Information Design Journal 25(1), **43–55**
© 2019 John Benjamins Publishing Company
DOI: 10.1075/idj.25.1.04kos

Doris Kosminsky, Jagoda Walny, Jo Vermeulen,
Søren Knudsen, Wesley Willett, & Sheelagh Carpendale

Belief at first sight

Data visualization and the rationalization of seeing

Keywords: data visualization, representation, objectivity, historical context

Data visualizations are often represented in public discourse as objective proof of facts. However, a visualization is only a single translation of reality, just like any other media, representation devices, or modes of representation. If we wish to encourage thoughtful, informed, and literate consumption of data visualizations, it is crucial that we consider why they are often presented and interpreted as objective. We reflect theoretically on data visualization as a system of representation historically anchored in science, rationalism, and notions of objectivity. It establishes itself within a lineage of conventions for visual representations which extends from the Renaissance to the present and includes perspective drawing, photography, cinema and television, as well as computer graphics. By examining our tendency to see credibility in data visualizations and grounding that predisposition in a historical context, we hope to encourage more critical and nuanced production and interpretation of data visualizations in the public discourse.

1. Introduction

Data visualization has moved beyond a set of tools and techniques for extracting knowledge, trends and insights from a dataset. Data visualization is becoming a new medium (Viègas & Wattenberg 2011) and as such, it has been represented in public discourse as a portrayal of objective facts. Data visualizations are used in news reporting and analytic work; for monitoring activities and to support data-driven decision making, as well as in other domains where truth and objectivity are considered of fundamental importance. Much of the training and research about visualization is also centered around an association with objectivity, including topics such as perceptual accuracy (Ware 2009), and cognitive bias in visualization (Dimara et al. 2017). Kennedy et al. (2016) have found that data visualization designers often employ certain conventions—simple two-dimensional viewpoints, clean layouts, geometric shapes and lines, and the inclusion of data sources—specifically to encourage a sense of objectivity.

While this association of data visualization with objectivity is strong, it has also been challenged. It is generally acknowledged that some misrepresentation or distortion is necessary in order to portray useful multi-dimensional relationships in a limited space. This is clear in cartographic map projections, which are a

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 license.

fundamental and necessary aspect of map representation, but have their own biases (Monmonier 1991). For example, the ubiquitous Mercator projection causes northern countries to appear larger than they truly are. In fact, scholars now routinely acknowledge that maps are interpretations of reality, which reflect the historical, political, and cultural values of the cartographers and of their benefactors (Klinghoffer 2006). As the use of data visualization spreads to wider social contexts, we see a growing advocacy of similarly critical approaches (Dörk et al. 2013; Hall 2008). There is a strong interest in examining visualization practices that emphasize the socially-situated construction of knowledge (D'Ignazio & Klein 2016) and the nature of data that is not collected (Onuoha 2019). Furthermore, the application of visualization in personal contexts has shown that deliberate subjectivity has an important place in visualization (Thudt et al. 2017).

In this paper, we examine the powerful association of data visualizations with notions of truth and objectivity which stem from a continuation of the historical context in which other modes of representation—specifically, perspective drawing and photography—flourished. We reflect on the parallels between the purported objectivity of those mediums (particularly at their inception) and that of data visualization. Furthermore, we argue that the implicit association with objectivity creates a risk that visualizations can be perceived uncritically and with a limited understanding of the influences that shaped their message, especially at first sight. We suggest that reflecting on the historical parallels of the discussions of objectivity in perspective and photography can help to mitigate some of those risks.

To establish data visualization within the lineage of conventions for visual representation grounded in objectivity and rationality, we draw on the concept of representation as developed by philosopher Nelson Goodman in his Theory of Symbols (Goodman 1976). As such, we view data visualizations, perspective drawing, and photography as symbol systems that arose as modes of representation within a continuously changing historical context. Although perspective and photography are often associated with art, we focus primarily on their use as tools for methodically representing the world. This methodical nature—inherent in the drawing rules used to produce perspective illustrations and the automated machinery of photographic cameras—gave both mediums a strong association with notions of truth, objectivity, and empirical thought, particularly at their infancy. However, both modes have been deeply studied and critiqued with respect to objectivity (Mitchell 2001; Flusser 1983/2000), and we draw on those critiques to anticipate similar critiques of data visualization.

We propose a framing that uses historical reflection to encourage awareness of the context and unique worldview associated with each new visualization. It is not our intention, however, to reject or diminish efforts focused on making visualizations more legible and on discouraging the use of visualizations for deceptive ends. We still place great importance on encouraging transparent visualization practices. Our consideration of earlier modes of representation such as perspective drawing and early photography offers designers an opportunity to consider the challenges posed by assertions of objectivity in data visualization and highlights the potential for more reflective and critical ways of presenting and interpreting visualizations.

2. Modes of representation and worldviews

We employ Nelson Goodman's Theory of Symbols (Goodman 1976) as a framework for analyzing data visualization as a mode of representation. Goodman's approach to representation considers all symbols to be equally imposed by cultural conventions and dissociated from resemblance. On exploring Goodman's theory, we intend to open a debate on data visualization as a mode of representation and its rapport with rationalism and objectivity. We make use of two main points in Goodman's theories: his notion of representation dissociated from resemblance, and the role of language in the construction of worldviews.

For Goodman, pictorial language is a symbol system, as are natural languages and other non-linguistic systems such as gestures or diagrams. In order to understand Goodman's concept of representation, it is important to set aside the approach with which representation is usually understood in the common sense, namely as resemblance. For Goodman, representation and resemblance are different notions. Unlike representation, resemblance is symmetric and reflexive. "An object resembles itself to the maximum degree but rarely represents itself" (Goodman 1976: 4). In order for a picture to represent an object, it "must be a symbol for it, stand for it, refer to it; and that no degree of resemblance is sufficient to establish the requisite relationship of reference. Nor is resemblance necessary for reference" (Goodman 1976). Rather than resemblance, data visualization uses combinations of marks (Bertin 1983/2010), which are symbols that stand for the correspondent data. In distinguishing resemblance from representation, Goodman's theory allows us to see perspective, photography, and data visualization all as modes of representation, which allows us to view critiques of perspective and photography's objectivity of representation in a similar light as data visualization.

As symbol systems, verbal and pictorial languages are based on conventions. Goodman states that "we are brought up to accept the conventions current in the society into which we are born" (Goodman 1976). We always need a key to read an image. Some pictures seem easier to read because the key is already embodied in our cultural background. New formats in data visualization can give evidence to this. For example, *The Ebb and Flow of Movies: Box Office Receipts 1986 — 2008* is an interactive streamgraph (Bloch et al. 2008) showing two decades of box office receipts. In 2008, its format, similar to the Theme River visualization type (Havre et al. 2000) but with a resultant flowing organic shape, was a new and relatively unknown data representation. Ten years later, this format is included in automatic visualization generation tools such as Rawgraphs (Mauri et al. 2017), and in libraries of data visualization types (Ribecca 2016). Although this does not mean that the streamgraph is universally understood, it points towards its increasing embedding in the vocabulary of visualization viewers.

Goodman's vision is that there are *world versions* —descriptions or views of how the world is (Goodman 1978). We cannot grasp the world as "it is", we can only experience world versions, which differ between disciplines or even within a discipline. World versions can be described and expressed using many symbolic systems: words, music, and pictures, among others (Goodman 1978). Similarly, interactive data visualization can be a rich medium for offering different world versions. In data visualization parlance, these visualizations are *worldviews*, as shown in this quote from Stefaner: "instead of presenting just one worldview, we have a couple of different views and perspectives that are embedded in this one graphic" (Stefaner 2013).

If we focus on all three modes of representation, according to Goodman's definition, we can apply the discourse surrounding objectivity and rationalism in perspective and early photography to reflect on similar discussions about data visualizations.

3. Perspective drawing

Perspective is a drawing method created at the beginning of the Italian Renaissance and documented by Alberti in 1435. It was arguably the first precise method for depicting three-dimensional space. Until the end of the fourteenth century, picture making was an inefficient mode of symbolization because there was no schema that could guarantee the correspondence of the pictorial representation of an object to its shape and location in space (Ivins 1938). The invention of perspective followed the advent of the woodcut and other printing technology that provided a way to exactly duplicate pictorial symbols. It is thus possible that the fundamental change in picture symbolization due to the invention of printing and perspective helped to forge the idea of rationality and competence in representation. In fact, the success of natural science may not have been possible without reliable pictorial representation and duplication techniques (Ivins 1938). The gestalt psychologist, Rudolf Arnheim, argues that central perspective was invented in the midst of the "search for objectively correct descriptions of physical nature" that sprang from the Renaissance interests in the sensory world, and led to "the development of experimental research and the scientific standards of exactitude and truth" (Arnheim 2009).

Perspective purports to guarantee a rational representation of a three-dimensional space. It does so on the basis of two assumptions encoded in its strict set of drawing rules: "first, that we see with a single and immobile eye, and, second, that the planar cross section of the visual pyramid can pass for an adequate reproduction of our optical image" (Panofsky 1997). In this way, this conventionally agreed-upon form of representing the visible world comes to be understood as representing the world "as it is". However, scholars have argued over whether these drawing rules indeed portray perspective as the one "natural" or "correct" mode of representation of a scene, or if they instead reflect a convention for exhibiting three-dimensional scenes. For Berger, the problem is that the set of conventions used in perspective implies that the resultant appearances are *reality* (Berger 1987: 16) rather than representation. It is now well known that the static eye assumption is an impossibility—human eyes make constant saccadic movements (Martinez-Conde & Macknik, 8/2007). Thus how can perspective truly portray reality when it is based on an impossibility?

The problem of representing three-dimensional objects in a two-dimensional plane can lead to different solutions, each one with its advantages and drawbacks. As a method "of copying an object or arrangement of objects from one fixed point of observation", perspective is not necessarily truer to that concept than other methods (Arnheim 2009). Arnheim exemplifies this idea through ancient Egyptian visuals. He explains that if this art looks "unnatural" to modern observers, it is because they judge the work by different standards. (Arnheim 2009). Nevertheless, perspective has made an impressive impact on the way that western civilization sees the world. Elkins clarifies this well, stating: "The first time I stood in front of a house and imagined all the lines in place, I was astonished. But perspective is also unremitting and it makes the world clearer and more obvious than I like it to be" (Elkins, n.d.). Panofsky (1997) considers the historical development of seeing in perspective as a habit. He calls linear perspective a 'symbolic form' of the modern age. Following this idea, Manovich (1999) uses the concept of database as a contemporary symbolic form.

These critiques show that in the very concept of the artificial perspective technique lies the implication that our senses can capture the world outside as it is and that it is an objective and rational way to represent it. Figure 1 shows an apparatus for perspective drawing, evidencing this purported relationship. The problem with the assumption of a "correct" mode of representation, rather than a convention, is that it leads to the idea that other modes cannot give a plausible representation of the world "as it is". In art, Cubism, for example, challenges the single fixed eye of perspective. Cubist art depicts the subject from a multitude of viewpoints to represent

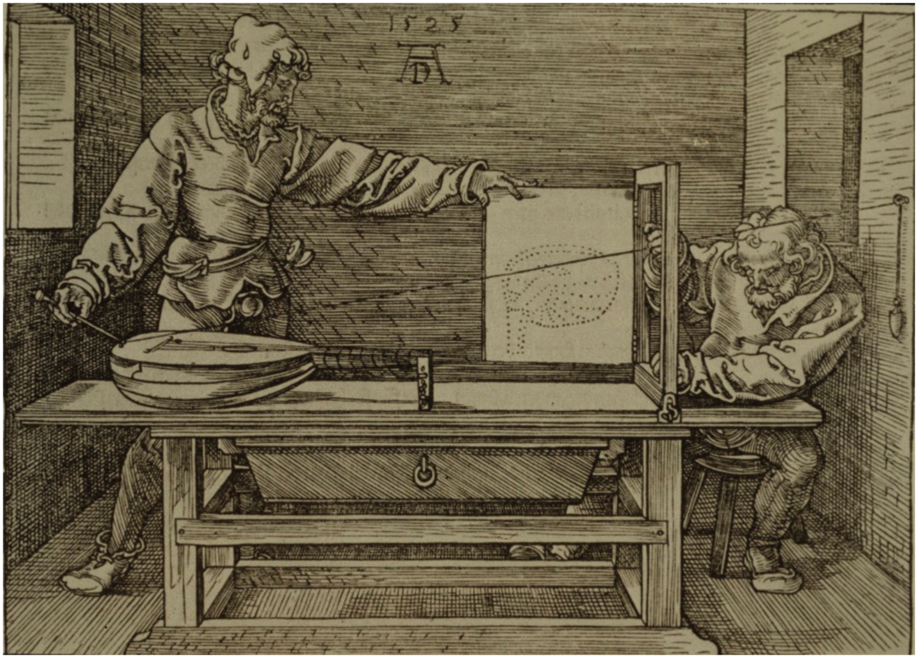

Figure 1. Albrecht Dürer (1471–1528), *Man Drawing a Lute*, 1525 (https://commons.wikimedia.org/wiki/File:D%C3%BCrer_-_Man_Drawing_a_Lute.jpg).

the subject in a greater context. Perspective drawing, photography and data visualization are all legitimate modes of representing the world. None of them, however, can capture the totality of the world.

4. Early Photography

Photography has changed so much since its inception that it is possible to talk about different types of photography that reflect distinct realities. Even in early photography, which is our focus in this section, we see distinct periods, spanning the pre-industrial origins of photographic methods to the industrial advances that led to the development of transportable cameras. At the beginning of the twentieth century, conventional industrial photography was full of portraits, but was also being used in other forms of documentation, notably by the French photographer Eugène Atget, who documented the empty streets of Paris (Figure 2).

Although photography has been employed extensively in the service of art, early photography was not seen this way. Rather than artists, the first practitioners were inventors, engineers, or scientists. Moreover, the level of detail rendered by photography put it far apart from what could be considered art. The French poet and essayist Charles Baudelaire highlighted the medium's realism when declaring that he did not recognize photography as art (Baudelaire & University of Florida 1956).

There is no doubt that a photograph depicts something and thus can represent something, as argued by Goodman. Through chemical, mechanical, and optical processes, a moment is permanently fixed

Figure 2. Eugène Atget, *The Pantheón*, 1924 (https://commons.wikimedia.org/wiki/File:Eug%C3%A8ne_Atget,_The_Panth%C3%A9on_-_Getty_Museum.jpg).

over a sensitive surface. A physical correspondence is established between the object and the image, "like a fingerprint left at the scene of a crime or lipstick traces on your collar" (Mitchell 2001). Susan Sontag highlights this when she explains the difference between a painting and a photograph. For her, "A photograph is not only an image (as a painting is an image), an interpretation of the real; it is also a trace, something directly stenciled off the real, like a footprint or a death mask" (Sontag 1977).

An old advertisement from Kodak demonstrates a crucial notion behind the invention of photography, stating that, to take a photo, "You Press the Button, We Do the Rest" (Riggs 2000). Photography reinforced the idea of automation in image construction, first presented in perspective drawing, as it enabled pictures to be taken with less interference of the human hand in the process. "The camera cannot lie", as the old saying goes, reflecting the idea that "for the first time an image is formed without the creative intervention of man" (Mitchell 2001). This leads to the idea of a camera as a mechanical or autonomous image production device that excludes human bias. If the reproduction of what is in front of the camera is automatic, then it is assumed to be objective.

The exclusion of human bias is fundamental to many scientific procedures and experiments which endeavor to overcome subjectivity and access the "real truth" (Mitchell 2001). Comparing the intentional and automatically constructed aspects of photography and painting, Mitchell suggested a spectrum running from non-algorithmic to algorithmic conditions of image-making. A non-algorithmic image like a painting, is a product of intentional acts, which can "reveal a lot about what was in the artist's mind" (Mitchell 2001). On the other hand, an algorithmic image which is automatically constructed, involves fewer intentional acts and "provides more trustworthy evidence of what was out there in front of the imaging system" (Mitchell 2001).

Photographs are technical images and, as such, are produced by apparatuses. This idea was introduced by Vilém Flusser (1983/2000), for whom these apparatuses are products of applied scientific thinking, which he calls "scientific texts". Flusser sees the camera as an encapsulation and application of the scientific thinking that led to the ability to produce a technical image. Apparatuses repeat the same movements over and over (Flusser 1983/2000). Despite being based on complex scientific and technical principles, it is simple to make the camera function (Flusser 1983/2000).

For Flusser (1983/2000), these apparatuses are "black boxes" that simultaneously capture a process of thinking and obscure it. This notion is evident in the disclosure of the "whiteness" bias in color film stock emulsions and television cameras. For years, pictures of people with dark skin showed less detail than those of people with lighter skin. This was because the engineers in charge of measuring and calibrating the skin tones for cameras and films used, as a basis, reference cards showing images of a Caucasian woman—so-called "Shirley cards". The film's bias in favor of Caucasian skin was largely accepted by the public at the time, obscured by the dominant concept that science, the basis for film production, was based on reasoned decisions without racial or cultural considerations (Roth 2009).

In early photography it was easy to trust these black boxes due to their automaticity and predictability. However, there is no such thing as an algorithmic image free from bias. Two photographers taking a photo of the same subject at the same time can create completely different photographs. Photographic manipulation can be traced from the invention of the medium (Sharma & Sharma 2017), all the way to the digital era, typified by efforts like the former Soviet Union's attempts to erase its enemies from history (King 1997). Yet, the "black box" also hides its bias. Just as with perspective drawing, a photograph is just one representation of the world, influenced by human choices and limited in the information it can capture and reflect.

5. Data visualization as representation

Echoes of the conversation surrounding the representational role of perspective and photography can today be found in conversations about data visualization. Although the conversation changes with each mode of representation as the societal, cultural, and technological context evolves, similar concepts and questions are threaded through all three representational modes. A key feature of data visualization is that it involves two distinct and separable representational stages. First, a set of data represents some aspects of the world. Second, a data visualization represents the data set and thus becomes a representation of the world. The conversations around data visualization encompass both stages of data visualization, separately and together.

Some of the strongest and longest-running conversations in data visualization involve the perceived correctness of the visualization as a representation of the data set. A long-running stream of data visualization research investigates the connection between visualizations and the human perceptual system (Cleveland 1985; Ware 2009) with the purpose of increasing the interpretability of the underlying data. This focus on perceptual accuracy has sometimes tipped into dogmatic territory, as seen in the debate over whether pie charts are acceptable (Kosara 2016). Similarly, Tufte's oft-cited data-ink ratio (Tufte 2001) has been debated as studies have shown that extraneous elements can improve the memorability of visualizations (Bateman et al. 2010; Borkin et al. 2013).

These discussions demonstrate an underlying attachment to the idea that some visualizations are *more correct* than others and that visualization designers should be primarily concerned with maximizing the degree to which the visualization accurately reflects the data. The same attitude made perspective drawing a compelling new mode of representation in its time—that there was, finally, a "natural" or "correct" way to represent the world using a system of drawing rules. This continued in the excitement about photography as a way to document the world "as it is". Conversations around visualization, meanwhile, tend to focus more directly on perceptually accurate representation of data. When examined in this historical context, the thought that an accurate representation can "correctly" represent the world also prevails in data visualization.

In practice, however, most visualizations represent data that is already an imperfect or incomplete representation of the world. People working closely with data and data processing tools have long advocated for transparency about the *provenance* of data—how it was collected, stored, processed, and analyzed. This includes work in databases (Buneman et al. 2001), scientific computing (Callahan et al. 2006; Davidson & Freire 2008), and in data visualization itself (Ragan et al. 2016). The importance of transparency has increased as the limitations of data as a means of representing the world become clear. This is due, in part, to the growing impact of machine learning. Training datasets for machine learning algorithms are being scrutinized as we realize their potential to unintentionally and implicitly encode biased human judgments about race, gender, and other social attributes (Hajian et al. 2016). Domain experts in most fields are keenly aware of these limitations and are often skeptical of representations that do not account for them. McCurdy et al. (2018) highlight the challenge posed by this sort of "implicit error" in visualization, noting that when data gives an incomplete or incorrect representation of the world, visual representations of it will inherit that inaccuracy. Recent work has considered how applying theories of indexicality from cinema, photography and contemporary art could increase the situatedness of data visualizations within the world (Schofield et al. 2013); while others have proposed indexicality as a new design strategy to communicate embodied and ambient information (Offenhuber & Telhan 2015).

Placing perspective, early photography, and data visualization along a historical continuum, we can see a tendency to systematize and automate methods of producing representations, from using rules, to machines, to algorithms. As discussed in section 3, perspective drawing introduced a set of rules for drawing that were seen as an "objective" way of representing the world, supporting the development of rationalism. Where perspective introduced a repeatable, learnable process for representing the world, photography encapsulated it in a mechanical black box. This drive to remove the bias and error of the human hand is evident in the current acceptance of algorithms, which are also "black boxes" that encapsulate repeatable processes. Data visualization has exploded in popularity in an age in which algorithms have been entrusted with a vast number of important tasks. In data visualization, algorithms are used in multiple stages, particularly in the data processing and data representation steps. Algorithms, however, are never completely free from human bias (O'Neil 2016: 8). Just as the human hand touches many aspects of a camera's technology, humans create the very algorithms we see as free from the human hand.

6. Discussion: belief at first sight

We urge creators and audiences of data visualizations to reflect critically on the strong entanglement of these ideas of objectivity and rationalism with visualization.

Otherwise, there is a risk of underestimating their influence on the message of visualizations and succumbing to what we call *belief at first sight*—the uncritical perception of visualizations as a sufficient representation of reality. When we first see a data visualization, we see more than just numbers. What we see is intertwined with our individual and cultural experiences, which are influenced by the history of how visual media have been perceived—as a way to portray an objective reality.

From a cognitive point of view, belief at first sight can be related to the "fast" mode of thinking described in the dual-system theory of behavioral economics (Kahneman 2012). This "fast" mode of thinking is not critical or reflective, but responsible for the viewer's first impression of a data visualization, and susceptible to cognitive biases and automatic inferences that can give misleading impressions. However, from a cultural point of view, belief at first sight can also happen when a society in general views a medium as fundamentally objective without further critique. In the early days of both perspective and photography, both mediums were initially perceived as technical inventions able to accurately represent reality. Over time, as critical and artistic works emerged questioning this assumption, this belief in the fundamental "correctness" of these modes of representation changed. In data visualization we are seeing increasing numbers of critical and artistic works, exploring and expanding the limits of this medium at the same time as a broader cultural conversation is happening around our increasing reliance on algorithms. It seems that we are in or nearing a phase of greater cultural awareness in the development of data visualization as a mode of representation.

To contribute to this growing cultural awareness, we suggest three directions for further discussion where looking to the history of other modes of representation can help deepen understanding of visualization. Understanding visualization is a shared responsibility between those who create, acquire, or select data (data providers), those who create representations of data (visualization creators) and those who read or use the visualization (analysts and viewers). Critical reflection on the historical relationship of objectivity and rationalism to visualization would benefit all of these groups. However, we aim our discussion primarily at visualization creators, who are tasked with creating new representations and conveying their meaning.

Deeper visualization literacy. History teaches that artefacts and modes of representation, and how these are viewed, change over time. Understanding these changes is essential to visualization literacy. However, it can be difficult to understand these changes as they are occurring. Studying and teaching the trajectories and critiques of analogous modes of representation can help creators and audiences alike gain awareness of and contextualize the changes happening in data visualization. Visualization creators can deepen their own visualization literacy by studying and considering data visualization as a part of the historical representation process

Awareness of black boxes. Data visualization in practice involves multiple modes of representation: first, data as a representation of the world and then visualization as a representation of the data. Moreover, these representations may be created at different times, by different people, using different processes. As such, many aspects of visualization can be hidden in "black boxes", from data collection and processing steps, to representation algorithms, to the reasoning behind design choices. Black boxes can be found where there is the greatest risk that viewers' understanding of the relationship between a visualization and the world will break down. Visualization creators are well-positioned to identify these black boxes and, where possible, open them up for viewers.

Develop critical reflexivity in visualization. Critical reflexivity means reflecting on the ways that data visualization as a mode of representation interacts with our personal and cultural biases and how visualizations may be inadvertently presented as neutral or as "the correct mode of representation". Understanding critiques of other modes of representation can help us to anticipate critiques of visualization and not wait for the future to reveal them. Visualization creators who understand this have the power to create more transparent visualizations.

7. Conclusion

By viewing perspective and photography as modes of representation parallel to visualization, we see that the historical context in which each came to be associated with objectivity and rationalism continues in data visualization. It becomes clear that the data visualization community's discussions of representational accuracy are rooted in discussions of "correct" representations that have endured across many centuries and representational modes. Reflecting on the debate surrounding whether it is even possible to have a "correct" representation can enrich the discussion in visualization as well. Furthermore, the drive to systematize and automatize representations to remove human biases is the next step in a trajectory that spanned from drawing rules, to photographic machines, to algorithms and computation. This understanding underscores questions about how much human involvement is occurring in the computational underpinnings of data visualization, and can help us to reflect on how much trust to place in such processes.

With this enriched perspective, we hope to contribute to a view of data visualizations that acknowledges that they are modes of representation and, as such, they mediate the emergence of meaning, which is always negotiated between all of the people involved in producing and using the visualization and the context where they all live. We conclude with the proposal that visualization is not about aspiring to show the most objective, neutral, and unbiased view, but rather about being aware of the context in which the data was collected, represented, framed and viewed, and the possible biases that may have influenced their portrayal. Visualizations that are transparent and straightforward about these aspects can, at first sight, inspire the reader to reflect upon the greater context in which they are created and consumed.

Submission date: 2 February, 2019
Accepted date: 4 July, 2019

Acknowledgements

The theme for this paper emerged from a 3-year project on visualizing open government data at the University of Calgary. During that time, we had many fruitful conversations over the implications of visualizing data for the public, and the implied trust in the data that this would or would not bring. This paper is a result of some of these conversations. We thank Sarah Storteboom and Annette Hester for their insightful comments on drafts of this article.

This project was funded in part by The National Energy Board of Canada, the National Sciences and Engineering Research Council of Canada, Alberta Innovates Technology Futures, SMART Technologies, the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 753816, and Information Plus Conference.

References

Arnheim, R. (2009). *Art and visual perception: A psychology of the creative eye; the new version* (Expanded and rev. ed., with some new ill., [Nachdr.], 50th anniversary printing). Berkeley, Calif.: University of California Press.

Bateman, S., Mandryk, R. L., Gutwin, C., Genest, A., McDine, D., & Brooks, C. (2010). Useful junk?: the effects of visual embellishment on comprehension and memorability of charts. In *Proceedings of the 28th international conference on Human factors in computing systems—CHI '10* (p. 2573). Atlanta, Georgia, USA: ACM Press.

Baudelaire, C., & University of Florida, G. A. S. L. (1956). *Mirror of art: Critical studies*. Garden City, N.Y.: Doubleday.

Berger, J. (Ed.). (1987). *Ways of seeing: Based on the BBC television series with John Berger* (Reprinted). London: BBC [u.a.].

Bertin, J. (2010). *Semiology of graphics*. Wisconsin: The University of Wisconsin Press. (Original work published 1983).

Bloch, M., Byron, L., Carter, S., & Cox, A. (2008). *The ebb and flow of movies: Box office receipts 1986–2008*. [Interactive graphic] NYTimes.com. Retrieved from http://archive.nytimes.com/www.nytimes.com/interactive/2008/02/23/movies/20080223_REVENUE_GRAPHIC.html

Borkin, M. A., Vo, A. A., Bylinskii, Z., Isola, P., Sunkavalli, S., Oliva, A., & Pfister, H. (12/2013). What Makes a Visualization Memorable? *IEEE Transactions on Visualization and Computer Graphics*, *19*(12), 2306–2315.

Buneman, P., Khanna, S., & Wang-Chiew, T. (2001). Why and Where: A Characterization of Data Provenance. In J. Van den Bussche & V. Vianu (Eds.), *Database Theory—ICDT 2001* (Vol. 1973, pp. 316–330). Berlin, Heidelberg: Springer Berlin Heidelberg.

Callahan, S. P., Freire, J., Santos, E., Scheidegger, C. E., Silva, C. T., & Vo, H. T. (2006). VisTrails: visualization meets data management. In *Proceedings of the 2006 ACM SIGMOD international conference on Management of data—SIGMOD '06* (p. 745). Chicago, IL, USA: ACM Press.

Cleveland, W. S. (1985). *The elements of graphing data* (Vol. 2). Wadsworth Advanced Books and Software Monterey, CA.

Davidson, S. B., & Freire, J. (2008). Provenance and scientific workflows: challenges and opportunities. In *Proceedings of the 2008 ACM SIGMOD international conference on Management of data—SIGMOD '08* (p. 1345). Vancouver, Canada: ACM Press.

D'Ignazio, C., & Klein, L. F. (2016). *Feminist data visualization*. Presented at the Workshop on Visualization for the Digital Humanities (VIS4DH), Baltimore: IEEE. Retrieved from https://static1.squarespace.com/static/574dd51d62cd942085f12091/t/5c157dfe562fa7836b296000/1544912383037/Feminist_Data_Visualization.pdf

Dimara, E., Bezerianos, A., & Dragicevic, P. (2017). The Attraction Effect in Information Visualization. *IEEE Transactions on Visualization and Computer Graphics*, *23*(1), 471–480.

Dörk, M., Feng, P., Collins, C., & Carpendale, S. (2013). Critical InfoVis: Exploring the Politics of Visualization. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*. New York, NY: ACM—Critical InfoVis: Exploring the Politics of Visualization.

Elkins, J. (1995). *The poetics of perspective*. Ithaca and London: Cornell.

Flusser, V. (2000). *Towards a philosophy of photography*. London: Reaktion. (Original work published 1983)

Goodman, N. (1976). *Languages of art*. Indianapolis: Hackett Publishing Co.

Goodman, N. (1978). *Ways of Worldmaking*. Indianapolis: The Harvester Press.

Hajian, S., Bonchi, F., & Castillo, C. (2016). Algorithmic Bias: From Discrimination Discovery to Fairness-aware Data Mining. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining—KDD '16* (pp. 2125–2126). San Francisco, California, USA: ACM Press.

Hall, P. (2008). Critical Visualization. In P. Antonelli & Museum of Modern Art (New York N.Y.) (Eds.), *Design and the elastic mind* (pp. 120–131). New York: Museum of Modern Art.

Havre, S., Hetzler, B., & Nowell, L. (2000). ThemeRiver: visualizing theme changes over time. In *IEEE Symposium on Information Visualization 2000. INFOVIS 2000. Proceedings* (pp. 115–123).

Ivins, W. M. (1938). *On the rationalization of sight: With an examination of three Renaissance texts on perspective*. New York: Da Capo Press.

Kahneman, D. (2012). *Thinking, fast and slow*. London: Penguin Books.

Kennedy, H., Hill, R. L., Aiello, G., & Allen, W. (2016). The work that visualisation conventions do. *Information, Communication and Society*, *19*(6), 715–735.

King, D. (1997). *The commissar vanishes: The falsification of photographs and art in Stalin's Russia* (1st ed). New York: Metropolitan Books.

Klinghoffer, A. J. (2006). *The power of projections: how maps reflect global politics and history*. Westport, Conn: Praeger Publishers.

Kosara, R. (2016). An Empire Built On Sand. *Proceedings of the Beyond Time and Errors on Novel Evaluation Methods for Visualization—BELIV '16*. https://doi.org/10.1145/2993901.2993909

Manovich, L. (06/1999). Database as Symbolic Form. *Convergence: The International Journal of Research into New Media Technologies*, *5*(2), 80–99.

Martinez-Conde, S., & Macknik, S. L. (8/2007). Windows on the Mind. *Scientific American*, *297*(2), 56–63.

Mauri, M., Elli, T., Caviglia, G., Uboldi, G., & Azzi, M. (2017). RAWGraphs: A Visualisation Platform to Create Open Outputs. *Proceedings of the 12th Biannual Conference on Italian SIGCHI Chapter—CHItaly '17*, 1–5. https://doi.org/10.1145/3125571.3125585

McCurdy, N., Gerdes, J., & Meyer, M. (2018). A Framework for Externalizing Implicit Error Using Visualization. *IEEE Transactions on Visualization and Computer Graphics*. https://doi.org/10.1109/TVCG.2018.2864913

Mitchell, W. J. (2001). *The reconfigured eye: Visual truth in the post-photographic era* (4. print). Cambridge, MA: The MIT Press.

Monmonier, M. S. (1991). *How to lie with maps*. Chicago: University of Chicago Press.

Offenhuber, D., & Telhan, O. (2015). Indexical visualization: The data-less information display. In U. Ekman (Ed.), *Ubiquitous computing, complexity and culture* (pp. 288–301). New York: Routledge, Taylor & Francis Group.

Onuoha, M. (2019). *An overview and exploration of the concept of missing datasets*. MimiOnuoha/missing-datasets. Retrieved from https://github.com/MimiOnuoha/missing-datasets

Panofsky, E. (1997). *Perspective as symbolic form*. (C. S. Wood, Trans.) (1st paperback ed.). New York, NY: Zone Books.

Ragan, E. D., Endert, A., Sanyal, J., & Chen, J. (2016). Characterizing Provenance in Visualization and Data Analysis: An Organizational Framework of Provenance Types and Purposes. *IEEE Transactions on Visualization and Computer Graphics*, *22*(1), 31–40.

Ribecca, S. (2014). *The data visualisation catalogue*. Retrieved from https://datavizcatalogue.com/

Schofield, T., Dörk, M., & Dade-Robertson, M. (2013). Indexicality and Visualization: Exploring Analogies with Art, Cinema and Photography. In *Proceedings of the 9th ACM Conference on Creativity & Cognition*. (pp. 175–184). New York, NY: ACM.

Sharma, J., & Sharma, R. (2017). Analysis of Key Photo Manipulation Cases and their Impact on Photography. *The IISU-JOA Journal of Arts*, pp. 88–99.

Sontag, S. (1977, June 23). Photography Unlimited. *The New York review of books*. Retrieved from https://www.nybooks.com/articles/1977/06/23/photography-unlimited/

Stefaner, M. (2013). *Finding truth & beauty in data: Moritz Stefaner at European Communication Summit 2013*. Retrieved from https://vimeo.com/71798105

Thudt, A., Perin, C., Willett, W., & Carpendale, S. (2017). Subjectivity in personal storytelling with visualization. *Information Design Journal*, *23*(1), 48–64.

Tufte, E. R. (2001). *The visual display of quantitative information* (2nd ed.). Cheshire, Conn: Graphics Press.

Viègas, F., & Wattenberg, M. (2011). Interview for infosthetics.com, In Manovich, L. What is visualization? *Visual Studies*, *26*(1), 36.

Ware, C. (2009). *Information visualization: Perception for design* (2nd ed.). Amsterdam: Elsevier.

About the authors

Doris Kosminsky is an associate professor in the School of Fine Arts at the Federal University of Rio de Janeiro where she's a faculty member in the department of Visual Communication and in the graduate programs of Visual Arts (PPGAV-UFRJ) and Design (PPGD-UFRJ). She also leads the Laboratory of Visuality and Visualization (LabVis), gathering undergraduate and graduate students in an interdisciplinary approach. Her main interests lie in information design, data visualization, animation for information, interaction design, and visual arts.

Email: doriskos@eba.ufrj.br

Jagoda Walny is a Postdoctoral Fellow at the University of Calgary as part of a project with the National Energy Board of Canada. She is currently studying how to aid the conversation around national energy production, distribution, and use through visualizations of open energy data. Her doctoral work focused on supporting everyday thinking practices in data visualization interfaces by studying sketched externalizations, or "thinking sketches".

Jo Vermeulen is an Assistant Professor in the Department of Computer Science at Aarhus University. His research interests lie at the intersection of Human–Computer Interaction, Ubiquitous Computing and Information Visualization, with a particular interest in designing interactive technologies that put people back in control of their digital environments.

Søren Knudsen is a Marie Curie post-doctoral research fellow at the Department of Computer Science at University of Calgary. His research interests on Human–Computer Interaction and Information Visualization, with particular focus on multiple views in visualizations, and how this might facilitate individual and shared data understanding. He received his PhD in 2015 from University of Copenhagen.

Wesley Willett is an assistant professor of Computer Science at the University of Calgary where he holds a Canada Research Chair in Visual Analytics. His interests span information visualization, social computing, new media, and human-computer interaction, and his research focuses on pairing data and interactivity to support collaboration, learning, and discovery. He leads the Data Experience Lab, is a member of the Interactions Lab, the University's human-computer interaction collective, and is faculty in the Computational Media Design and Data Science programs.

Sheelagh Carpendale is a Professor in Computing Science at Simon Fraser University. She leads the Innovations in Visualization (InnoVis) research group, in the Interactive Experiences Lab. She is a well known researcher in both information visualization and multi-touch interaction, for which she has received many awards including IEEE Visualization Career Award, the E.W.R. NSERC STEACIE Memorial Fellowship; and a BAFTA (British Academy of Film & Television Arts Interactive Award). She has taken many organizational roles in the international research community and currently Chairs the IEEE InfoVis Steering Committee.