Uncertainty Visualisation: An Interactive Visual Survey

Amit Jena*
IITB-Monash Research Academy
Mumbai, India

Ulrich Engelke†
CSIRO Data61
Perth, WA, Australia

Tim Dwyer‡
Monash University
Melbourne, VIC, Australia

Venkatesh Rajamanickam§
IIT Bombay
Mumbai, India

Cecile Paris¶
CSIRO Data61
Sydney, NSW, Australia

2020 IEEE Pacific Visualization Symposium (PacificVis) 978-1-7281-5697-2/20/$31.00 ©2020 IEEE 10.1109/PacificVis48177.2020.1014

ABSTRACT

There exists a gulf between the rhetoric in visualisation research about the significance of uncertainty and the inclusion of representations of uncertainty in visualisations used in practice. The graphical representation of uncertainty information has emerged as a problem of great importance in visualisation research. This contribution presents a survey of 286 uncertainty visualisation research publications. All publications are categorised with regard to publication type, publication venue, application domain, target user, and evaluation type. We present an interactive web-based browser that facilitates easy visual search and exploration of the publications included in the survey. We conclude that uncertainty visualisation is severely limited by the quality and scope of uncertainty data, by the limited confidence in the data, and by the perceptual and cognitive confusion that the graphical representation of the data can generate.

Index Terms: Human-centered computing—Visualization—Uncertainty Visualization; Human-centered computing—Visualization—Visualization application domains

1 INTRODUCTION

Uncertainty arises from the statistical error, ambiguous or limited data, oversimplification of complex risk information, scientific disagreement, ignorance, among other factors [13, 16, 19]. There is no consensus among researchers and practitioners of uncertainty visualisation regarding the optimum means of communicating such uncertainty. Moreover, literature [9, 13] indicates that some people may welcome the additional acknowledgment of uncertainty but others, and in particular non-experts, may become overwhelmed with the additional uncertainty information if it is not represented effectively. Information visualisation is widely used for effective communication of data and semantic information with the aim to amplify human cognition, create deeper insight, and facilitate reasoning. Uncertainty information can arise at any stage of an analysis process [20]. It may increase, decrease, split, or merge through the entire process. With the increasingly complexity of modern analytical processes, identifying and managing uncertainty information through the entire visualisation pipeline has become even more challenging.

Uncertainty visualisation is typically concerned with presenting visualised data along with supplementary information like accuracy, error, and other factors of provenance that influence understanding and interpretation. In physical science and engineering domains, visual representations of data sets are always provided with associated error, accuracy or levels of confidence. Providing such indicators of associated uncertainty are yet to become a norm in information visualisation.

Despite the ever-increasing interest in visualisation of uncertainty, there is limited empirical evidence as to how different types of visualisations are processed, interpreted and used by both practitioners and non-experts, although the effectiveness of some graphics and visualisations clearly depends on the relative spatial and numeracy ability of the user. Fortunately, it is becoming easier to present data in the form of interactive visualisations and in multiple types of representations that can be adapted to meet the specific context and capabilities of the user and the problem; however, there is no standard tooling for incorporating uncertainty information into these interactive visualisations, or commonly recognised best practice for how this should be achieved. To inform the design space of uncertainty visualisation it is instrumental to have an overview of previous successes and failures of integrating uncertainty into information visualisation. Towards this end, we present a general survey of uncertainty visualisation based on the collection and analysis of a substantial number of publications. The main contributions of this paper are the following:

1. a survey of 286 uncertainty visualisation publications in multiple research disciplines;
2. a categorisation that provides an overview of the landscape in uncertainty visualisation;
3. an interactive, web-based survey browser facilitating search, exploration, and future extension of the survey publications; and
4. suggestions and recommendations for future work in uncertainty visualisation.

The interactive survey browser (see Fig. 1) is available at `https://amitjenaiitbm.github.io/uncertaintyVizBrowser/`. We encourage the research community and practitioners to use the browser to discover relevant research publications and to contact the authors with any suggestions including additional publications that should be included in the survey browser.

The remainder of the paper is organised as follows. In Section 2 we discuss related interactive browsers, survey papers, and taxonomies for uncertainty visualisation. In Section 3 we discuss the categorisation of publications. In Section 4 we present the visualisation browser. We finish the paper with a brief discussion in Section 5 and conclusions in Section 6.

2 RELATED WORK

In the following we present an overview of existing uncertainty visualisation surveys to motivate the need for the survey presented in this paper. We distinguish here between traditional written surveys, interactive survey browsers, and uncertainty taxonomies. We note that we do discuss all 286 surveyed publications in this paper but refer the reader to the interactive survey browser.

*e-mail: amit.jena@monash.edu
†e-mail: ulrich.engelke@data61.csiro.au
‡e-mail: tim.dwyer@monash.edu
§e-mail: venkatra@iitb.ac.in
¶e-mail: cecile.paris@data61.csiro.au

2020 IEEE Pacific Visualization Symposium (PacificVis)
978-1-7281-5697-2/20/$31.00 ©2020 IEEE

2.1 Uncertainty Visualisation Surveys

Most of the survey papers in uncertainty visualisation have focused on a specific topic related to uncertainty. Arriola *et al.* [3] discuss the application, implementation, and underlying principles of sensitivity and uncertainty quantification. Beniger *et al.* [4] present a historical perspective of the development of quantitative graphics from 3800 B.C. until 1977 A.D. Fienberg [6] surveyed recent advances in graphical methods for statistics and illustrated many graphical methods for statistical presentation of data. Brodlie *et al.* [5] in their survey present a reference model for data visualisation, that sees data pass through a pipeline of processes. They argue that this allows them to establish clear distinction between *visualisation of uncertainty* - which is how we depict uncertainty specified with the data — and the *uncertainty of visualisation* — which considers how much inaccuracy occurs as the data is processed through the pipeline. With reference to Pang *et al.*'s [12] uncertainty visualization pipeline, Zuk [21] argues that combining the uncertainties from different stages of the pipeline is important for designing new visualisation method as it separates out the uncertainty introduced by a representation and the visualization itself. For user evaluation this also suggests the benefits of comparing multiple visualizations so that the uncertainty in the "combine stage" may be roughly estimated. Hullman *et al.* [10] analysed common themes in evaluation practice concerning the interpretation and semantics of uncertainty, the use of confidence reporting, and a bias toward evaluating performance as accuracy rather than the decision quality.

2.2 Interactive Survey Browsers

Interactive web-based surveys [1] have increasingly been established to provide ongoing overviews of the steady growth of visualisation research. Recent surveys are either entirely web-based or if they are published then accompanied with by an interactive web-based survey that is capable of including new research publications as and when they are published. The InfoVis Wiki [1] provides a list of available online visual surveys from the visualisation domain. While not being a necessity for a survey paper, for researchers and readers of surveys in the visualisation community, it will be helpful if such web resources can be made available along with the published surveys. There are a number of survey papers in the uncertainty visualisation literature that provide their findings in the form of interactive web-based browsers including Potter's Uncertainty Vis Library [14] and Hullman *et al.*'s [10]. Both of these browsers offer very useful and broad perspectives. Potter's browser, however, is limited in interactivity for exploration of listed publications and appears to have not been updated since 2013. Hullman's browser provides an extensive overview that is limited to uncertainty visualisation evaluation though.

2.3 Taxonomies of Uncertainty

Many surveys both web-based and traditional [10, 12] present typologies or taxonomies inherited from literature or new, for easy organisation of materials. Pang *et al.* [12] provided multiple classification schemes based on the uncertainty, data, and on the methods used to create visualisations. In Griethe and Schumann's [8] survey they discuss Pang *et al.* [12]'s categorization, but based on the dominance of existing methods for scalar uncertainty visualisations and proposed two main categories: direct uncertainty visualisation and using uncertainty indirectly.

Most typologies for uncertainty and its representation include one or more levels of abstraction for uncertainty representation. Positional and temporal error describe uncertainty in a metric sense within a space-time framework, whereas completeness and consistency represent more abstract concepts describing coverage and reliability [17]. The abstract notions of uncertainty are more problematic to describe and quantify, consequently, most typologies tend to focus on the types of uncertainties that can be quantifiable and represented as a measure of error and precision. Watkins presented a holistic taxonomy of uncertainty based on the taxonomies by Kahneman-Tversky [11], Smithson [15], and Giarratano and Riley [7]. The Taxonomy of Uncertainty [19] facilitates the characterisation and categorisation of conditions, events, and sources associated with and resulting in uncertainty. This taxonomy provides a wide-ranging categorisation of the causes for the uncertainty that should encapsulate and include virtually every reason for uncertainty.

The existing surveys review challenges to the epistemological nature of uncertainty, and provide specific suggestions related to representation and communication of uncertainty. The taxonomies provide a choice of identifying the source and nature of uncertainty in the visualisation pipeline. The proposed stakeholders as per the taxonomies are the domain experts who visualise the associated uncertainty, the end consumers, and the validation of the work by experts and by user studies. To identify the experts and their expertise working in this domain, we categorised the research publications as per the *publication type*, *publication venue* and *application domain*. The end consumers are categorised under *target user* as non-expert and expert users. And for validation of the work, we have the category *evaluation type*.

3 Categorisation of Publications

3.1 Survey Scope

We considered research publications for our survey which discuss at least one of the following topics: *statistical graphics*, the *visual and textual representation of uncertainty*, the *impact of an uncertainty visualisation* on user's performance, or behaviour. The included publications are not restricted to any specific domain but uncertainty visualisation in general. In addition to research papers, we also included thesis reports, posters, technical reports and books.

3.2 Categories

The categories that we provide are Publication Type, Publication Venue, Application Domain, Target User, and Evaluation Type. The motivation for each of the categories is briefly described below. From the publications we included in our survey, we identified different subcategories (Table: 1) for each of the categories. We note that these categories can be easily extended with the inclusion of new publications in the survey. The publication type, publication venue and application domain give us a brief idea about the experts, venues and areas in which uncertainty visualisation is being used. The evaluation type category help us understand the general approaches used by the research publications in this domain. And the target user category give us a clear distinction between non-experts and experts, or both, as the end consumer of the uncertainty visualisation in discussion.

- **Publication Type**: Journal, Conference, Poster, Thesis, Technical Report, Book.
  The role of literature like journal papers, conference proceedings, theses and dissertations is to share new findings with the broader community. Where as literature like books and posters compile and organize the information in the primary literature into an easily accessible and understandable format. Technical report is a document that describes the progress, process, or results of scientific or technical research. It also can include some recommendations and conclusions. Technical reports may be considered as grey literature because they rarely undergo comprehensive independent peer review before publication.

- **Publication Venue**: Cartography/GIS, Cognitive Psychology, Health Analytics, Human Factors, Decision Making, Information Visualisation, Scientific Visualisation, Cyber Security, Ubiquitous computing, Statistics, Data Science.

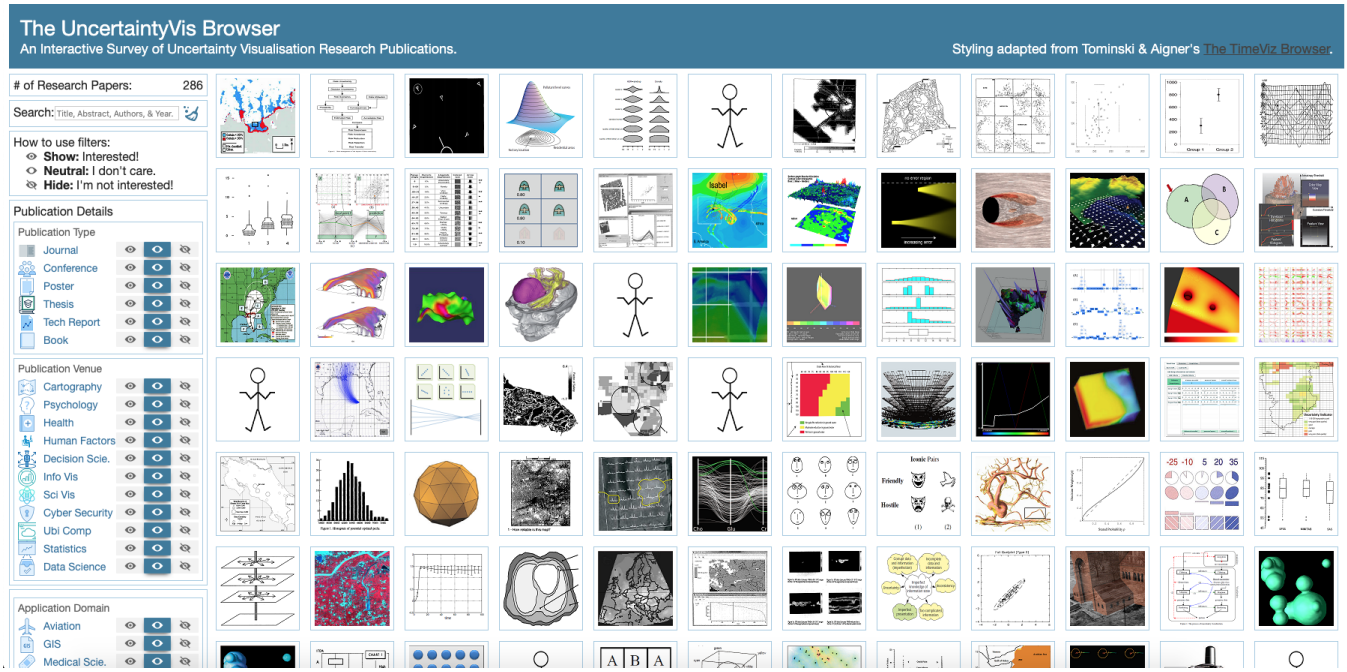

Figure 1: The Uncertainty Vis Browser with the textual search, filtering of categories, and the total number of publications included.

The choice of a venue for publication of a manuscript is rarely a clear-cut decision. Several factors are considered in this decision, such as the audience for whom you are writing, the topic of the manuscript, the purposes for which you are writing, and the tracks in the conference. There are dedicated conferences and journals in fields like cartography, human factors, cyber security, etc. which allow a narrow band of tracks specific to that domain. At the same time we have conferences and journals in InfoVis, SciVis which allow research publications from diverse application domains but contributing to visualisation research in general. We categorised each publication by identifying the track of the conference or journal in which it was presented or published.

- **Application Domain**: Aviation, Cartography/GIS, Medical Science, Manufacturing, Astrophysics, Urban Planning, Management, Transport, General.
  The application domain is identified on the basis of the data set used in the study like *spectroscopy data, hurricane tracks*, any specific user group included in the study like pilots, urban planners, or self reporting of application domain by the authors like *geographic information*, or *sensitivity of ECG*. If the publications is a survey paper in uncertainty visualisation, involves no evaluation or is not discussing any particular domain problem then we list that as *general*. We acknowledge the fact that there may be some overlap in the subcategories for *Publication Venue* and *Application Domain* as in the case of Cartography/GIS as it is highly unlikely that publications published in conferences and journals with very specific tracks will have different application domains. But for venues with broad range of accepted tracks say InfoVis attract publications from various application domains. We categorised each publication by identifying the use-case or data set mentioned in the respective publication.

- **Target User**: Non-Expert, Domain Expert.
  A domain expert is a person with special knowledge or skills in a particular area of endeavour (e.g. a cartographer is an expert in the domain of cartography). But it to be noted that a domain expert in a domain will be treted as a non-expert in another domain. In visualisation research it is significant to identify the target user group as it affects how the visualisations are perceived by the user depending upon their existing knowledge, cognitive bias, among other factors.

- **Evaluation Type**: No Evaluation, Case Study, User Study, Expert Review, Survey.
  Inspired from Hullman et al's [10] work we categorised the publications depending upon the type of evaluation they conducted in their study. Case Study is defined as " The detailed examination of a single example of a class of phenomena, a case study cannot provide reliable information about the broader class, but it may be useful in the preliminary stages of an investigation since it provides hypotheses, which may be tested systematically with a larger number of cases." [2]. User study involves testing with human participants. Expert Review refers to the more formal method of Heuristic Evaluation, which refers to domain experts reviewing a visualisation tool or technique for its adherence to common guidelines (or heuristics). A survey is made of at least a sample (or full population), a method of data collection (e.g., a questionnaire) and individual questions or items that become data that can be analyzed statistically.

3.3 Publication Samples

To start with we have enlisted research papers from Kristi Potter's Uncertainty Vis Library [14] and Hullman *et al.*'s [10] survey. Potter's online library enlists 241 research publications published between 1990 and 2013 from various domains presenting uncertainty visualisation techniques and studies. Hullman's study is about the evaluation of uncertainty visualisation and includes 86 uncertainty visualisation publications which have at least one visual representation of uncertainty and at least one research question concerning the impact of an uncertainty visualisation on a user's performance, impressions, or behaviour. The publications included are from core

Table 1: Number of research publications in different categories from our sample of 286 uncertainty visualisation publications.

Publication Venue	#	Application Domain	#	Publication Type	#	Evaluation Type	#
Cartography/GIS	63	Aviation	3	Journal	137	No Evaluation	179
Cognitive Psychology	30	Cartography/GIS	78	Conference	122	Case Study	7
Health Analytics	12	Medical Science	15	Poster	3	User Study	83
Human Factors	12	Manufacturing	9	Thesis	9	Expert Review	8
Decision Making	16	Astrophysics	11	Technical Report	14	Survey	9
Information Visualisation	79	Urban Planning	27	Book	1		
Scientific Visualisation	13	Management	13				
Cyber Security	9	Transport	21				
Ubiquitous Computing	9	General	109				
Statistics	37						

venues associated with the research fields of InfoVis, SciVis, Cartography, Medicine, Psychology, Human Factors, and Security among others. We removed the common publications and added new publications from our own search. To identify studies both recent and past that are not included in either of the above lists, we used a set of queries containing terms like "uncertainty visualisation", "representation of uncertainty", "communication of uncertainty", "risk visualisation", "graphical representation of uncertainty", "probabilistic information", "statistical error". We queried Google Scholar for each possible combination of methodological terms, domain-specific terms like weather, and medicine combined with uncertainty visualisation terms. We manually went through each list of results, stopping after the first 50 recommended results. At the time this paper is submitted we have included 286 research publications.

4 Design and Features of the Browser

The uncertainty visualisation browser is an interactive web-based visualisation tool that provides an electronic review of published publications in uncertainty visualisation. This is a work in progress and we are continuously adding new research publications related to uncertainty visualisation from various domains. The design style of the browser is adapted from Tominski and Aigner's *The TimeViz Browser* [18]. Our browser is hosted on Github `https://github.com/amitjenaiitbm/uncertaintyVizBrowser` and can be cloned by others for further development.

Users can explore the browser using textual search and filtering of categories. Each of the subcategories is provided with an identifier icon which resonates with the inherent meaning of the subcategory. By default the browser shows the total number of publications included. For each publication, we have included its first figure present as the corresponding reference image in our browser. On hover over the images the users can see the title of the publications near the pointer. On clicking an item users are presented a pop-up screen showing the enlarged image, title, associated subcategory icons, authors, abstract, key words, and citation details of the publication (see Fig. 2). If the image shows a "stick figure" then corresponding publication does not contain an image that can be included. A button at the bottom right of the image allows the user to view the full resolution image.

The textual search field supports queries on title, author, abstract, and keywords from the publications. It does a string matching and dynamically filters the matching publications as the user continues to enter the query. The number of filtered publications are also updated and shown as a fraction of the number of matches versus the total number of publications.

At present, there may be some unresolved technical issues with the browser, like missing tags, advanced filtering, cluster search. We are continuously improving the browser to include more research publications and add better search capabilities.

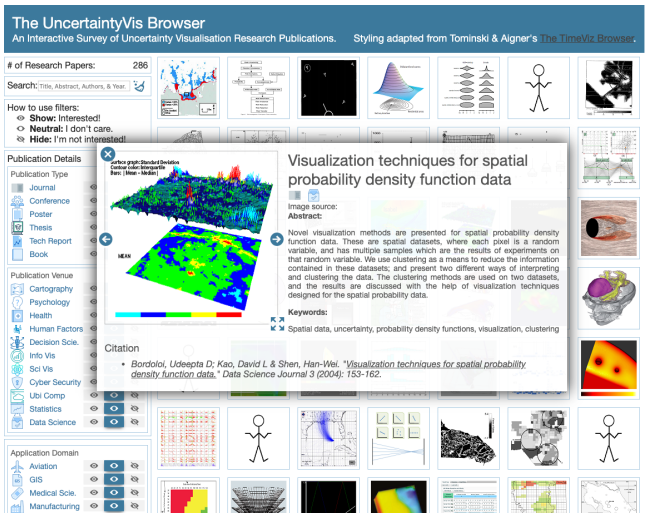

Figure 2: The screen showing the details of the selected publication.

5 Discussion

To ensure that our browser design can be reused by others we have hosted it on GitHub under the MIT license. With an aim to make the browser accessible for all and make it screen reader ready we have used *alt* attribute in HTML5. Using "alt" attribute we can specify alternate text for the images. Currently, we have just included the corresponding captions of the figures as alternate text. But often the captions for the figures in research publications are not expressive enough to communicate the associated message. In the text search option, if the user enters the full name of the author then it does not work as expected and returns zero results. This happens because we have included the author's names as *last name*, *first name* in vanilla HTML, without using any database. But if the user queries either the first name or the last name then the browser performs the filtering correctly.

The paper does not present the survey itself but an interactive website to browse the collection and the categorisation that is being used. It allows to update the online resource continuously and the paper will act as a reference to this online resource. The browser is an ongoing work and it will be updated with new research publications. We believe the work to be a reasonable starting point that could mature to a useful online resource for uncertainty visualisation in the future.

6 Conclusion and Future Work

We presented an interactive survey browser of research publications in uncertainty visualisation which supports categorisation. The collected survey data indicates the expanding multidisciplinary interest

for visualisation of uncertainty. We observed that the research in uncertainty visualisation is no more limited to lab-based study but is being implemented into the state of the art visual analytics systems across the domain. Studying the development of the field based on the collected research publications, it suggests that there are many open challenges and interesting research problems. The greatest challenge is to make a visualisation that is aesthetically attractive and informative, and yet conveys its own contingency and limitations. Future work on this survey may include updating the survey data set, refinements of the categorisation, additional features for the interactive browser, extensive analytic work based on further analysis, and updating the alternate text for the images with more descriptive text as compared to using just the captions from the corresponding publications.

REFERENCES

[1] Interactive online surveys. https://infovis-wiki.net/wiki/Interactive_Online_Surveys.

[2] N. Abercrombie. Stephen hill i bryan s. turner. 1984. dictionary of sociology.

[3] L. M. Arriola and J. M. Hyman. Being sensitive to uncertainty. *Computing in Science & Engineering*, 9(2):10, 2007.

[4] J. R. Beniger and D. L. Robyn. Quantitative graphics in statistics: A brief history. *The American Statistician*, 32(1):1–11, 1978.

[5] K. Brodlie, R. A. Osorio, and A. Lopes. A review of uncertainty in data visualization. In *Expanding the frontiers of visual analytics and visualization*, pp. 81–109. Springer, 2012.

[6] S. E. Fienberg. Graphical methods in statistics. *The American Statistician*, 33(4):165–178, 1979.

[7] J. C. Giarratano and G. Riley. *Expert systems: Principles and programming*. Brooks/Cole Publishing Co., 1989.

[8] H. Griethe, H. Schumann, et al. The visualization of uncertain data: Methods and problems. In *SimVis*, pp. 143–156, 2006.

[9] P. K. Han, W. M. Klein, T. Lehman, B. Killam, H. Massett, and A. N. Freedman. Communication of uncertainty regarding individualized cancer risk estimates: effects and influential factors. *Medical Decision Making*, 31(2):354–366, 2011.

[10] J. Hullman, X. Qiao, M. Correll, A. Kale, and M. Kay. In pursuit of error: A survey of uncertainty visualization evaluation. *IEEE transactions on visualization and computer graphics*, 25(1):903–913, 2019.

[11] D. Kahneman and A. Tversky. Variants of uncertainty. *Cognition*, 11(2):143–157, 1982.

[12] A. T. Pang, C. M. Wittenbrink, and S. K. Lodha. Approaches to uncertainty visualization. *The Visual Computer*, 13(8):370–390, 1997.

[13] M. C. Politi, P. K. Han, and N. F. Col. Communicating the uncertainty of harms and benefits of medical interventions. *Medical Decision Making*, 27(5):681–695, 2007.

[14] K. Potter. Uncertainty visualization and data references. http://www.sci.utah.edu/~kpotter/Library/Catalogs/uncertaintyVis/, may 2013.

[15] M. Smithson. Ignorance and uncertainty: Emerging paradigms. 1989.

[16] D. Spiegelhalter, M. Pearson, and I. Short. Visualizing uncertainty about the future. *science*, 333(6048):1393–1400, 2011.

[17] J. Thomson, E. Hetzler, A. MacEachren, M. Gahegan, and M. Pavel. A typology for visualizing uncertainty. In *Visualization and Data Analysis 2005*, vol. 5669, pp. 146–158. International Society for Optics and Photonics, 2005.

[18] C. Tominski and W. Aigner. The timeviz browser. http://vcg.informatik.uni-rostock.de/~ct/timeviz/timeviz.html?, 2015.

[19] E. T. Watkins. Improving the analyst and decision-maker's perspective through uncertainty visualization. Technical report, AIR FORCE INST OF TECH WRIGHT-PATTERSONAFB OH SCHOOL OF ENGINEERING, 2000.

[20] Y. Wu, G.-X. Yuan, and K.-L. Ma. Visualizing flow of uncertainty through analytical processes. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2526–2535, 2012.

[21] T. D. Zuk. *Visualizing uncertainty*. PhD thesis, University of calgary, 2008.