Seeking New Ways to Visually Represent Uncertainty in Data: What We Can Learn from the Fine Arts

Aaron Hill*
Parsons School of Design

Clare Churchouse†
Parsons School of Design

Michael F. Schober‡
New School for Social Research

Abstract

In data visualization, the representation of uncertainty and error estimation is often difficult to display effectively. Constraints on the number of dimensions that can be expressed visually as well as limitations of statistical graphing software often lead to data visualizations that inadvertently omit and/or poorly convey the uncertainty and vulnerability of the underlying data.

This research is based on more than 400 works of fine art from museum collections and galleries across several countries, curated and analyzed for inspiration and information on potentially effective ways to visually communicate uncertainty, ambiguity, and vulnerability. We chose these artworks because we feel they have a unique ability to convey uncertainty using a range of approaches and techniques. This paper includes observations from the analysis, examples of compelling works of art from the research, and an exploration of ways these works might inform data visualization practice, specifically for the visual display of uncertainty.

Index Terms: I.2.3 [Artificial Intelligence]: Deduction and Theorem Proving—Uncertainty, fuzzy, and probabilistic reasoning; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Screen design

1 Introduction

Any time that data is used to better understand the world—for any reason, from any source—there exists the possibility of error. Every presentation of data involves transformation, reduction, and the potential for measurement error and various forms of bias. However, because the visual display of uncertainty and error is difficult, this vulnerability is rarely graphically communicated. The fact that the results of the 2016 Brexit vote and the November 2016 U.S. election were surprising, even though polling and modeling allowed for the possibility of those outcomes, demonstrates the extent to which popular understanding of uncertainty is inadequate. The implications for data and identities are profound. As the visual presentation of data takes a greater role in our lives, we lack effective and intuitive visual cues that communicate the degree to which an estimate could be wrong.

The scientific visualization community has been at the forefront of addressing this problem, proposing new ways of representing uncertainty and new techniques for visual rendering [5]. But in the mainstream, error bars are still the predominant way to visualize statistical uncertainty[1]. In the first 50 results of a Google Image search of "uncertainty graph," three-quarters contained bounded error bars which, though widely used, are frequently misinterpreted, even by experts [1]. Research on the "cone of uncertainty" often used in hurricane forecasts demonstrates the multitudinous ways that laypeople incorrectly interpret confidence intervals [4, 13, 14].

Another problem with error bars is that they represent only one of many kinds of uncertainty. There are many other types of statistical uncertainty beside variability in the sampling distribution [10, 15, 16]. Furthermore, beyond the framework of statistical error, emerging philosophical views of inference seek a broader understanding of *the complex interconnections between the methodological and philosophical dimensions* [12]. Johanna Drucker urges that the ultimate challenge is *to accept the ambiguity of knowledge, the fundamentally interpreted condition on which data is constructed* [8]. Let's consider that ideal alongside a common dilemma in data visualization that Drucker articulates: *the rendering of statistical information into graphical form gives it a simplicity and legibility that hides every aspect of the original interpretive framework on which the statistical data were constructed.* Data visualization practitioners often neglect this statistical reality, leading to graphs that inadvertently depict a more confident representation than such an abstraction warrants. By default, most graphing software renders perfectly shaped points and precise delineations in high resolution, conveying exactitude.

Multiple approaches are being explored for visual properties that would *intuitively* convey uncertainty [6, 9, 11, 13, 14]. Researchers are also furthering our understanding of how effectively and accurately these visual properties are being understood by end users [3, 14]. This paper is a preliminary exploration of new ways to visually represent the uncertainty inherent in data by turning to the fine arts for inspiration.

2 Methodology

The data for this paper consists of photographs of 404 works of fine art and their corresponding metadata. We selected them for inclusion in this dataset through an expansive search for artworks that we felt had visual properties and characteristics that conveyed a feeling of uncertainty or ambiguity (but this doesn't mean the artists necessarily intended to express uncertainty). We stopped collecting new data at 404 because we felt we had a good representative set and needed to move to the analysis but there are certainly many more relevant pieces and we hope to add to the database in the future.

Metadata for each item includes artist name, title of work, medium, size, date, country of origin, and collection. The works come from a variety of museums and galleries. A great many of them are held by the Museum of Modern Art in New York and the Tate in London, but they also come from other museums and private collections. Most of the work is modern and contemporary; only 21 works date earlier than 1900.

Table 1 shows the frequency of the medium of each piece. Roughly a third of the works are paintings. The next largest mediums are photographs and drawings, with each making up about 15% of the total. Sculptures, prints, and installations each make up around 10% of the total. Only nine items are videos or films, and although we believe that one of the most promising ways of expressing uncertainty is through animation and motion, the focus of this analysis is on the still, visual qualities in the abstraction and how we feel they express the essence of uncertainty or ambiguity. We propose that our findings should be applicable across mediums,

*e-mail:aaron.hill@newschool.edu
†e-mail:churc186@newschool.edu
‡e-mail:schober@newschool.edu

[1] *There are some notable exceptions, such as the jitter effect used in the New York Times election results needle: https://nyti.ms/2GlFhRV*

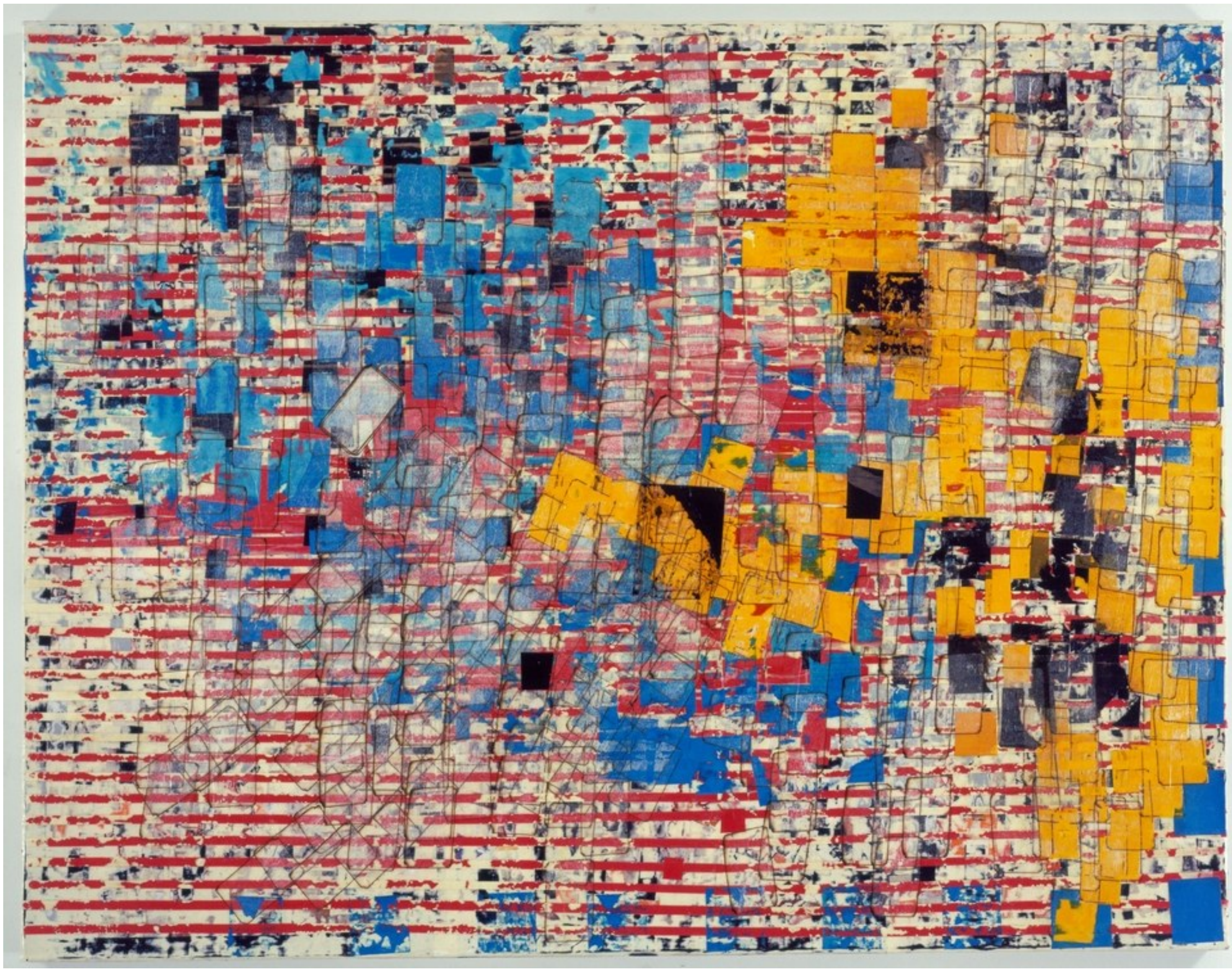

Figure 1: Mark Bradford, *Disappear Like a Dope Fiend*, 2006. Mixed media on canvas, 120.3 x 155.2 cm.

whether still or moving, and so this analysis focuses on visual attributes, not movement. That said, the combination of motion with placement adds possibility and complexity of expression that warrants further exploration.

To encode the visual characteristics of each piece, we adopted the system Jacques Bertin articulated in his 1967 book *The Semiology of Graphics* [2]. We used Bertin's model to measure and articulate the qualities of the visual elements of these works of art, in order to select images based on their visual properties and also to analyze them in the aggregate. Although we could have chosen any of a number of languages, grammars, or systems of graphics, we chose Bertin's *Properties of the Graphic System* for its encompassing yet economical aspect.

Bertin defines three elemental marks: points, lines, and areas. The qualities of these visible marks can vary, the nature of which Bertin articulates with seven visual variables: placement (called *position* by Bertin), shape, orientation, color, texture, value, and size. These elemental marks and variables form the world of images, and with them *the designer suggests perspective, the painter reality, the graphic draftsman ordered relationships, and the cartographer space* [2].

We must strongly assert and acknowledge here that Bertin's system was created for graphics, not for art. We also recognize that the purposes and functions of art and those of graphs are different. With those caveats, we used Bertin's system to measure and encode the visual qualities of the artworks in our data, and found it to be a useful system for this purpose. From our perspective, we found that marks on the various canvases and mediums could be classified as a point, line, or area, without being too reductive. We also found that the seven visual variables were encompassing and effective at defining the visual attributes of modern and contemporary art, also without being too reductive. This framework was effective for encoding the characteristics of the artworks in our data for the purposes of this analysis.

For each of the 404 pieces, we estimated the presence of each visual variable on a six-point scale. We assigned a value of five to the works we felt exhibited the strongest presence of a given visual variable to express uncertainty, and a value of zero to indicate the absence of a given visual variable for this purpose. For the elemental marks, we rated their presence on a three-point scale, with a value of two for prominent use of a given mark and a value of zero for the absence of a given mark. We also used similar coding schemes to record the presence of other attributes, such as whether it contained text, was kinetic, had a spatial dimension, etc. The process of assigning values for these ratings was based on our own determination of whether the artist was using the variables in a way

Table 1: Artworks by Medium

Medium	N
painting	143
photograph	61
drawing	55
sculpture	52
print	48
installation	32
video	6
film	3
projection	2
collage	1
performance	1

that might convey uncertainty (whether intentional or not). The marks and visual variables are not mutually exclusive. In nearly all of these pieces, the artists have used a combination of visual variables, attributes, and techniques.

3 Analysis of the Visual Properties of a Subset of Individual Artworks

From the full set of 404 images, we selected seven to show and describe in this paper—one for each of the seven visual variables. We feel that each chosen image exhibits strong properties for a given visual variable, allowing for greater discussion on the use of that particular variable for expressing uncertainty. Although each artwork uses multiple variables with complex combinations, the discussion will focus on the strong presence of one of the variables.

3.1 Placement

Bertin defines placement as a *given location on the planar dimensions* [2]. Its use in expressing uncertainty involves ways of placing marks in relation to the edge of the canvas or offset and dislodged from the locations of the original data points. When marks are placed precisely where the data dictate, the viewer loses the sense that these points are not in fact precisely known locations, but rather belong in some larger distribution of probable locations; placement may be used to better articulate that distribution. This section explores the use of placement in visual expression.

Mark Bradford created a mixed media assemblage in *Disappear Like a Dope Fiend* (see Figure 1). The collage layers small, similarly shaped pieces of papers and materials of varying transparencies, which are placed in horizontal and vertical alignments. This results in a grid-like structure that evokes a map or urban street pattern. The surface is sanded and scraped back to expose parts of underlying layers, thus merging various layers. Patterns emerge and are clear, but not so much so that one can say definitively where one color pattern ends and another begins. Over the red lines that together read as an imperfect grid, two areas surface: a group of blue shapes and one of yellow. They are clearly distinct and separate groups, but their borders and boundaries are complex and somewhat overlapping. We cannot say with certainty the exact coordinates of their boundaries. The curved placement of semi-transparent papers on the left side are juxtaposed against the more regularly placed multiples underneath.

In assessing how this work conveys a degree of uncertainty that might have parallels in data visualization, the use of placement in relation to multiples is of particular interest here, together with the use of uneven edges of each of the elements. Even modern maps, for example, contain some error and imprecision, yet the borders on those visual representations read as precise and perfect. What if we were to perturb and displace segments of areas and borders to better communicate the nature of these abstractions? What if we invited the viewer to remember that there is some ambiguity and distribution of possibility, even in the best of measurements?

Besides placement, other visual variables also help contribute to a sense of uncertainty that is not often utilized in graphs and data visualization. In Bradford's work, the semi-transparent, overlaying, different angles, and textural effects create traces of what is underneath. We can see the earlier iterations, which suggests that there are other versions of these boundaries and that they should not be interpreted as conveying exactitude. These techniques might be useful in showing various values for points in a distribution. For example, rather than showing a single point estimate, could we effectively show multiple points in a possible distribution to give users a stronger sense of probability density? Statistically, we can generate these values as *multivalue data* from simulations in ensemble computing or as values generated from a probability density function [5]. It can be difficult to render these kinds of generated multivalues because of overplotting and a danger of cognitive overload for viewers. But placement, combined with other techniques such as layering and animation, offers promising ways to effectively express distribution over specificity.

Figure 2: Cai Guo-Qiang, *Drawing for Transient Rainbow*, 2003. Gunpowder on two sheets of paper, 455 x 405 cm. Digital Image © The Museum of Modern Art/Licensed by SCALA / Art Resource, NY.

3.2 Shape

Bertin characterizes shape as *a mark with a constant size [that] can nonetheless have an infinite number of different shapes* [2]. The form of any point, line, or area can be modified to possess different outlines and qualities. This section explores the use of shape in visual expression.

Cai Guo-Qiang created a unique piece in *Drawing for Transient Rainbow* (see Figure 2). The drawing was created by exploding gunpowder sandwiched between two large sheets of paper, unfolding the result, the double arc creating a circle. The resulting textural marks embed into the paper and evidence of combustion debris darts out in various directions, creating a range of dynamic, surreal, specific, seemingly handmade delicate marks—each of a unique shape. It is hard to tell precisely where all these multiple active points exist spatially.

In Cai's work, the chemical transformation changes the original form and shape, and we see the residue. We have evidence that what we're seeing isn't what we started with. In graphing data points, perhaps we can bring the spirit of this kind of transformation to plotted elements. Instead of rendering perfect dots and other geometrical shapes, we can alter them to appear irregular and ephemeral. A perfectly round dot conveys exactitude, but what if it were altered to appear more vulnerable to external forces? What if dots appeared as perforations, or splatter? What if geometric transformations rendered each point a unique shape with varied or smudged edges?

Figure 3: Monika Sosnowska, *The Tired Room*, Freud Museum, Vienna, Austria, 2005. Painted mdf, installation view.

3.3 Orientation

Bertin defines orientation as *ranging from the vertical to the horizontal in a distinct direction* [2]. Variation on orientation offers a visceral and naturally intuited expression of being off-kilter. This section explores the use of orientation in visual expression.

Monika Sosnowska created *The Tired Room* at the Freud Museum in Vienna in 2005; see Figure 3. The room installation features angular, slanted walls and surfaces. The physical space creates a sense of uncertainty by disorienting the viewer with a tilted floor and walls that are not perpendicular to the floor. Angular shapes protrude inward from the walls and ceiling. The hanging light does not appear to follow the laws of gravity. And yet, despite the strange and disorienting space, we can easily and quickly recognize that it is in fact a room. Although familiar as an interior, the surrealism may serve as a powerful prompt and reminder of the abstract nature of the space, of gravity, and of our perception of physical spaces in relation to ourselves.

This use of orientation to unsettle the viewer's relation to space may also be useful to convey uncertainty in graphs. What if points, lines, and areas were modified so that they were easily recognizable, yet clearly serving as a non-concrete representation of some real phenomenon? Could these transformations serve to disorient and remind us that what we're seeing is only a representation of some imprecisely known reality? Or can lines and shapes be tilted in relation to the edge of a work to convey falling or slippage?

3.4 Color

Bertin defines color as *hue, using the repertoire of colored sensations which can be produced at equal value* [2]. This section explores the use of color in visual expression.

Catherine Yass used a screenprinting technique to create *Stage* (see Figure 4). This print has a distinct color combination of yellow/green together with purple/blue. There are no hard-edged shapes; outlines are fuzzy and indistinct. The image in general is somewhat ambiguous, depicting some kind of architecture or infrastructure in perspective. The print was made using photographs of a theater backstage area at the Barbican Arts Centre in London, but that would not be apparent without reading a description of the piece[2], even for those few who may be familiar with that theater's backstage area. The blurring and color effects are created through a process of combining positive and negative transparencies.

These effects might also be used to convey uncertainty and ambiguity in graphs and data visualization. The unusual color combined with translucent, almost x-ray effects and blur in *Stage* could read as an indicator of areas of uncertainty. Color is often used in graphs to convey difference in some classification or ordering scheme. But could it not also be used to help distinguish areas of uncertainty? Gone are the days of black and white graphs; the visual variable of color is now used in the vast majority of data visualization. But because of its prevalence, this visual variable has likely already been mapped to another dimension in the data and thus unavailable for use to express this additional dimension. Nonetheless, use of specific colors juxtaposed together may help serve as a visceral indicator of uncertainty.

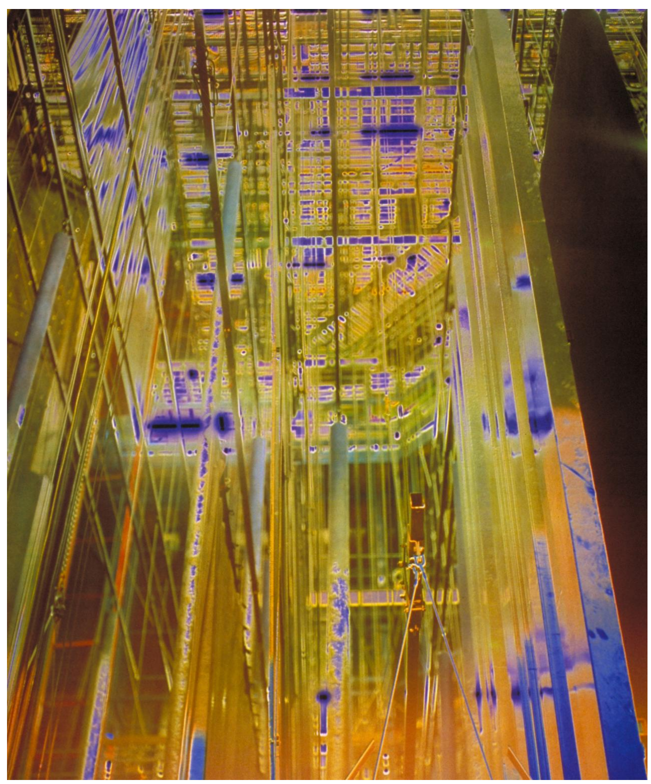

Figure 4: Catherine Yass, *Stage*, 1997. Screenprint on paper, 89 x 74 cm. ©Tate, London 2018.

[2] *Stage* is held by the Tate Museum in London, which provides a thorough description of its creation and meaning at: http://www.tate.org.uk/art/artworks/yass-stage-p78088

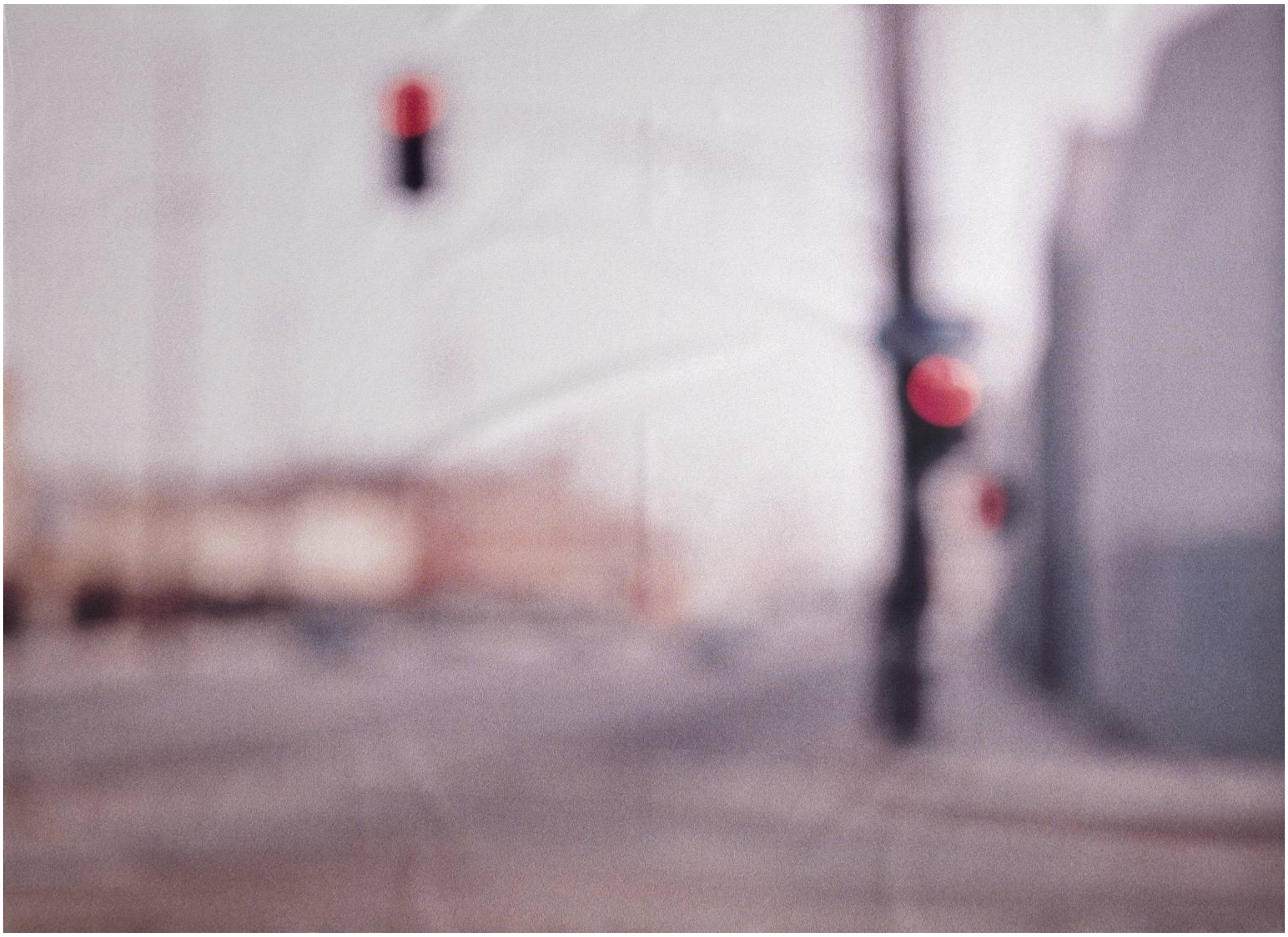

Figure 5: Uta Barth, *Field #20*, 1997. Digital print with acrylic paint on canvas, 346 x 416 cm. ©Tate, London 2018.

3.5 Texture/blur

Bertin defines texture as *variation in the fineness or coarseness of the constituents of an area having a given value* [2]. Others might define it as smoothness or roughness, or the appearance of a surface. Texture may be hard to precisely define, but most have a tacit understanding of its essence. We have added to Bertin's definition by explicitly including *blur* as an effect that could be considered texture. This section explores the use of texture and blur in visual expression.

Uta Barth's printed photograph with acrylic on a very large canvas in *Field #20* (see Figure 5) forms a gigantic, very pixelated image of a street scene. In fact, when up close, you can only see pixels. The shapes are uneven and normally distinct objects like the street lamps are disfigured because of the pixelation. If this were a crisp, high resolution photo, it would feel extremely different. Nonetheless, from afar one can make out that this photograph shows some street corner, somewhere. But it would be nearly impossible to say for sure where it is.

The use of texture and blur in graphics to render elements tactile and ambiguous is especially promising for the expression of uncertainty in a way that could be intuitive even to audiences unfamiliar with statistical methodology. The visceral technique forces a viewer to reckon with the imprecise nature of the abstraction. With the right application of texture and blur, users should still be able to see graphical elements well enough to recognize and comprehend, but not so well that they inadvertently get a false sense of exactitude in the data.

3.6 Value

Bertin defines value as *the various degrees between white and black* [2], but most think of value as lightness or darkness of a given color. This section explores the use of value in visual expression.

Lee Ufan painted a series of grouped parallel blue lines in *From Line* (see Figure 6). The lines run nearly the full height of the canvas, but they become harder to see the further down you go as they start to fade into, or be engulfed by, the pale yellow ground. It's as though the brush did not have sufficient paint to sustain the full length of each line. Yet even in the lightest areas, the entirety of each line is visible.

This use of value may translate well to convey uncertainty in linear relationships. In most linear models, there is variation in the level of confidence between segments. Perhaps in segments of a linear representation that are less confident or more prone to error, the value of the line could be lightened. Additionally, modulation in value also offers rich opportunities within and across points and shapes, such as fading parts of an area into a light ground to create a sense of tentativeness and incompleteness.

There are other visual properties in Ufan's painting that could also be helpful in expressing uncertainty. Each stroke is similar but distinct, making the lines much more varied than those that would typically be rendered in graphing software. The differences in textures, stroke widths, and straightness of the lines invite interpretations of nuance and ambiguity.

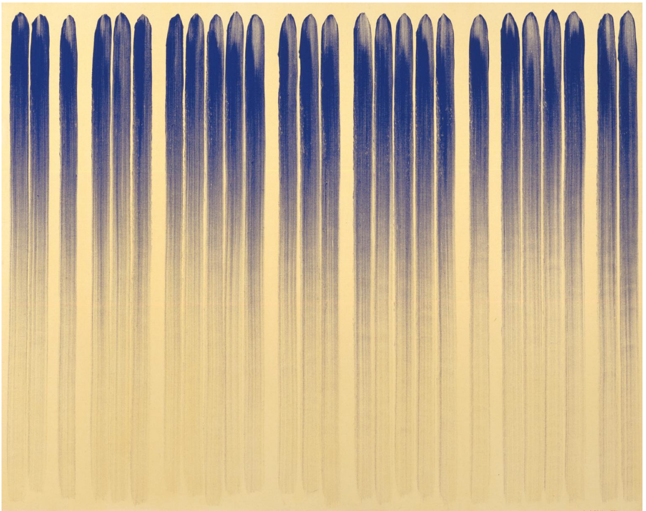

Figure 6: Lee Ufan, *From Line*, 1978. Oil paint and glue on canvas, 182 x 228 cm. ©Tate, London 2018.

3.7 Size

Bertin defines size as *variations in height, width, area* [2]. Size also shows the scale of one element beside another as well as in relation to the canvas. As such, size is a strong visual variable for inviting comparison. This section explores the use of size in visual expression.

Ed Ruscha used acrylic on canvas to create the untitled work shown in Figure 7. He uses size in a very literal way (along with other visual variables) to create a sense of uncertainty. There are seven levels of size from the largest at the top, down to the smallest at the bottom. However, the seven units of time start with the smallest (seconds) at the top, down to the longest (years) at the bottom. Are we counting down? Or counting up? Is the size conveying that the smallest unit of time is the most important? Or the most certain?

Fading between the dark and light background areas is also used to help contrast between the text and a white void. A curved shape fades and encroaches on the text, creating a sense of a setting sun or a burning light. The delineation is soft and fuzzy, though it does separate the text from the rest of the canvas, and changes the sense of space.

Size could also be used to express uncertainty in graphs. It could be used very literally, with larger sizes for data points that are known to be precise measurements of a phenomenon and smaller sizes for data points that are more volatile in a more expansive probability distribution. Size could also be used in combination with other variables to introduce dissonance, similar to Ruscha's treatment in his 2015 untitled work, giving the largest size to the smallest unit and vice versa.

4 Analysis of the Full Set of Artworks

This section presents descriptive statistics for the artwork metadata on the full corpus of 404 images. As described in the methodology (Section 2), we estimated the attributes of each of the artworks to quantify the presence of various visual properties and characteristics. We remind readers that the scoring is based on our interpretation that these visual variables convey *uncertainty* or *ambiguity*, not as an indicator of their general presence. For the visual variable

Figure 7: Ed Ruscha, *Untitled*, 2015. Acrylic on canvas, 183 x 315 cm. © Ed Ruscha. Courtesy Gagosian.

Table 2: Occurrence of Visual Variables That Express Uncertainty in These Artworks

Visual Variable	Mean Score	% 4 or Greater
placement	2.98	39.6
shape	2.92	45.0
texture/blur	1.98	20.0
value	1.97	20.5
orientation	1.68	20.0
size	0.99	7.9
color	0.42	2.0

encodings, values range from zero to five, with the value five indicating our estimate of the strongest expression of a given attribute and zero indicating its absence. Although these encodings represent the interpretation of the authors, we believe that the distribution of the visual variables—while not guaranteed to generalize beyond the artworks selected here—might offer some preliminary indication of their potential role in expressing uncertainty.

Table 2 shows the mean encoding for the occurrence of each visual variable, over the full set of artworks. The two most prevalent visual variables we saw are placement and shape, with mean scores of approximately three. Nearly 40% of the works are thought to make strong use of placement (a score of four or greater) and 45% are thought to have a strong use of shape. Texture, value, and orientation were also strongly represented in our encodings, texture and value with mean scores of approximately two, and orientation with a mean score of nearly 1.7. Texture, value, and orientation were each seen as strongly used in about one in five of these artworks. Size and color were seen as the least frequently used visual variables to convey uncertainty here, with low mean scores and rarely a strong presence for the expression of uncertainty.

The frequency of our observations of the seven visual variables to express uncertainty in these artworks is not uniformly distributed, which may be indicative of their availability to map to uncertainty after other variables have been used to render the primary dimensions. Because visualizing uncertainty adds a dimension [5] and is generally not the primary dimension, some visual variables may no longer be available to the artist or designer. In the case of color in data visualization, for example, it is almost always used for indicating different qualities or categories in a chart or graph. Thus, to use color to express uncertainty could create confusion and invite misinterpretation. Placement, size, and texture may be the most frequently observed variables in this data for showing uncertainty because color, size, and value are so commonly mapped to fundamental dimensions.

5 A Research Tool for Filtering on Visual Properties

While the prevalence of visual variables across the full dataset may be informative and useful for thinking broadly about techniques for expressing uncertainty, we feel that the primary value of this data source is in its ability to inform and inspire graphs and data visualizations, demonstrating some of the vast range of visual approaches that can be used to convey complex concepts, not in an attempt to imitate or copy art but instead to draw inspiration for treatments on points, lines, and areas that will intuitively and viscerally convey a sense of uncertainty. We have created an interface to the data source used in this paper—a new, publicly available research tool for filtering and selecting images on their metadata. It is available at: **http://www.visualizeuncertainty.io/art/**.

This interactive interface enables browsing of images and metadata, based on Bertin's properties of the graphic system and other indicators. Selections are first narrowed by choosing visual variables (and the strength of their presence in the artwork, for each of the chosen variables). Selections may be further narrowed by applying filters for marks (point, line, and/or area) and specific attributes (contains text, is a map, is spatial, etc.). Depending on the specified parameters of the filters, users may end up with a large, broad set of results (for general exploration) or a small, narrow set of fewer than five results (for very specific applications). Results are hyperlinked to their sources at various museums and galleries for further research on individual artworks.

We created this research tool in order to aid designers and analysts by showing varied works that may convey a degree of uncertainty, offering a rich array of uses of visual variables for graphical purposes. The artwork examples contain particular, specific uses of each of the variables (as we have observed them), and the database as a whole allows for comparisons of the use of a variable with other artworks that may exhibit that same variable from similar and differing perspectives. Although there are numerous interfaces to expansive art collections, this interface offers an efficient, narrow search of artworks that we feel have effective representations of uncertainty. Additionally, the works may be filtered on attributes defined for a graphical system.

6 Limitations and Future Work

Work on this data source and interface will continue. We would like to include more artworks, and we encourage contributions of references to relevant artworks. Limitations of the encoding scheme arise through the subjective interpretations of the authors; we would like to remedy this by crowdsourcing the encodings, with appropriate redundancies and aggregations to achieve better measurements. We would also like to add machine learning functionality to allow users to upload a graph and receive a small subset of artworks that are most characteristically similar to that graph, as another means of searching and filtering for related approaches and particular uses of specific variables to expressive ends.

The goal of this paper is to take a preliminary look at art as a possible source of knowledge and inspiration for new approaches in the challenge of conveying the uncertainty of complex phenomena. We hope that this research tool inspires visualization creators to broaden the possible space of representations. Any new visualizations that result from such an exploration are worthy of empirical testing of graphical perception [7], especially as it relates to the use of specific visual variables [3]. Future work is needed to test the effectiveness of arts-inspired visual representations to intuitively communicate various forms of uncertainty—both quantitative and qualitative.

7 Conclusion

To the extent that art imitates life, modern art rarely seeks to impose a level of order and certitude that doesn't exist in this uncertain world. Data visualization typically isn't intended as a purely artistic expression, and art is absolutely not data visualization. Yet when it comes to the rendering of abstractions of the inherent uncertainty in data, graphics and data visualization stand to gain from a strong artistic influence, particularly as we look for visceral and intuitive expressions. This opens the possibility of visually conveying the essence of a broader uncertainty, including both the measurable and immeasurable ambiguities and vulnerabilities, most of which are rarely shown. But to express this well would be to do so without undermining the data. Knowledge is built in spite of the uncertainty of measurement and inference.

The nature of this sort of experimentation with visual form calls for careful research and evaluation. A well-designed data visualization is a hypothesis until it has been validated with evidence that intended users have accurately perceived and comprehended the uncertainty in the representation.

The defaults in most graphing software nudge us toward perfect-looking points, lines, and areas, but systems such as Bertin's offer a freedom to transcend the limitations of software. Visual art often uses handmade marks, unconstrained by predetermined drop-down menus of software programs that tend to offer straight lines, perfect, equally-sized shapes, circumscribed color choices, opaque fills, sharp edges, and geometric, centered elements. Yet even the most restrictive software can be manipulated (sometimes post hoc) to achieve a desired rendering.

Fine art can serve as a reference and source of inspiration for visual cues and treatments that could alter our demarcations, delineations, and planes. Although error bars are still by far the predominant way to express uncertainty in data, there's more to uncertainty. Maybe that is where art can be most influential—not for showing the precisely estimated and known sources of uncertainty and error in data, but for rich, subtle prompts and reminders that all data represent an abstraction and not a hard truth.

References

[1] S. Belia, F. Fidler, J. Williams, and G. Cumming. Researchers Misunderstand Confidence Intervals and Standard Error Bars. *Psychological Methods*, 10(4):389–396, 2005.

[2] J. Bertin and W. J. Berg. *Semiology of graphics: diagrams, networks, maps*. ESRI Press : Distributed by Ingram Publisher Services, Redlands, Calif, 1st edition, 2010.

[3] N. Boukhelifa, A. Bezerianos, T. Isenberg, and J.-D. Fekete. Evaluating Sketchiness as a Visual Variable for the Depiction of Qualitative Uncertainty. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2769–2778, Dec. 2012.

[4] K. Broad, A. Leiserowitz, J. Weinkle, and M. Steketee. Misinterpretations of the "Cone of Uncertainty" in Florida during the 2004 Hurricane Season. *Bulletin of the American Meteorological Society*, 88(5):651–667, May 2007.

[5] K. Brodlie, R. Allendes Osorio, and A. Lopes. A Review of Uncertainty in Data Visualization. In *Expanding the Frontiers of Visual Analytics and Visualization*, pages 81–109. Springer, London, 2012.

[6] S. B. Broomell and P. B. Kane. Public perception and communication of scientific uncertainty. *Journal of Experimental Psychology: General*, 146(2):286–304, 2017.

[7] W. S. Cleveland and R. McGill. Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods. *Journal of the American Statistical Association*, 79(387):531, Sept. 1984.

[8] J. Drucker. *Graphesis: visual forms of knowledge production*. MetaLABprojects. Harvard University Press, Cambridge, Massachusetts, 2014.

[9] D. G. Goldstein and D. Rothschild. Lay understanding of probability distributions. *Judgment and Decision Making*, 9(1):1–14, Jan. 2014.

[10] R. M. Groves and L. Lyberg. Total Survey Error: Past, Present, and Future. *Public Opinion Quarterly*, 74(5):849–879, Jan. 2010.

[11] C. Johnson and A. Sanderson. A Next Step: Visualizing Errors and Uncertainty. *IEEE Computer Graphics and Applications*, 23(5):6–10, Sept. 2003.

[12] D. G. Mayo and A. Spanos, editors. *Error and inference: recent exchanges on experimental reasoning, reliability, and the objectivity and rationality of science*. Cambridge University Press, Cambridge New York Melbourne, 2010. OCLC: 845521030.

[13] L. M. Padilla, G. Hansen, I. T. Ruginski, H. S. Kramer, W. B. Thompson, and S. H. Creem-Regehr. The influence of different graphical displays on nonexpert decision making under uncertainty. *Journal of Experimental Psychology: Applied*, 21(1):37–46, 2015.

[14] I. T. Ruginski, A. P. Boone, L. M. Padilla, L. Liu, N. Heydari, H. S. Kramer, M. Hegarty, W. B. Thompson, D. H. House, and S. H. Creem-Regehr. Non-expert interpretations of hurricane forecast uncertainty visualizations. *Spatial Cognition & Computation*, 16(2):154–172, Apr. 2016.

[15] J. Thomson, E. Hetzler, A. MacEachren, M. Gahegan, and M. Pavel. A typology for visualizing uncertainty. pages 146–157, Mar. 2005.

[16] L. Wilkinson and G. Wills. *The grammar of graphics*. Statistics and computing. Springer, New York, 2nd edition, 2005.