analyze use of visualizations through the lens of active reading. GraphScape [KWHH17] formalizes and extends earlier work by Hullman et al. [HDR*13] to suggest appropriate visualization sequences. Ellipsis [SH14] is a domain-specific language (DSL) and graphical interface for augmenting visualizations for use within narratives. Idyll [CH18a] is a DSL for authoring interactive articles, providing a markup language, component library, and reactive variable system to orchestrate interactive content. Vuillemot et al. [VBT*16] note a challenge for analyzing visualization usage is that it often necessary for authors to build their own logging tools to support relevant event tracking. Here, we leverage Idyll's architecture – in which reactive variables directly drive interactive updates to the presented document content – to collect detailed content-specific usage logs across articles, without writing additional instrumentation code. These variables typically fully specify the state of an article, and so tracking their changes over time is sufficient to represent the interactions occurring during a reader's session.

3. Case Study Article Design

To better understand how readers on the web engage with interactive narrative content, we instrumented three interactive articles before they were published online. The articles covered varying topics (music theory, guitar tuning, dimensionality reduction) and targeted different readerships, but each used design techniques common to contemporary interactive articles. All articles were authored using Idyll [CH18a]. Idyll's reactive runtime is powered by a single global state, an architecture that lends itself to instrumentation for easy logging and replay, allowing us to generalize and automate the data collection process. We collected reader data on each of the articles for several weeks, however the vast majority of reader sessions came within the first two days of the articles' publication.

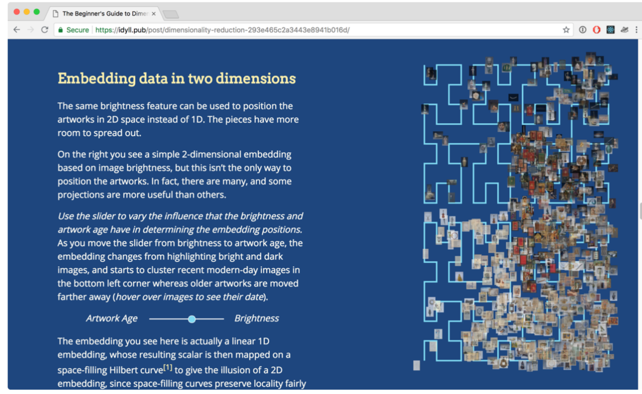

Figure 3: *The* Beginner's Guide to Dimensionality Reduction *uses artworks from the Metropolitan Museum of Art as examples for introducing dimensionality reduction techniques.*

Here we give an overview of the article designs; in later sections, we apply our logging and analysis tools to each of the articles and discuss our findings. Each case study concerns a text-driven, linear narrative accompanied by interleaved interactive graphics and control widgets. The articles draw on a variety of design techniques that are prevalent in online articles from news outlets, for example scroll-based navigation and interactivity, inclusion of buttons that can be used to start and stop animations or audio clips, and custom interactive graphics. The articles were chosen in part because of these representative features as well as our ability to instrument them. Importantly, each article was designed by the authors to address a topic of personal interest that they believed to be of value to a broader audience, providing an authentic and realistic motivation.

3.1. *Beat Basics*

Beat Basics (Figure 2) was written by a computer science undergraduate as a submission to the 2018 Explorables Jam [jam18], a three week online hackathon that solicited submissions of explorable explanations covering any topic. The article teaches readers about the difference between two non-standard musical time signatures ($\frac{3}{4}$ and $\frac{6}{8}$), using interactive graphics based on John Varney's rhythm wheel [var14]. The article was written to be accessible to an audience without formal training in music theory, and uses audio-enabled interactive graphics to convey rhythms. There are 7 distinct sections of content. Most of the user interactions are tied to hover events: readers can move their mouse cursor over different graphics on the page to trigger audio playback and animation. There are also buttons that may be clicked in order to reveal additional information. At the end of the article users can listen to a section of a classical song and watch it synchronize with the interactive rhythm wheel.

3.2. The *Beginner's Guide to Dimensionality Reduction*

The *Beginner's Guide to Dimensionality Reduction* [CH18b] (Figure 3), was created as a submission to the 2018 Workshop on Visualization for AI Explainability [vis18]. It was written by two computer science Ph.D. students. The article was crafted to make dimensionality reduction techniques accessible to those who did not have a pre-existing intuition for why the techniques are useful or how they work, and consists of 7 distinct sections. It starts by introducing a dataset of artworks from the Metropolitan Museum of Art [oA17], and uses this data in examples throughout the article. Dimensionality reduction is introduced first in one dimension, sorting the artworks by brightness, moves on to a simple but naïve 2-dimensional projection, and ends with an overview of three algorithms that are used in modern data science practice: PCA [AW10], t-SNE [LvdM08], and UMAP [LM18]. Readers can hover over an artwork to call up more details. As they scroll through different sections, the graphics update automatically in response. Other interactions are available,including a parameter to the naïve 2-dimensional projection, a button that can be clicked to display more technical details, and buttons to reveal details about the algorithms discussed.

3.3. *How To: Tune a Guitar*

How To: Tune a Guitar (Figure 1) uses interactive graphics and audio to teach readers techniques for tuning guitars. The article was written by two co-authors of this paper. The topic was chosen because we expected that it would be interesting to a wide audience, and the article was written to be accessible to beginners without prior musical knowledge while still being of interest to experienced musicians. We developed an interactive guitar widget with audio and dynamic visualizations to create a fun yet educational article. The article asks readers to tune the interactive guitar, and use several different methods to achieve the goal of tuning the guitar properly. This article is the longest of the three discussed in this paper, consisting of 13 distinct sections. The interactive graphics update in response to readers scrolling through content. There are several opportunities for direct user interaction with the widgets, including strumming the guitar, modifying tuner knobs, clicking buttons to trigger audio playback, and adjusting parameters that drive specific features such as adding distortion or modifying beat frequency playback.

4. Tools for Capturing Reader Activity

To automate article instrumentation, we developed an extension to the Idyll runtime that records a number of attributes that are semantically relevant to the reader experience (i.e., beyond low-level mouse, touch, or keyboard events). When a reader first loads an article, metadata is collected about their browser, device, and screen size. A scroll event listener is added to produce a time-series of user scroll positions. A timer is used to track the duration of user visits to each article. State changes to Idyll's reactive variables are recorded, allowing for reconstruction of the usage patterns in individual reader sessions. Google Firebase is used for data storage and user identification, although a different backend could be configured if desired. By default users are anonymous, but identifiers are stable: if the same browser visits the page multiple times, each of these visits will be associated with the same identifier.

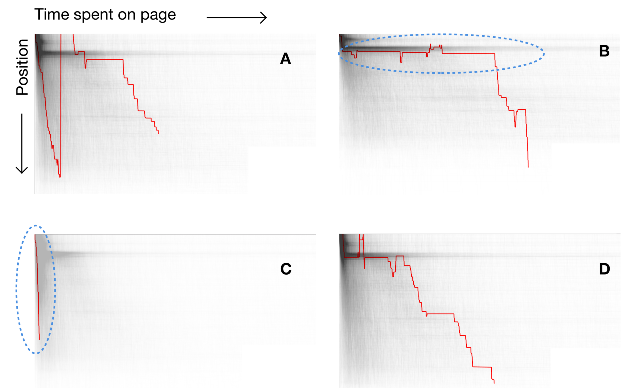

Figure 4: *Scroll positions over time for* How To: Tune A Guitar. *Plots highlight exemplary patterns: (A) Preview & Read, (B) Super Tuners, (C) Scroll & Bounce, and (D) Balanced Engagement.*

The recorded variables come directly from Idyll's reactive runtime state and parameterize article components, tracking changes in response to user input. This allows us to automate the construction of user models that incorporate article specific features. For example, in *How To: Tune a Guitar* a variable update is emitted each time a user mouses over a string on the guitar or adjusts a tuning knob, allowing us to reconstruct in detail how users interacted with the widget. In *Beat Basics* and *Dimensionality Reduction* a variable is updated each time a reader scrolls through one of several waypoints, triggering additional updates to the display. While it is possible for article authors to define private state in components that would not be captured in our instrumentation code, this is uncommon in practice and wasn't the case in any of the articles examined here; Idyll's variables typically fully specify the state of an article's interactive components. The correspondence between Idyll variables and user interaction is not a coincidence particular to these articles, but follows directly from the design of the language. Our capture methods can be used directly by any Idyll article. We have released our logging extension as open source software and hope that it will enable further study of interactive article usage.

5. Tools for Analyzing Reader Activity

To analyze captured reader activity logs, we start by computing aggregate statistics about usage of various article features, then use custom visual analysis tools (*ScrollHop* and *Readuction*) to perform exploratory analysis and identify patterns of user engagement. We also work with domain experts (the article authors) in order to create high level metrics concerning article usage, and use these to analyze the usage of features specific to each of the articles. Our analysis tools are applicable to data from any interactive article with appropriate instrumentation. To gain a high-level overview, we calculate aggregate usage statistics for each article. This includes distributions of the amount of interactions with each variable, the amount of time spent on the page, and the amount of progress made through the content. We compute these distributions by aggregating log data, and generate visualizations of usage of key variables and scroll progress (available as supplementary material). Since *How To: Tune a Guitar* did not implement explicit waypoints, we track

scroll position at the pixel level and later bin the positions to a particular section in a post-processing step. We also asked authors of each article to formulate questions about how users might interact with their articles. We prompted authors to test their assumptions of usage as well as consider interactions that might exhibit critical engagement or content understanding. We operationalize each of these questions by writing a corresponding query over the log data and present the results among the calculated statistics.

5.1. ScrollHop: Visualizing Scroll Positions over Time

It is difficult to use existing techniques to identify common patterns in user scroll data. One possibility is to use dynamic time warping [BC94] techniques to cluster the scroll timeseries, however the size of our data set made this computationally infeasible. The timeseries could be transformed into a series of events (e.g., navigations between article sections) and analyzed using event flow visualization, however there are challenges in using these techniques at scale [DSP*17], and we wished to be able to inspect nuanced scroll behavior within sections. To gain insight into patterns of reader behavior, we created *ScrollHop* (Figures 1, 4), a tool that visualizes each visit to the page as a single line displaying scroll position over time. Overlapping behaviors form dark bands, allowing us to assess how readers cluster in their movement through the webpage. By sequentially highlighting individual scroll timelines in red, we can see how individual scroll behaviors relate to the space of all scrolling behavior within the captured data. Prior work in uncertainty visualization [HRA15] suggests that animating through individual outcomes is an effective strategy for understanding the variance among possible outcomes in a set. ScrollHop uses a custom WebGL shader to interactively (re-)render tens of thousands of scroll traces in response to axis scale and opacity adjustments.

Through the use of this tool we discovered interesting user behaviors such as *preview & read*, where users briefly scroll down the page to examine the content before returning to the top of the page and going back through the page more slowly. Users who *scroll & bounce* were the most prominent group, moving quickly through the webpage and exiting after a short time. The behaviors that we highlight throughout this paper map onto behaviors that we observed to be common when viewing samples drawn from the population of all user scroll patterns.

5.2. Readuction: Supporting Nuanced Segment Analysis

To assess more nuanced behaviors, we analyze feature vectors that summarize reader interaction with an article. Some analysis tools perform clustering to identify segments of the user population (e.g. [CD18]), but depending on the parameters these approaches may suffer from over- or under-clustering of groups, and can require careful evaluation [HC02]. As each interactive article consists of customized content and interactions, we reasoned that tools for this domain should privilege nuanced inspection and interpretation over potentially misleading discrete categories. This led us to consider dimensionality reduction methods that can provide a continuous representation of similarities among reader sessions.

We define feature vectors to numerically encode reader behavior in a multi-dimensional space. The vector dimensions consist of (1) count aggregations of state changes for each Idyll variable, (2) the amount of time spent in each section, and (3) associated data such as the maximum scroll depth that a reader reached. Feature vectors are automatically computed from Idyll usage logs, with each article using a different set of dimensions depending on the Idyll variables employed. These variables fully specify the state of the article. The counts of their changes correspond to the overall usage of the article widgets. These features represent both the content that a reader engages with and the amount of time that they spent doing so.

We then use the feature vectors as input to the Uniform Manifold Approximation and Projection (UMAP) dimensionality reduction algorithm [LM18], which uses feature similarity to form a topological mapping that is then projected into a Cartesian coordinate space. We chose the UMAP algorithm over alternatives such as t-SNE [LvdM08] or PCA [AW10], as we found UMAP produced useful projections that allowed us to identify different user behaviors without over-clustering, revealing smooth gradations of behavior, aligning with our design goals above. We visualize the projected 2D coordinates in a scatter plot; adjacent points represent visits which are similar in some subset of the selected features.

Readuction is an interactive tool for generating and exploring these UMAP visualizations (Figure 1). It displays a data point for each reader session, projected into UMAP coordinates. On the right-hand side, two bar charts show the median value of reader time spent per article section and variable usage counts. The UMAP projection and bar charts are linked so that the user can select subsets of sessions and examine the corresponding feature vectors. For each of the articles examined, we used *Readuction* to identify usage patterns which were representative of large groups (hundreds to thousands) of users. To do this, we selected different regions of reader sessions, observing the varying distributions of time spent and variable usage. We utilized the expertise of article authors to understand how these distributions map onto real-world article usage. The tool enabled us to discover cohorts of users defined by similar engagement with article content. For example, in the analysis of *How To: Tune a Guitar* we call one such group *super tuners*.

6. Case Study Article Analysis

In this section we analyze each article independently using the tools and methods previously discussed. In the ensuing discussion we tie together patterns observed across the articles, highlight our conclusions, and suggest areas of future research. Because the articles were designed primarily for laptop and desktop users, we put the primary focus of the analysis on these users; throughout the analysis that follows statistics refer to desktop users, except where we explicitly refer to mobile users. Many of the article features were disabled or shown in a static format for mobile readers, so this helps us make uniform comparisons when discussing feature usage.

6.1. *Beat Basics*

After submission to the 2018 Explorables Jam, *Beat Basics* was posted online to Twitter, Hacker News, and a music education community on Reddit. We collected data from 10,000 sessions by 8,368 users, 4,456 of which viewed the desktop version of the article.

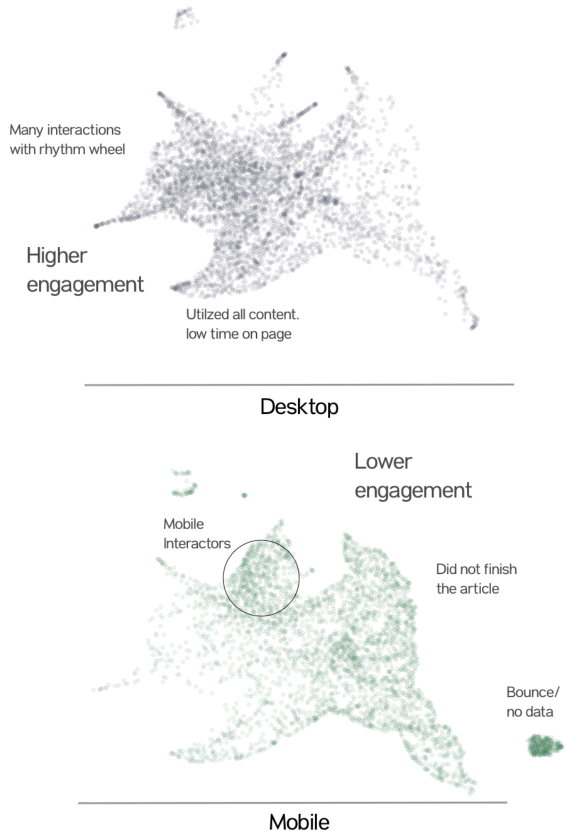

Figure 5: *An annotated UMAP projection of* Beat Basics *reader sessions. We used the Readuction tool to identify cohorts of readers exhibiting similar behavior by observing the distributions of feature vectors for subsets of reader sessions. The feature vectors consist of counts of variable changes (a proxy for engagement with interactive widgets) and time spent on each section of content.*

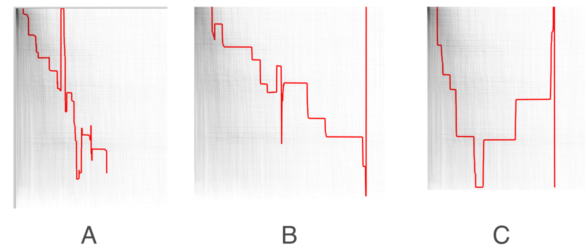

Figure 6: *Example scroll paths from* Beat Basics. *(A) shows a reader who backtracks in the content several times; (B) a reader progresses linearly before scrolling down quickly to preview a section and subsequently spend time reading it; (C) shows a reader who read through the content forward and then in reverse.*

6.1.1. Aggregate Statistics

The median time spent on the page was 86 seconds (36-183 IQR), and 85% of readers interacted with the interactive content to playback the beats (median 16 interactions, 6-27 IQR). Of the two example songs featured at the end of the article, both the $\frac{3}{4}$ and $\frac{6}{8}$ songs were played a median of two times, indicating that these readers reached the end of the content and engaged with the audio playback mechanism for each of the time signatures multiple times. Mobile readers spent less time on the page (median 20 seconds, 6-57 IQR). In both formats, there were outliers who drove up the mean amount of time on the page (3,224 seconds desktop, 510 seconds mobile), likely due to readers leaving the page open while they performed other tasks. On mobile the median number of interactions with an audio component was one, the top 25% interacted 3 or more times. Only 10% of mobile readers triggered one of the example audio clips at the article's end.

We asked the article author to produce a set of questions about her audience that she would like answered, without discussing the details of our data collection process. She wanted to know:

Q1. The article featured rhythm wheels positioned alongside the text, one near the top of the page and one near the bottom. *Did the differing placement of the rhythm wheels affect their usage?*
Q2. Audio playback could be triggered by hovering over the rhythm wheels, or links in text. *How did interaction levels vary between different input modalities?*
Q3. Readers were prompted to interact with various widgets at different points in the text. *Were readers following along and interacting in accordance with the narrative?*

To answer Q1 and Q2 we can consult the aggregate usage statistics. The distribution of usage of the $\frac{3}{4}$ circle (the one placed in the top half of the page) skews slightly higher (median 8 hovers, 4-14 IQR) than the $\frac{6}{8}$ circle (median 8 hovers, 2-12 IQR). The circles are featured more prominently and were used more than the inline links in the text. 75% of readers interacted with one of the two rhythm circles, while 54% hovered over one of the two links in the text, indicating that they seemed to be aware of the inline links, but preferred interacting directly with the larger graphic. To answer Q3, we measure the number of times that readers switched between engaging with the two different rhythms. The article used several different techniques to explain how the two rhythms compared. Readers that were following along closely with content should have switched between the two multiple times. The median number of switches was 6 (2-9 IQR), indicating that most readers were following along with the content and were completing the tasks setup by the author in the manner that she expected. This calculation is straightforward to compute via a query over our collected interaction data, suggesting that the data collected is appropriate for answering these kinds of content-specific queries.

6.1.2. Observations from ScrollHop

About three quarters (73%) of *Beat Basics* readers reached the end of the article. In observing the scroll data we noticed a few trends. The first — common throughout all three articles, perhaps common to any content distributed to a broad online audience — is that many readers simply scroll through to the end of the content very quickly and leave the page. Many of these readers interact with various interactive components, although the length of time that they spend doing so suggests a very superficial level of engagement. We also noticed that some readers' trajectories were erratic, moving backwards and forwards in the article. These readers seemed to be engaging with the content as a whole rather than one individual sec-

tion at a time to support their understanding of the topic, drawing on the multiple visualizations which presented the information in different ways. Figure 6 shows examples of these reading patterns including two individuals whose path through the content was mostly linear but included backtracking (A, B) and one who read forward through the content and then viewed it in reverse (C).

6.1.3. Observations from Readuction

Figure 5 shows both desktop and mobile readers plotted according to the UMAP dimensionality reduction algorithm; both groups are plotted using a shared projection. We used Readuction's interactive selection tool to view time and usage distributions and identify regions of interest, and then manually added annotations. Outliers who bounced from the page without interacting can be seen clustered away from the central group. Different regions of the main group can be inspected to reveal the most engaged readers, the least engaged, and the many that lie in between. We dragged the brush tool across regions of users to view aggregate feature vectors and selection counts, revealing the density and behavioral patterns exhibited in different areas of the visualization. Towards the edges of the main group are users who went furthest above or below average in utilization of different article features or time spent on the page. Throughout the plot the usage patterns of neighboring clusters of readers tended to be quite similar, indicating a continuum of engagement behavior rather than clearly separable groups.

6.2. The *Beginner's Guide to Dimensionality Reduction*

The *Beginner's Guide to Dimensionality Reduction* was submitted to the IEEE VisxAI workshop, posted to Twitter, and subsequently appeared on the Data Science community on Reddit, and on datacamp.com. The post received 7,055 visits from 4,549 readers; 3,170 sessions were on desktop devices.

6.2.1. Aggregate Statistics

The median time spent on the page was 116 seconds (33-386 IQR). 76% of readers reached the end of the article. Of the readers who reached the end, 59% clicked one of the buttons to select an additional algorithm. This means that 41% of the readers who "finished the article" did not read all of the content. The details of the other algorithms weren't necessary for the high-level takeaways of the articles, but they were needed for informed application of the technique in practice. The median number of times a reader hovered over an artwork was 4, the median number of interactions with the algorithm details button and with the slider was zero. Many readers quickly bounced from the page. However, many readers also engaged with the article, interacting with the various widgets and some manipulating features a great many times. Graphs of the usage distributions of key article variables are available as supplementary material. The median time that mobile readers spent on the page was 40 seconds (10-131 IQR). 48% of mobile readers reached the final content of the article, and of those 38% utilized the functionality to observe details of the other algorithms. Across the articles we consistently noticed that many mobile readers would consume all of the textual content even though they did not engage with interactive features. This is likely due in part to the fact that these articles were designed with desktop readers in mind, and though

Figure 7: *The distribution of minimum values of a range slider in* The Beginner's Guide to Dimensionality Reduction*. The slider started in the far right position. Many users did not engage with it; others moved it all the way to the left.*

responsive to some extent, did not offer a polished experience for mobile readers. It may also be due to time or environmental factors affecting mobile readers, leading them to be less likely to dig deep into features and more likely to read for the high-level takeaways.

We interviewed an author of this article to understand what features he considered most valuable for tracking user engagement. He was interested in high level information such as completion rate and time on page, as well as granular information about how readers engaged with specific widgets. He commented that he wanted to see specific metrics for different parts of the interactive content.

Q4. The article featured a slider allowing readers to adjust a parameter of a two-dimensional embedding. *Were readers engaging with this slider? If so, how were they using it?*
Q5. At the end of the article readers could click on buttons to see details about three different dimensionality reduction algorithms. Clicking a tab caused the visualization to be redrawn using the corresponding algorithm. *Were readers examining these details? Were they engaging with the visualization in order to understand different algorithms' output?*

When discussing Q4, the author commented "If I had a distribution of slider values, I could see how people were using it. If it's bimodal maybe we should have used a button." The distribution of values taken on by the slider represents all values with approximately equal weight. However, if we look instead at the minimum value that the slider took on, shown in Figure 7, there is clearly a bimodal distribution. This indicates that very few readers left the slider in the middle without first moving it to the lower end of the range. The readers tended to rarely interleave usage of the slider and hovering over artworks—only ~5% of readers did this—indicating that readers weren't spending time examining the consequences of moving the slider, and that this presentation was not as effective as intended. Overall about 45% the readers engaged with the algorithm details buttons. Only about 15% of readers used one of these buttons and subsequently engaged with the visualization.

6.2.2. Observations from ScrollHop

We noticed several trends when observing the scroll behavior for this article. First, the data seem to display much heavier horizontal banding than either of the other two articles, indicating that readers were spending more time pausing to read content. Because this is both the most technical and the most didactic of the three articles this pattern is not surprising. Readers tended to scroll through in a linear manner, working their way forward through the article, seldom jumping between sections. This may imply that the content

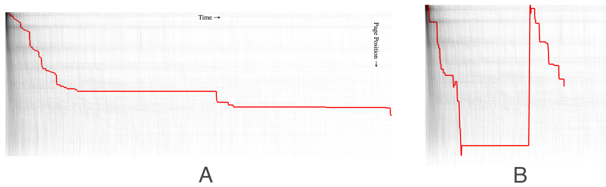

Figure 8: *Example scroll paths from the* Beginner's Guide to Dimensionality Reduction. *(A) shows a reader who skimmed the beginning of the article, but spent more time in the later sections; (B) shows a reader who quickly reached the end of the article, spent time there, and then went back to re-read earlier content.*

was well motivated and well matched to the audience, or it may be an artifact of our design choice to use scroll-based waypoints and animations, perhaps making the process of switching sections more burdensome than free-scrolling. As with all of the articles we noticed a *preview & read* behavior, where users would quickly scroll down the page before scrolling back up and either bouncing or continuing to read through at a slower pace. We also noticed that some readers would progress quickly downwards into the story before pausing at one of the sections and continuing to engage more heavily (Figure 8.A). This may indicate that the content after a certain point in the article was well matched to their background, or that the article's design piqued an interest [GB18]. Some readers went back and re-read sections after finishing the content (Figure 8.B).

6.2.3. Observations from Readuction

Figure 9 shows the UMAP projection for desktop readers of this article. Most readers cluster into one mass, with several smaller "tendrils" detached from the main group. This view was helpful in allowing us to identify subsets of users based on where they spent their time and what they interacted with. Using the selection feature we further identified groups of readers who exhibit similar behavioral quirks, such as leaving the web page open for some time before actually reading the article. Users with no or low engagement are visible off the main cluster. Within the main cluster we can identify users who engaged with interactive components to varying degrees, for example, those used the buttons to click through details of all of the algorithms several times (*algorithm explorers*), those who engaged heavily with the weight parameter (*weight shifters*), and those who scrolled through the article multiple times (*re-readers*).

6.3. *How To: Tune a Guitar*

How To: Tune a Guitar was published and posted to *Twitter* and *Hacker News*, and was subsequently covered by *GIGAZINE*, a Japanese news blog, and *Codedrops Collective*, an online web design publication. It also appeared in Google search results for the search term "how to tune a guitar." We collected data from 55,193 sessions by 46,347 readers, including 27,603 desktop sessions.

6.3.1. Aggregate Statistics

The median time spent on the page was 78 seconds (27-210 IQR), and readers performed a median of 22 "plucks" of the guitar string (6-56 IQR), and 42 tuning adjustments (6-119 IQR). 23% of readers tuned all six strings of the guitar. Usage of the more detailed

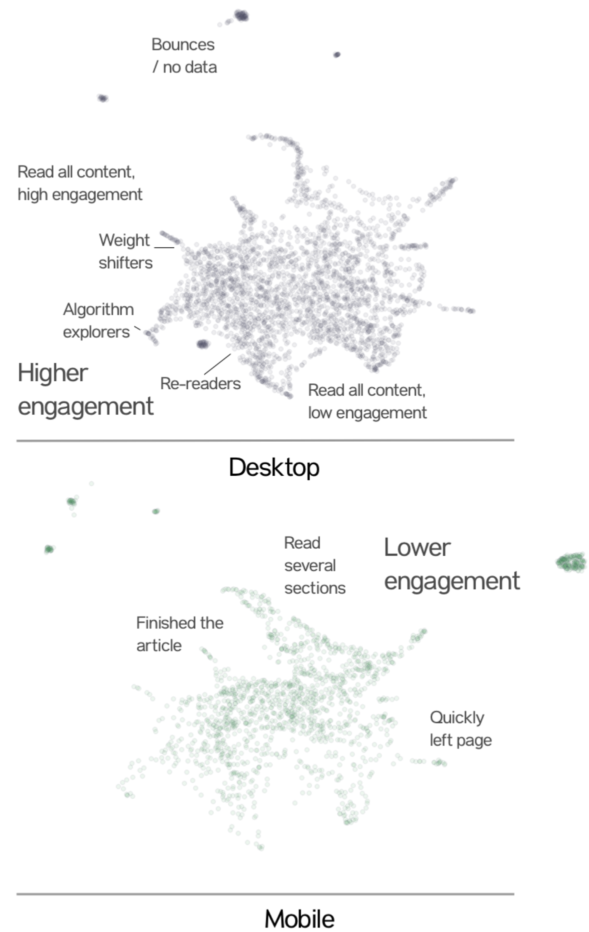

Figure 9: *UMAP projection of feature vectors for* Beginner's Guide to Dimensionality Reduction *readers. The projection reveals broad clusters of readers, such as those who consume all the content, those who leave the page quickly, those who engage heavily with article features, and those read the content multiple times.*

interactive features was relatively low: just 14% of readers clicked the button to play an example of beat frequencies, 2% modified the beat frequency playback. For mobile readers, the median time on page was 41 seconds (10-131 IQR). 82% of mobile readers advanced through at least some of the content, even though they needed to dismiss a warning about download size; however, only 34% attempted to tune the guitar and just 6% tuned all six strings. These observations suggest that mobile users are willing to engage with interactive content, and that the specific interactions should have been refined to better accommodate them. The author-posed questions revealed additional information about reader interactions:

Q6. The article featured an interactive guitar widget that would play audio when a reader hovered over a string. Readers could quickly move their mouse over multiple strings to "strum the guitar". *How many times did readers strum the guitar?*
Q7. The article asked readers to use tuners on the guitar widget to tune the guitar multiple times. *How many unique times did readers actually tune the guitar?*

By querying the dataset for interactions with multiple strings on the guitar in quick succession, we can answer Q6 and determine how many times readers were strumming the guitar (median 1 strum, 0-3 IQR). Readers triggered the audio playback of an individual string (median audio triggered 22 times, 6-56 IQR) more than they strummed, indicating that they tended to use the guitar for tuning (as the narrative suggested), rather than playing freely. We answer Q7 by counting the number of times that readers interact with a guitar tuner, separated by some other interaction on the page. We found that readers had a median of 1 tuning session (0-4 IQR). This suggests that most readers did interact with the tuners when prompted initially, but only the most engaged readers continued to follow along through the rest of the content, including attempting to tune by beat frequency. This content may have been too advanced for readers without musical experience, or users may have been less inclined to continue interacting after the novelty wore off.

6.3.2. Observations from ScrollHop

Only 45% of readers reached the final section. This completion rate is considerably lower than the other two articles; this article had the most content, it also was shared with the largest and most general audience. Figure 4 shows four exemplary scroll patterns. As in other articles, some users would *preview and read* (A), and some would *scroll and bounce* (C); (B) shows a reader playing with the guitar near the beginning of the article but skimming through later content; in (D) a reader exhibits balanced engagement.

6.3.3. Observations from Readuction

The UMAP projection (Figure 10) again reveals a central group of users, separated from notable outliers. Near the edges of the central cluster we can identify interesting groups, such as *super tuners* who spent most of their time on the page tuning the guitar, *music theory* readers who engaged heavily with more advanced topics but skimmed through earlier sections, and *speed readers* who spent less than 10 seconds on average in each section, yet still engaged with many of the interactive components. Of the three articles, this plot shows the least obvious separation between mobile and desktop readers, likely stemming from the fact that this article offered the most polished presentation on mobile devices and readers could still engage with many of the interactive features. However, we also noticed a large group of mobile readers who engaged with interactive content but did not finish the article, possibly indicating that the novelty of the guitar interaction had worn off or that these readers were responding to other time or environmental issues. We noticed a group of desktop readers separated from the main cluster who attempted to interact with the guitar but did not appear to do anything else on the page; we believe that these users may have hit a bug related to the Chrome WebAudio API that some users had reported.

7. Discussion

Through our case studies of article instrumentation and analysis, we have demonstrated the feasibility of large-scale *in situ* deployment and logging to study interactive article readers, and validated the use of our proposed tools to gain insights into reader behavior. We observed many nuanced patterns of reader engagement, including some that corroborate prior research and some that are new to this work. Certain behaviors were consistent across the articles, including patterns of scrolling through content and the distributions of some aggregate usage statistics. We conclude by sharing recurring findings and implications of our techniques and analysis.

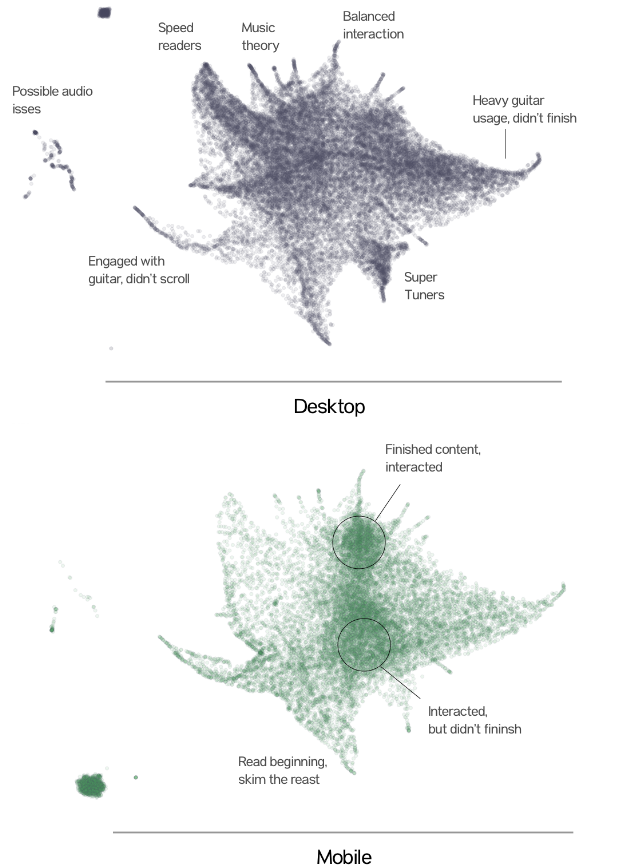

Figure 10: *UMAP projection of feature vectors for readers of* How To: Tune a Guitar. *This article offered the most polished mobile experience of the three, and we see a less stark difference in the distributions between the desktop and mobile readers. Through interactive use of our Readuction tool we identify clusters of users who exhibit interesting engagement patterns.*

7.1. Recurring Reader Behaviors

We saw many readers quickly scroll through article content before leaving the page [BDF15] or engaging in depth (*preview & read*). This suggests that readers make an initial assessment for quality and content, and aligns with prior work which found that aesthetics play a large role in the levels of user engagement [GB18]. We found that readers who do interact display a *continuum of behaviors* and do not necessarily fall into clearly separable groups. While many readers interacted with the articles in a manner that suggests they are *following the narrative*, some readers will engage disproportionately with various article components, likely *matching on content* that they find the most relevant. Both form and content seemed to impact behavior: in *Beat Basiscs*, which allowed for free scrolling between sections, readers would often *backtrack* to

compare the behavior of different interactive audio widgets; in the *Beginner's Guide to Dimensionality Reduction*, a highly technical article, readers would progress through the article linearly, pausing in each section to consider the content. A list of all observed recurring reader behaviors is available in the supplementary material.

There has been a debate in the data journalism community about the effectiveness of interaction [Tse16, Bau17, Ais18]. One suggestion is that content central to a narrative should not be hidden behind a click [Tse16]. In this work we similarly saw that if details were only revealed after a click, readers may never see it. In *Beginner's Guide to Dimensionality Reduction*, roughly half of desktop readers and 38% of mobile readers who made it to the end of the article clicked to reveal more details about the projection algorithms. This may indicate that some readers were not aware of the functionality, or that they were content with more high-level information. On the other hand, we also found that readers were more likely to interact with widgets which played a central role in the narrative. This can be seen in the high usage levels of the guitar widget in *How To: Tune a Guitar*, the artworks in *Beginner's Guide to Dimensionality Reduction*, and the rhythm wheels in *Beat Basics*. This indicates that users are willing to engage with interactive content on the page, but most are focused on content that is crucial to the central narrative.

For each of the case study articles, we noticed that the time that mobile users spent with the content was lower than that of desktop users. The median time spent on page for mobile users was 23-52% of the median time of desktop users. As more articles are evaluated, it should be possible to refine these statistics to better understand how a mobile article is performing relative to a desktop one, even if we expect readers to spend less time with the content. The results from *How To: Tune a Guitar* indicate that mobile users desire to view this style of content, and the majority (86%) are willing to click through a warning note about application download size, indicating that developers should take care to consider these users, noting that they are often equal to or greater in number than desktop readers. Mobile readers utilized fewer of the available interactive features than their desktop counterparts, but still largely followed the presented narratives. This result indicates that designers should ensure that the narrative is intact and comprehensible even if a reader chooses not to engage with the interactive widgets.

7.2. Tooling for Capture and Analysis

To understand diverse reader behaviors, we found it critical to provide insight into both aggregate (macro) behavior and individual (micro) experiences [Tuf90]. For example, both our HopScroll and Readuction visualizations provide overviews of user behavior and reveal clusters, while also supporting inspection of the particulars of individual traces. We found the smooth alternation between these levels of detail to be indispensable. Formulating metrics in conjunction with domain experts, on the other hand, helped to check author assumptions and key interaction patterns that might not otherwise be clear in the mass of log data. Going forward, our presented tools can be used to automatically generate interactive reports. Given author-guided queries as input, the various components described above — log analysis, aggregate statistics, feature vector calculation, and resulting interactive visualizations — could be synthesized to produce article dashboards for real-time tracking by authors and editors. The system can operate by analyzing usage of all Idyll variables (or a user-defined subset), and support linking between views, for example highlighting ScrollHop traces of reader sessions selected in the Readuction tool.

Further work is needed to adapt HopScroll to articles which don't rely on the browser's built-in scrolling functionality for content navigation. For example, an article which utilizes a stepper or slideshow motif may not require the reader to scroll at all. In these cases we expect that the same visualizations will be effective, so long as reader progress can be modeled as a linear progression with a corresponding progress fraction. In addition, we do not yet render desktop and mobile reader data simultaneously in HopScroll because the different article layouts lead to differences in where the content is displayed on the page and makes comparison difficult. A normalization step is needed to visualize and compare the scroll behavior of these two groups directly.

The use of Idyll to author these articles greatly simplified article instrumentation: in addition to scroll position, we could track all changes to Idyll's state to produce relevant reader feature vectors and queries to answer author inquiries. These experiences point to the value of domain-specific languages or design tools to not only author content, but help evaluate its use. To enable more systematic study of the effects of different choices or article structure or presentation, future work might augment Idyll to support authoring alternative versions in parallel. Akin to A/B testing, Idyll's runtime and analytics system could then assign incoming readers to article versions, enabling experimental control at the language level.

7.3. Implications for Future Research

A difficulty of conducting research on interactive articles "in the wild" is access to log data from a broad audience, especially when private media companies are reticent to share metrics publicly. One possibility is to use Mechanical Turk, but it is not clear that crowd workers behave in the same manner as intrinsically-motivated online readers. A nice property of interactive articles is that there is an online community who is interested in consuming this type of content. During the course of this research we took care to design articles in such a way that they would be appealing to specific audiences as entertaining and educational, regardless of the fact that they were also being used for research.

Our work demonstrates that publishing public content is a viable complement to laboratory studies and paid crowdsourcing. This approach introduces article design challenges beyond standard research design issues, but holds the promise of more comprehensive and realistic study of narrative visualization. We advocate that research goals in this domain should be pursued by studying authentic stories of genuine interest to the authors and intended readers. We hope the contributions of this paper provide first steps down this path, and expect that controlled comparisons of article variants can be performed using these tools and methodology. To facilitate future research, our instrumentation and analysis tools will be available as open-source software as part of the Idyll project, and the full interaction logs from our case studies are available online at `https://s3-us-west-2.amazonaws.com/interactive-analytics-eurovis/data.zip`.

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