

# The Noisy Work of Uncertainty Visualisation Research: A Review

Harriet Mason

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# 1 Background

From entertainment choices to news articles to insurance plans, the modern citizen is so over run with information in every aspect of their life it can be overwhelming. In this overflow of information, tools that can effectively summarize information down into simple and clear ideas become more valuable. Information visualisations remain one of the most powerful tools for fast and reliable science communication.

Visualization is an important step in exploratory data analysis and it is often utilised to **learn** what is important about a data set. Datasets such as Anscombe’s quartet (Anscombe 1973) or the Datasaurus Dozen (Locke and D’Agostino McGowan 2018) highlight this power in visualisation. Additionally, visualisations allow for efficient and memorable communication. Even something as simple as sketching a distribution before recalling statistics or making predictions can greatly increase the accuracy of those measures (Hullman et al. 2018; Goldstein2014?).

Uncertainty visualisation is a relatively new field in research. Early papers that specifically reference “uncertainty visualisation” appear in the late 80s (Ibrekk and Morgan 1987), with geospatial information visualisation literature in the early 90s declaring this to be essential aspect of information display (MacEachren 1992; Carr, Olsen, and White 1992). These early experiments typically involved showing participants a distribution, such as those depicted in Figure 1, and asking the viewers to extract a probability or average. Despite the new terminology visualisation of uncertainty has been present since the earliest times. For example, box plots or histograms can be considered to be displaying uncertainty in the sense of variability in observations sampled from a population distribution. Today, there is an abundance of publications on the topic which makes it is timely to construct a review of the field. In fact, there have already been several reviews published.

Reviews on uncertainty visualisation rarely offer tried and tested rules for effective uncertainty visualisation, but rather comment on the *difficulties* faced when trying to summarize the field. Kinkeldey, MacEachren, and Schiewe (2014) found most experiments on the methods for uncertainty visualisation evaluation to be ad hoc, with no commonly agreed upon methodology or formalisation and no greater goal of describing general principals. Hullman (2016) commented on the difficulty in taking overarching themes from uncertainty visualisation, as several conflated issues make it unclear if subjects did poorly in an experiment because they misunderstood a visualisation, because the question was misinterpreted, or because they used a specific heuristic. Spiegelhalter (2017) commented that different plots are good for different things, and disagreed with the goal of identifying a universal “best” plot for all people and circumstances. Griethe and Schumann (2006) was unable to find common themes, but instead listed the findings and opinions of a collection of papers. L. Padilla, Kay, and Hullman (2022) summarized several cognitive effects that have repeatedly arised in uncertainty literature, however these effects were each discussed in isolation as a list of considerations an author might make. While these reviews are thorough in scope, none discuss how the existing literature contribute to the commonly state goal of uncertainty visualisation, scientific transparency. The problem faced by the literature is easily summarized with a famous quote by Henri Poincaré.

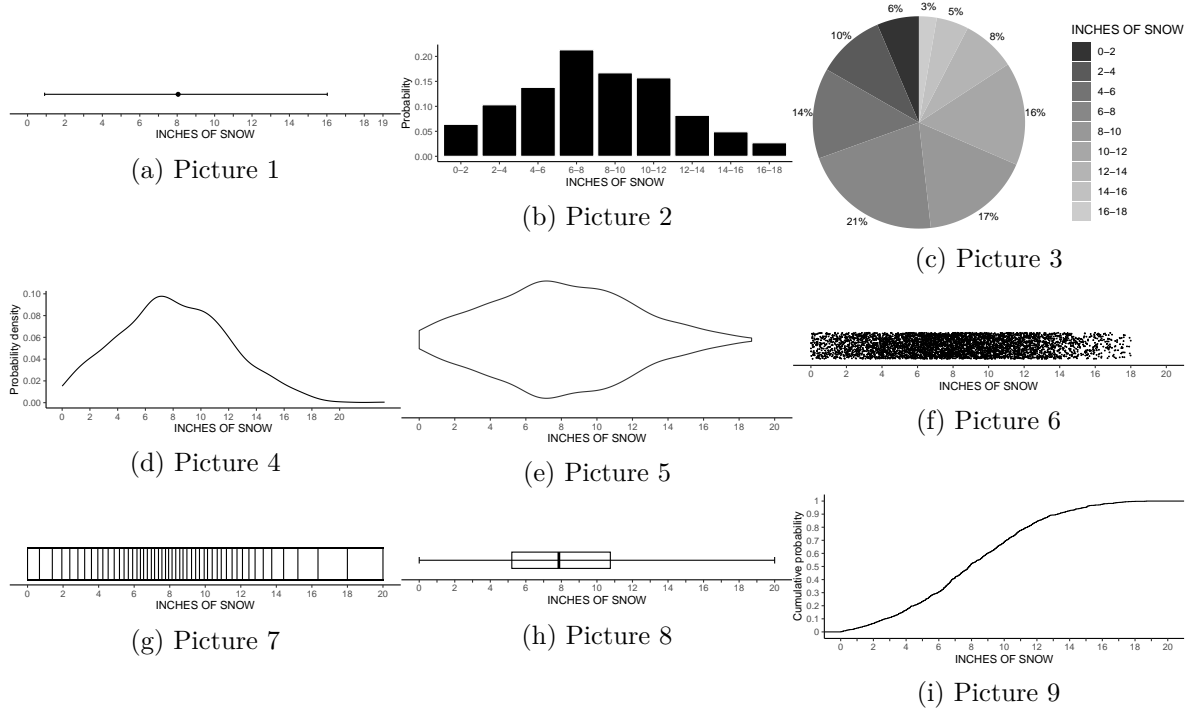


Figure 1: A replication of the the uncertainty visualisations shown by Ibrenk and Morgan (1987) in one of the earliest uncertainty visualisation experiments. This early experiment is a good example of many of the issues that are still common in uncertainty visualisation today. For example, the ‘95% confidence interval’ is more accurately a ‘95% prediction interval’. Additionally graphics that depict different mathematical objects that are also different on their visual components are compared because of a percieved relation to uncertainty. So visualisations of the mean, PDF and CDF, are all discussed as though they all contain the relevant statistical information. The axis also have different scales, and visualisation methods that are now unpopular for displaying proportions, such as a pie chart, are used.

“Science is built up of facts, as a house is built of stones; but an accumulation of facts is no more a science than a heap of stones is a house.” - Henri Poincaré (1905)

That is to say, despite the wealth of reviews, the field of uncertainty visualisation remains a heap of stones. This review attempts to address this issue by offering a novel perspective on the uncertainty visualisation problem, and hopefully laying the foundations on which we can build a house. This review is broken into several parts that each reflect a different approach to uncertainty visualisation. First we look at graphics that ignore uncertainty entirely and discuss why uncertainty should be included at all. Second, we look at methods that consider uncertainty to be just another variable and discuss the characteristics of uncertainty that make it a unique visualisation problem. Third, we look at methods that explicitly combine our estimate and its uncertainty and discuss if the visualisations created by these transformations are still “uncertainty visualisations”. Fourth, we will discuss methods that implicitly include uncertainty by depicting a sample or original data in place of an estimate. Finally, we discuss how uncertainty visualisations can be effectively evaluated. When discussing each of these methods, we consider the *purpose* of uncertainty visualisation and comment on how effective each visualisation is at fulfilling that purpose.

Due to the field's origins and focus in geospatial information visualisation, there have been a large number of suggested variations on the choropleth map that allow authors to include uncertainty. We will use these maps to provide simple examples for each approach that can be easily compared to the “no uncertainty” choropleth map to better understand the costs and benefits of each approach. Despite the example of each method focusing on variations of the choropleth map, it is important to understand that the approaches we are discussing are universal and are not unique to maps.

## 2 Ignoring uncertainty

A good place to start might be at deceptively straight forward question, why should we include uncertainty at all?

Figure 2 depicts a choropleth map of the counties of Iowa. Each of these counties are colored according to an estimate of average daily temperature that was simulated so that the values followed a clear spatial trend (hot in the middle of the map, and cold on the outside). The variance of these estimates were simulated such that a hypothesis test would indicate the existence of a spatial trend in the low variance map, while the trend in the high variance map should be indistinguishable from noise. Is this distinction in validity of the spatial trend clear in the map? Is the validity of the trend communicated through the visualisation?

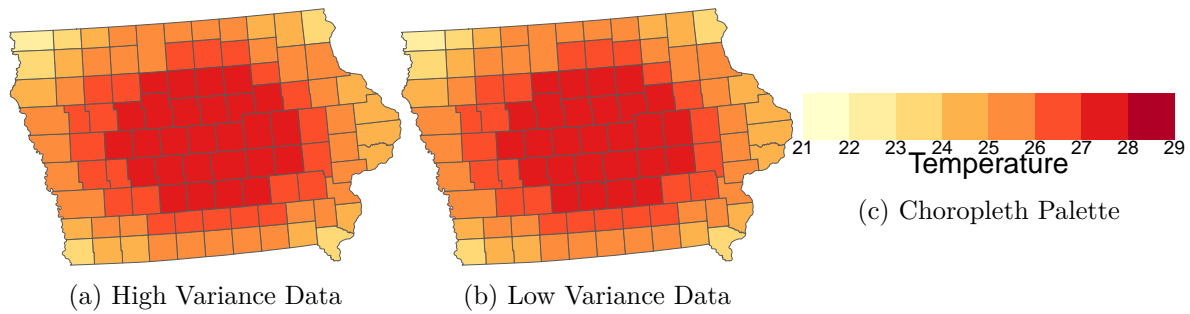


Figure 2: Two choropleth maps that depict the counties of Iowa where each country coloured according to a simulated average temperature. Both maps depict a spatial trend, where counties closer to the center of the map are hotter than counties on the edge of the map. This trend is only technically there in the low variance condition, i.e. if we performed a hypothesis test we would conclude the trend exists. The high variance condition displays a spatial trend that could simply be the result of noise, which means the plot is displaying a false conclusion.

### 2.1 Signal-suppression

The two choropleth maps appearing to be identical in Figure 2 highlights the need for uncertainty visualisations. Uncertainty visualisation is required for transparency and this sentiment has been repeated. Some authors suggest uncertainty is important to include as it communicates the legitimacy (or illegitimacy) of the conclusion drawn from visual inference (Correll and Gleicher 2014; Kale et al. 2018; Griethe and Schumann 2006). Some authors have said that uncertainty should be included to degree of confidence or trust in the data (Boukhe-lifa et al. 2012; Zhao et al. 2023). Some authors directly connect uncertainty visualisation to hypothesis testing as it ensures the “validity” of a statement (Hullman 2020; Griethe and Schumann 2006), but allows for a proportional level of trust that is more detailed than the binary results of a hypothesis test (Correll and Gleicher 2014; Correll, Moritz, and Heer 2018).

Some authors even go so far as to claim that failing to include uncertainty is akin to fraud or lying (Hullman 2020; Manski 2020).

This consensus leads us to understand that uncertainty visualisation is motivated by the need for a sort of “visual hypothesis test”. A successful uncertainty visualisation would act as a “statistical hedge” for any inference we make using the graphic. This implies three key criteria for a good uncertainty visualisation:

- 1) Reinforce justified conclusions to encourage confidence in results
- 2) Prevent unjustified conclusions that are indistinguishable from noise
- 3) Perform tasks 1) and 2) in a way that is proportional to the level of confidence in those conclusions.

We can refer to the we draw from a graphic to be its “signal” and the variance that makes this signal harder to identify as the “noise”. As Figure 2 showed, visualisations that are unconcerned with uncertainty have no issue showing justified signals, but struggle with the display of unjustified signals. Therefore, we coin this approach to uncertainty visualisation as “signal-suppression” since it primarily differentiates itself from the “noiseless” visualisation approach through criteria (2). That is, the main difference between an uncertainty visualisation and a “normal” visualisation, is that an uncertainty visualisation should prevent us from drawing unjustified conclusions.

### 3 Visualising uncertainty as signal

Uncertainty visualisation is not only motivated by signal-suppression, and we would be remiss to ignore these alternative motivations. Some authors claim the purpose of uncertainty is to improve decision making (Ibrekk and Morgan 1987; L. Padilla, Kay, and Hullman 2022; Hullman 2016; Cheong et al. 2016; Boone, Gunalp, and Hegarty 2018; L. M. Padilla, Ruginski, and Creem-Regehr 2017). While uncertainty can provide useful information in decision making, it is important to recognize the “uncertainty” in these cases is not acting as “uncertainty” at all. It is acting as signal. This is easiest to understand with an example.

Imagine you are trying to decide if you want to bring an umbrella with you to work. An umbrella is annoying to bring with you, so you only want to pack it if the chance of rain is greater than 10%. Unfortunately, your weather prediction app only provides you with the predicted daily rainfall. Therefore, your decision will be improved with the inclusion of uncertainty, *not* because uncertainty is important for your decision, but because it gives you the tools required to calculate the *actual* statistic you are basing your decision on. In this sense, uncertainty is no more “special” to decision making than weight is in a BMI calculation.

Other authors do not describe uncertainty as important for decision making, but rather explicitly state it as variable of importance in of itself (Blenkinsop et al. 2000). This group are *also* viewing uncertainty as a signal, albeit more explicitly than the decision making group. If the purpose of uncertainty in these cases is to convey information rather than obfuscate it, then there is no reason to assume these “uncertainty visualisations” would behave any differently to normal information visualisations. This is exactly what the literature shows.

Uncertainty visualisation experiments often compare graphics on the basis of being “uncertainty visualisations” (Ibrekk and Morgan 1987; Hullman, Resnick, and Adar 2015; Hofman, Goldstein, and Hullman 2020) with little consideration for how difficult the information is to extract from the chart. Experiments where users are asked to make a decision based on a probability, and experiments where users need to extract a variance or some feature of the distribution both have the implicit belief that uncertainty visualisation is a “class” of visualisation, and a “good” uncertainty visualisation allows us to extract all information with ease. This is the logic that results in predictable results. Ibrekk and Morgan (1987) found that participants were more accurate at extracting a statistic when it could be directly read off the graphic, than when it required an area estimate (which is the case if using the PDF), or when there was no visual indicator for the statistic at all (which is the case when using the CDF of an asymmetric function). Hullman, Resnick, and Adar (2015) found that a visualisation that allows viewers to count outcomes to estimate a probability outperformed one that required a complicated area calculation. Hofman, Goldstein, and Hullman (2020) and Zhang et al. (2022) found that participants were better at answering questions about a prediction intervals when shown a prediction interval instead of a sampling distribution. Gschwandtnei et al. (2016) found that graphics where the required statistic could be directly read off the plot outperformed those that involved guesswork due to a gradually decreasing line. Cheong et al. (2016) found that participants made better decisions when they were explicitly given



the relevant probability in text rather than when they needed to read it off a map. These experiments all have the same fundamental finding, if we create a problem by obfuscating information, then the representation that makes the obfuscated information easier to extract outperforms those that don't. This is why text representations or graphics that allow users to simply count a value to extract the required statistic outperform those that require any perceptual tasks. We have known perceptual tasks have more noise than text representations for a long time (Cleveland and McGill 1984) and it has little to do with uncertainty.

Additionally, if uncertainty visualisation for decision making is a “wrong information” problem, then we would expect uncertainty visualisations made for this purpose to simply adjust the statistic they display of rather than a change the visual elements of the graphic. This is precisely what we observe. Figure 3 depicts an exceedance probability map that has been designed as an alternative to the choropleth map to improve decision making under uncertainty (Kuhnert et al. 2018; Lucchesi, Kuhnert, and Wikle 2021). A keen viewer may notice that the “exceedance probability map” is actually just a choropleth map. While the input into the graphic has changed, graphics, just like statistics, are not defined by their input data.

This seems to be an accepted fact for all visualisations *except* for uncertainty visualisation, and this creates disagreement in what is even considered to be an uncertainty visualisation. For example Wilkinson (2005) mentions that popular graphics, such as pie charts and bar charts omit uncertainty, and Wickham and Hofmann (2011) suggests their product plot framework, which includes histograms and bar charts, should be extended to include uncertainty however at least one or both of these charts are used in a significant number of uncertainty visualisation experiments (Ibrekk and Morgan 1987; Olston and Mackinlay 2002; Zhao et al. 2023; Hofmann et al. 2012). We believe this disagreement comes from two different conceptualisations of what an uncertainty visualisation *is*. This issue causing confusion in the literature was also commented on by Kinkeldey, MacEachren, and Schiewe (2014), who explained it was unclear if uncertainty should be treated as a variable, as metadata, or as something else entirely (Kinkeldey, MacEachren, and Schiewe 2014). There are those that describe *any* visualisation of error as an “uncertainty visualisation” and those that believe “uncertainty visualisation” is a function that can be *applied* to any graphic that depicts an estimate. The former group view the purpose of uncertainty visualisation to provide signal about a distribution, while the latter believe it should act as noise to obfuscate a signal.

The easily explained results in evaluation experiments, and the exceedance probability map show the problem of viewing uncertainty as a signal instead of noise. If we view the purpose of viewing uncertainty visualisation to simply extract a probability or variance (regardless of whether or not it is for value extraction or decision making) then the best performing visualisation will be one that makes that statistic easy to extract. Even better is to avoid displaying a visualisation all together and simply provide the probability or variance with text.

Of course, we do not believe there is anything wrong with explicitly visualizing variance, error, bias, or any other statistic used to depict uncertainty as a signal. Just like any other statistic, these metrics provide important and useful information for analysis and decisions. However,

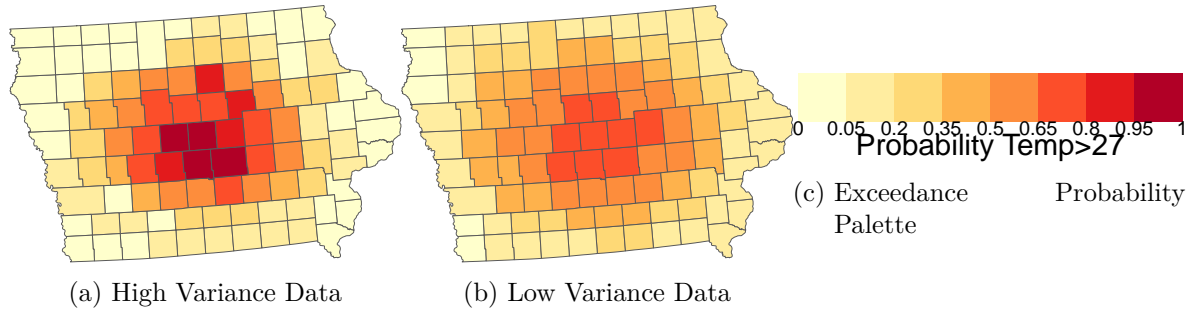


Figure 3: An exceedance probability map that depict the counties of Iowa where each country coloured according to the probability that the average temperature exceeds 27. This map is a choropleth map where the variable of interest is a probability.

there is no interesting visualisation challenge associated with these graphics, and they do not require any special visualisation, they are acting an estimate and they should be treated as such.

For these reasons decision making and visualisations that explicitly depict uncertainty measures will not be the focus of this review. We will instead focus on the perspective that uncertainty visualisation serves to obfuscate signal, and should be considered a function that can be *applied* to any graphic to suppress false signals. The following sections will investigate several approaches to uncertainty visualisation and discuss how successful each approach is in fulfilling the signal-suppression criteria.

## 4 Including uncertainty as an independent variable

Upon hearing that uncertainty needs to be included for transparency, the solutions may seem obvious. You may think “well, I will just add a dimension to my plot that includes uncertainty”. This makes sense, as this is the simplest way to add uncertainty to an existing graphic is to simply map uncertainty to an unused visual channel.

Figure 4 a variation of the choropleth map, where we have a two dimensional colour palette. Not only is temperature mapped to hue, but variance is also mapped to saturation. While these two maps *do* look visually different (which was not the case in the choropleth map) the spatial trend is still clearly visible in both graphics. This means the uncertainty *is* being communicated, however the primary take away in the graphic is the spatial trend (that does not exist). The graphic no longer has a transparency issue as the uncertainty *is* technically included, but is this a uncertainty visualisation? And if not, why?

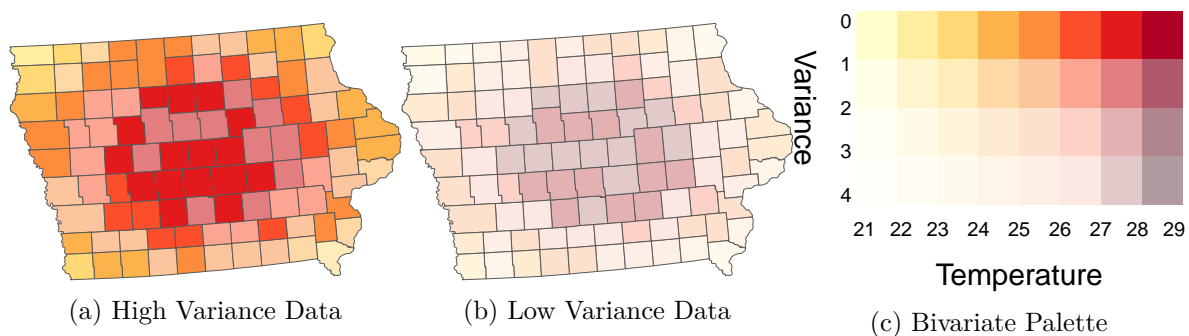


Figure 4: A bivariate map that depict the counties of Iowa where each county is coloured according to its average daily temperature and the variance in temperature. This map is a choropleth map with a two dimensional colour palette where temperature is represented by colour hue, and variance is represented by colour saturation. Even though uncertainty has been added to the graphic the spatial trend is still clearly visible in the case where the spatial trend could be attributed to noise.

### 4.1 What makes uncertainty visualisation difficult?

Uncertainty visualisation is a uniquely difficult problem in visualisation. Hullman (2016) commented that it is straightforward to show a value but it is much more complex to show uncertainty. There are two primary theories as to *why* uncertainty visualisation is unique.

The first group believes uncertainty visualisation are unique due to the psychological heuristics involved in interpreting uncertainty (Spiegelhalter 2017; Hullman et al. 2019). While it is true that heuristics lead people to avoid uncertainty (Spiegelhalter 2017) there is no evidence that this psychological effect translates to a problem in visualisation. Were this the case,

visualisations of death, poverty, and any other variable that elicits poor feelings would require its own field of visualisation.

The second group sees uncertainty as a high dimensional visualisation problem as the difficulty is in working out how to add uncertainty into already existing graphics ([moritz2017trust?](#); Griethe and Schumann 2006). If we view uncertainty visualisation as a high dimension problem we include uncertainty as we would any other variable, and allow for the signal to be interpreted independent of the variance. This prevents uncertainty and signal being read together as a “single integrated uncertain value” (Kinkeldey, MacEachren, and Schiewe 2014) and allows for uncertainty to be ignored (L. Padilla, Kay, and Hullman 2022). Additionally, even when reading a map that has a more complicated colour palette than a choropleth map (such as a bivariate map) participants still read the map according to the same principles of the choropleth map (Ndlovu, Shrestha, and Harrison 2023). This means that even when uncertainty is technically included in the graphic, the take away can still be invalid if the map is read incorrectly. The signal-suppression needs to be communicated through the “gist” of the graphic, as that is primary purpose of a visualisation (Spiegelhalter 2017). The Figure 4 plot’s “gist” is “this data has a spatial trend and the estimates have a large variance”. It is clear the uncertainty and signal are being communicated separately rather than as a single uncertain value.

This highlights the key problem of viewing uncertainty visualisation as a simple high dimensional problem. While we are trying to include a new variable, uncertainty cannot be treated the same as any other variable. Typically we want visual channels to be separable, that is, the data represented in one visual channel does not interfere with the others, and most research in this area is for this goal (Smart and Szafrir 2019). Uncertainty visualisation, however, should endeavor for integrability, that is, the channels interfere with one another to allow the uncertainty to suppress the signal. While most aesthetics *are* read separately, colour hue and brightness seem to be integrable (Vanderplas, Cook, and Hofmann 2020) so even though they can be individually manipulated, they are processed by the brain as a single visual channel. Additionally color value has a more intuitive connection to uncertainty than hue (Maceachren et al. 2012), but it should be mapped such that lighter colours are more uncertain than darker colours. If we could utilise integrability effectively, then the two dimensional space defined by colour value and colour hue could be mentally “flattened” into a single dimension of “statistically valid signal”.

Figure 5 shows a bivariate colour map where uncertainty is mapped to colour value, and temperature is mapped to colour hue. It is clear the spatial trend is still visible in the high uncertainty case. This does not necessarily mean integrability will never be a useful tool for signal suppression, but without a strong understanding of how these visual channels collapse down into a single channel, it may not be a reliable option. A more viable option might be to warp the space uncertainty and signal are mapped to ourselves.

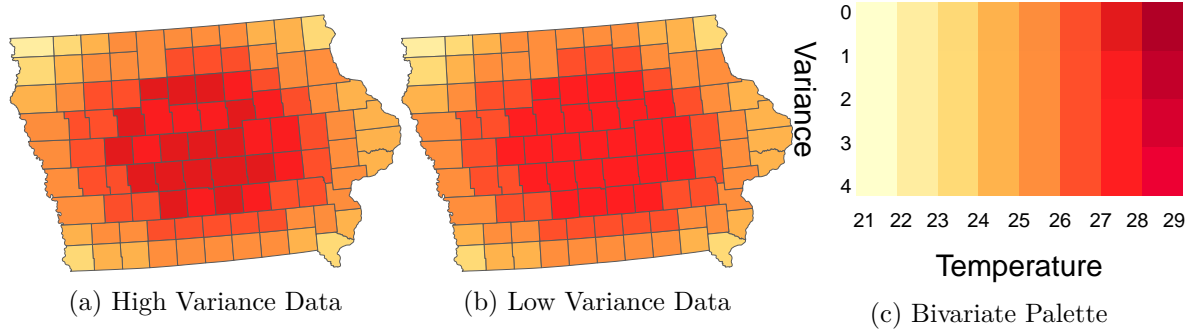


Figure 5: A bivariate map that depicts the counties of Iowa where each county is coloured according to its average daily temperature and the variance in temperature. This map is a variation on the previous bivariate map where instead of variance being mapped to colour saturation, it is mapped to colour value. Even though colour value is intergrable with colour hue, and colour value is naturally associated with uncertainty, the spatial trend is still visible in the map.

## 5 Visualising uncertainty and signal in a new space

Instead of hoping that uncertainty might collapse signal values into a single dimension, we can do some of that work ourselves.

by using a VSUP which collapses the colour space such that high uncertainty values cannot be extracted. It is unclear how useful VSUPs are at actually combining signal and noise and therefore suppressing plot level insights, as they have only been tested on simple value extraction tasks that require evaluating a single point (Correll, Moritz, and Heer 2018; Ndlovu, Shrestha, and Harrison 2023) rather than looking for spatial relationships (which is arguably what maps are for). Following along with this trend, the next way we might consider visualising uncertainty is to combine uncertainty and signal at the earlier stage so the “suppressed signal” is represented by a single variable. This statistic can then be expressed in a one dimensional colour space, which is a method adopted by the Bayesian surprise metric map (Ndlovu, Shrestha, and Harrison 2023) and the exceedance probability map [Lucchesi2017].

This problem has been noticed by others in the field, that typically use this method (specifically in the spatial uncertainty context) and a desire for representations that integrate uncertainty and signal is one of the reasons for the invention of the value-suppressing uncertainty pallet (Correll, Moritz, and Heer 2018).

Value-suppressing uncertainty pallets (VSUP) were developed as a method that would allow the signal and the noise to be interpreted together such that insights gained by the viewers of a plot are appropriately *suppressed* by the uncertainty. Hence the name of the pallet. depicted this map colouring approach and several other extensions on the typical choropleth map that

differ in where in the visualisation process they combine the noise and signal information into a single concept of “valid signal”.

### **5.0.1 Value Suppressing Uncertainty Palettes**

### **5.0.2 There is no such thing as a test for everything**

As we move through these methods, it seems that the validity of any overarching insight becomes more visible at the cost of our ability to extract particular values of signal or noise. Therefore, given that the primary goal of visualisation *is* insights (North 2006), visualisation authors should err on the side of representing suppressed signal as a single variable, rather than visualising uncertainty separately using two different channels.

## **6 Implicitly Combining Uncertainty and Signal**

### **6.1 Pixel maps**

### **6.2 Show me the data**

## 7 Evaluating uncertainty visualisations

## 8 Current methods

## 9 Testing signal suppression

### 9.1 Current methods

#### 9.1.1 Secondary effects

- trust, confidence, etc

#### 9.1.2 Direct questions

Most studies that assess the usability of uncertainty visualisations do not contribute to this aspect since they test the retrieval of data and uncertainty separately, but from the perspective that there is nothing special about uncertainty. Traditionally, studies in this field focus on the ability to read both the map content and its uncertainty at the same time. This may be the mandatory criterion for a successful use of uncertainty, but the question that remains is whether this is sufficient to ensure that a user does not only have two separate values in mind but an integrated uncertain data value. (Kinkeldey, MacEachren, and Schiewe 2014)

Hullman et al. (2019) found that the majority of papers evaluate visualisations on performance (approximately 65% of the papers they surveyed).

By far the most common metric used is accuracy, which is used by approximately 36% of evaluation studies (Hullman et al. 2019).

The final method used by authors is to just explicitly ask about uncertainty and signal information separately. Sanyal et al. (2009) mapped uncertainty to dots and signal to a 3D surface and asked participants to identify areas of high and low signal and high and low uncertainty. Participants were not asked to combine that information in any way, and the signal and the noise were treated as separate variables. Correll and Gleicher (2014) asked participants to separately extract the mean and variance from four uncertainty visualisations. These methods explicitly view the uncertainty and signal as two separate variables that should be extracted from a plot, and not two variables that should be interpreted together. Even viewing these questions as a routine check to make sure the signal information isn't impacted by the uncertainty is counter intuitive, because the whole point *of* the uncertainty is to impact the signal information.

- definition of uncertainty



There are many secondary benefits that come with this improved transparency, such as better decisions, more trust in the results and more confidence in the authors. These secondary benefits are, however, *not* the immediate goal of uncertainty. The following sections will discuss the issues and limitations in measuring uncertainty through these secondary metrics and provide suggestions as to how future studies should consider measuring uncertainty.

Trust is a by product of displaying uncertainty rather than the goal of it, and viewing the relationship in the converse direction can lead to misguided research. Considering trust, and not transparency, as the metric of importance in uncertainty communication can lead to a questionable subtext that argues against transparency, something that has been noticed by several other authors [Spiegelhalter (2017); O'Neill2018]. Hullman (2020) found that author simultaneously argued that failing to visualise uncertainty was akin to fraud, but also many avoided uncertainty visualisation because they didn't want their work to come across as "un-trustworthy". These authors are optimising *trust* rather than *transparency*, which means they opt to leave out uncertainty information when it does exactly what it is supposed to, decrease certainty in conclusions.

Science communication should be primarily concerned with accuracy. Setting trust and risk-aversion as the variables of interest implicitly encourages statisticians to set trust and risk-aversion as the primary goals of communication. The issue of trust being divorced from trustworthiness has been commented on by other authors (O'Neill 2018), however the issue still persists in the uncertainty visualisation literature. Zhao et al. (2023) displayed a several variations of a visualisation of a model prediction and its uncertainty and took participants using the model prediction as a sign of trust. They reported that visualising uncertainty information caused participants to trust the model in the low variance case, but the results in the high variance case were inconclusive. The discussion made it clear the authors thought the uncertainty information should make the visualisation more trustworthy, but conflating trust and the use of a prediction implied uncertainty information should somehow influence participants to use their own prediction, even though a prediction being uncertainty does not necessarily mean it is incorrect. Despite this, the authors seemed to assume that the uncertainty information *should* have an influence on that, showing they had not deeply considered *how* uncertainty information should influence the choices of the participants. (*Cite Gap 18: examples of studies where authors measure trust*)

A similar measure to trust is using "confidence" in an extracted value or a decision. Interestingly, "confidence" is also used to try and capture the clarity of a message in a normal visualisation. Confidence cannot simultaneously be a measure of clarity of visualisation *and* a way to capture the uncertainty expressed in a visualisation.

## 10 Bibliography

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## 12 MAPS

## 13 What is an uncertainty visualisation?

Kinkeldey, MacEachren, and Schiewe (2014) categorised uncertainty according to five criteria depicted in fig-tax which considers if a visualisation is implicit or explicit, intrinsic or extrinsic, visually integrable or seperable, coincident or adjacent, and static or dynamic. A similar version of this taxonomy was presented by L. Padilla, Kay, and Hullman (2022) who commented that visualisation can be organised into two categories, “graphical annotations of distributional properties” and “visual encodings of uncertainty” which seems to functionally align with the intrinsic/extrinsic distinction by Kinkeldey, MacEachren, and Schiewe (2014). Griethe and Schumann (2006) organised uncertainty visualisations into two cases (1) a hypothesis test was preformed to confirm the validity of the visualisation and (2) the visualisation has uncertainty depicted. Kristin Potter, Rosen, and Johnson (2012) organised several existing uncertainty visualisations into groups based on the dimensionality of the data (1D, 2D, 3D, and No Dimension) and the dimensionality of the uncertainty (Scalar, Vector, Tensor). However, because the term “PDF”, function that is used to describe a random variable, is used to describe both the data and the uncertainty for all dimensions. Grewal, Goodwin, and Dwyer (2021) created a taxonomy that mapped uncertainty visualisations to some point in a 2D space defined by the “domain expertise” and “continuum of discreteness” (that scaled from “point estimate” to “continuous distribution”).

The authors of these taxonomies did not intend for them to be complete descriptions of uncertainty visualisations, however they do paint a picture of the what authors consider to be important. There are common themes in the taxonomies that ensure we differentiate between a sample and a mass, consider if uncertainty should be depicted with the estimate or as a second variable, identify the parallel of hypothesis testing, and consider the dimensionality, sample size and precision depicted by the visualisation. These taxonomies may highlight perceived important differences, but they do not help us understand what *is* or *is not* an uncertainty visualisation. For that we need to understand *why* uncertainty visualisation exists as a sub-field at all.

### 13.0.1 What is uncertainty?

The ramifications of this is seen throughout the literature, as a survey of visualisation authors cited “not knowing how to calculate uncertainty” as one of the primary reasons they did not include it in visualisations (Hullman 2020). Some works (Hullman et al. 2018; Maceachren et al. 2012; Thomson et al. 2005) get around this definition issue by focusing narrowly on specific terms defined mathematically, such as probability, variance, error, or precision. Others (Griethe and Schumann 2006; Pang, Wittenbrink, and Lodha 1997; Pham, Streit, and Brown 2009; Boukhelifa et al. 2017) include broader loosely related elements, such as missing values, but ignore these concepts when translating that uncertainty to a visualisation. Existing mathematical definition of uncertainty (or related concepts) have been unable to unify this range of diverse concepts. For example, Thomson et al. (2005) suggests a mathematical formula for *examples* of uncertainty, and information theory tries to quantify uncertainty using the idea of entropy, but the disconnect between the broad concept of uncertainty and what we can reliably quantify remains a problem.

Some authors prefer to define uncertainty in qualitative terms, often through the use of taxonomies. In these cases, uncertainty is split using an endless stream of ever changing boundaries, such as whether the uncertainty is due to true randomness or a lack of knowledge (Spiegelhalter 2017; Hullman 2016; Walker et al. 2003), if the uncertainty is in the attribute, spatial elements, or temporal element of the data (Kinkeldey, MacEachren, and Schiewe 2014), whether the uncertainty is scientific (e.g. error) or human (e.g. disagreement among parties) (Benjamin and Budescu 2018), if the uncertainty is random or systematic (Sanyal et al. 2009), statistical or bounded (Gschwandtner et al. 2016; Olston and Mackinlay 2002), recorded as accuracy or precision (Griethe and Schumann 2006; Benjamin and Budescu 2018), which stage of the data analysis pipeline the uncertainty comes from (Walker et al. 2003), how quantifiable the uncertainty is (Spiegelhalter 2017; Walker et al. 2003), etc. In their own way, each of these approaches show an aspect of uncertainty that an author felt was important to differentiate.

What is interesting about all these views of uncertainty, is that they all imply that it is a latent feature of our data. That is, it is something that can be revealed through exploration, and not something that needs to be explicitly calculated. The constant stream of new definitions that are unable to capture the true essence of uncertainty might be a result of this false assumption that underpins every definition. Uncertainty cannot be defined without a signal because uncertainty does not exist without a signal, is a by-product of inference.

#### 13.0.1.1 Uncertainty as a by-product of inference

It is easy to see uncertainty's relationship to inference when we consider what might *not* be considered uncertain rather than just trying to think about what *is*.

Descriptive statistics simply describe our sample as it is and summarize large data down into an easy to swallow format. Descriptive statistics are not seen as the primary goal of

modern statistics, however, this was not always the case. Around the 19th century in England, *positivism* was the popular philosophical approach to science (positivists included famous statisticians such as Francis Galton and Karl Pearson) and practitioners of the approach believed statistics ended with descriptive statistics as science must be based on actual experience and observations, therefore anything that refers to the unobservable (such as new observations or population statistics) is not true science (Otsuka 2023). In order to make statements about population statistics, future values, or new observations we need to perform inference, which requires the assumption of the “uniformity of nature” (i.e. that unobserved phenomena should be similar to observed phenomena) (Otsuka 2023). This subtle shift, from descriptive statistics to inferential statistics was shunned during the positivism era *due to the fact it introduced the unknowable*, or in other words, uncertainty.

This approach to uncertainty is embedded in the idea that descriptive statistics do not have uncertainty, which some readers may disagree with. Specifically, because it means uncertainty is *not* a latent attribute of data, but rather an attribute of a specific hypothesis or estimate. Deniers of this fact follow a consistent logical path and it is easy to identify the common mistake. We know that variance and probability are typically considered types of “uncertainty” *and* descriptive statistics can have variance and probabilities *therefore* descriptive statistics must have uncertainty. The flaw in this logic comes from the first step, assuming that the tools with which we measure uncertainty *are* uncertainty in of themselves. This confusion is common and there are many papers that spend a great deal of time clarifying the difference. Begg, Welsh, and Bratvold (2014) highlight that uncertainty is related to not knowing a specific value, while variability refers to the range of values a quantity can take at different locations, times or instances. Spiegelhalter (2017) made sure to comment on the difference between precise random events (such as the probability associated with a coin flip), and uncertainty (such as the estimated probability associated with a coin that might be biased). The variance of a sample variance can be calculated and know, therefore it is not uncertain but rather it a precise description of dispersion. If we were to discuss drawing a new observation, or estimating the true mean of a population *then* the variance would become relevant in our discussions of uncertainty.

Several authors have connected the issues around defining uncertainty to inference, however it is often discussed as a *task* or *goal* dependence. Multiple authors have commented on the need to consider quantifying and expressing uncertainty at every stage of a project as the “goal” shapes every step of the analysis (Kinkeldey, MacEachren, and Schiewe 2014; Hullman 2016; Refsgaard et al. 2007). Otsuka (2023) suggested that the process of observing data to perform statistics is largely dependent on our goals, because the process of boiling real world entities down into probabilistic objects (or “probabilistic kind” as he puts it) depends on the relationship we seek to identify with our data. Meng (2014) commented what is kept as data and what is tossed away is determined by the motivation of an analysis and what was previously noise can be shown to become signal depending on the the question we seek to answer. Kale, Kay, and Hullman (2019) discussed how the choices we make in our analysis impact our outcomes and introduce uncertainty. Carlin and Moreno-Betancur (2023) mentions that each research question can be can be categorised as descriptive, predictive, or causal, each

of which has its own appropriate statistical methods and motivation agnostic model selection leads to statistical analysis that is devoid of meaning. Wallsten et al. (1997) argue that the best method for evaluating or combining subjective probabilities depends on the uncertainty the decision maker wants to represent and why it matters. Fischhoff and Davis (2014) looks at uncertainty visualisation for decision making decides that we should have different ways of communicating uncertainty based off what the user is supposed to do with it. The importance of inference when discussing uncertainty is never directly acknowledge, but it is always present. It is clear that the relationship between uncertainty and inference is noticed at every stage in an analysis, however combining these uncertainties into a single “uncertainty” value is near impossible (Spiegelhalter 2017).

With this understanding it becomes clear to see why uncertainty is tied to an endless string of examples in the data analysis pipeline. Uncertainty examples include imputed data, model selection, inherent randomness, biased sampling, etc, not because these things *are* uncertainty, but because they *create* uncertainty when we perform inference. Whether or not these elements are relevant is highly dependent on what statistic you are trying to draw inference on, and by extension, the purpose of your visualisation.

### 13.1 What is an uncertainty visualisation?

The concept of uncertainty as a by-product of inference, not a latent feature of data, extends naturally to visualisation. There are two primary reasons for making a visualisation, to perform exploratory data analysis (EDA) or communication. Communication involves identifying a signal we want to communicate and designing the visualisation that best conveys that, while EDA involves creating a versatile visualisation without an explicit purpose and using it to extract several signals.

Since EDA is the visual parallel to descriptive statistics, it is performed without an explicit hypothesis which means there *is* no uncertainty in the visualisation. Similarly to our issues with descriptive statistics, this is not well understood by the uncertainty visualisation community. Some authors simply confuse variance for uncertainty. For example K. Potter et al. (2010) aimed to create a summary plot that “concisely presented data with uncertainty information” to create an exploratory visualisation tool that visualised uncertainty. Other authors recognise inference will occur (in some shape or form) and believe uncertainty *should* be visualised but do not recognise *how* uncertainty would be visualised. Hullman and Gelman (2021) argued that there is no such thing as a “model-free” visualisation, therefore visualisation require robust visualisations of uncertainty as we are always performing inference. Griethe and Schumann (2006) commented that “if visualization is used as a means to explore a data volume or to communicate its contents the uncertainty has to be included”. While we agree people cannot prevent themselves from performing inference, that does not mean it is possible for uncertainty to be included in an EDA visualisation. A versatile visualisation such as a scatter plot allows for a viewer to consider several hypothesis at once, each of which will be a different inferential

statistic with a different distribution that depicts its uncertainty. It is likely impossible to suppress all possible signals at once.

## 14 How do we evaluate uncertainty visualisations?

If asking direct questions about uncertainty causes us to treat it as a signal, how do we evaluate uncertainty as *noise*? When we ask the viewer of a plot to look at data and extract a value, we are asking them to perform inference on that value. There will be noise associated with that answer and that is uncertainty. If we ask direct question about some uncertainty metric, we have turned the uncertainty into signal because that is what the participants are drawing inference on.

### 14.1 Current attempts to measure uncertainty

There is also a swath of studies that are aware a question that boils down to a value extraction experiment, or a question that should be answered by literally ignoring uncertainty information is not what we want when we consider uncertainty visualisations. These papers often try to ask a question that should utilise both the uncertainty and signal in the response, however this is rarely what actually occurs. This method typically results in in cryptic or confusing questions that create a large amount of noise on the interpretation side of the analysis (Hullman 2016).

Some authors opt for asking slightly vague questions that imply a use of uncertainty, but compare it to a ground truth that is very specific. Ibrek and Morgan (1987) asked participants for the “best estimate” which was evaluated in accuracy by comparing it to the mean, however the “best estimate” depends on the loss function we are using, and a loss function of minimised error was not implied by the question. Hofmann et al. (2012) showed two distributions in 20 different visualisations (a line-up protocol) using a jittered sample, a density plot, a histogram, and a box plot and asked participants. Participants were asked to report in which of the plots was “the blue group furthest to the right” The experiment set up is shown in fig-right. The participants answers were then compared to a ground truth where the correct plot had a blue distribution with a right shifted mean. By comparing the results to a ground truth statistic and marking participants as “wrong” or “right”, the error from the participants that had an alternative interpretation to the concept of “furthest right” was conflated with the error from a the visualisation choice. These papers make it unclear if the participants got the answers wrong because they misunderstood the question or because of something related to the plot. Therefore, this method leads to inconclusive results about the plot design, and is not advised.

Another method used by authors is to ask a deterministic question about a random event. L. M. Padilla, Ruginski, and Creem-Regehr (2017) provided participants with a visualisation of the cone of uncertainty and asked then to “decide which oil rig will receive more damage based on the depicted forecast of the hurricane path”. The cone of uncertainty provides a

60% confidence interval for the location of the eye of a hurricane, which allows us to know the area where the eye of the storm will go, it does not given any information about the intensity of a storm, the size of a storm, or even if a location will be hit. This inclusion of determinism seems to cause the authors to stumble themselves, as they are not consistent with their assumptions. In their first experiment L. M. Padilla, Ruginski, and Creem-Regehr (2017) indicated the correct answer was to assume that the storm was equally intense no matter how far from the centre of the distribution an oil rig was, however answering their third experiment correctly hinged on assuming the intensity of the storm at a particular point (which in this experiment they phrased as damage) *does* change in intensity as you move away from the centre of the distribution. Given these conflicting assumptions, it is unclear how the participants were supposed to adjust the probabilistic path information to answer a deterministic question about which oil rig would receive the most damage. Other authors have commented on the complexity of communicating hurricane risk because the path, storm surge and wind speed are all important and cannot be ignored (Spiegelhalter 2017). The flip side of this is asking participants for a deterministic answer to a probabilistic question. Correll and Gleicher (2014) asked participants “how likely is candidate B to win the election?” when the two distributions indicated voter preference. Participants were not able to answer the question about likelihood in term of probability, but were instead given seven options from 1=Outcome will be most in favour of A to 7=Outcome will be most in favour of B. The ground truth statistic for this question was a scalar multiple of Cohen’s d, indicating participants were supposed to incorporate uncertainty information using a very specific formula that was likely unknown to them but assumed to be used implicitly.

These examples are a bit complete mishmash of methods, however they point to a larger issue that goes beyond decision making, trust and confidence experiments. Authors *have no idea* how to evaluate the effects of uncertainty in an uncertainty visualisation.

## 14.2 How to test uncertainty as noise

So, the current methods of measuring or understanding the role of uncertainty in a visualisation is questionable at best, however this is not because visualisation authors are missing the mark, but rather uncertainty is *particularly* difficult to express in a visualisation. In simple estimates or verbal communication, the signal is often easy to identify because it is what we are explicitly saying. Unlike statistical models, visualisations are used in both data exploration and communication. This means what exactly is a *signal* in any particular visualisation is hard to identify, since we often let the visualisation *tell us* what the signal is. Additionally, you cannot add noise to *every single possible* signal one might take from a visualisation. Two people looking at the same visualisation might, just by chance, develop two entirely different insights and draw inference on two completely different statistics. These unique and fascinating challenges that are faced by uncertainty visualisation have been completely untouched by the literature. This section will cover some interesting research in uncertainty visualisation and suggestions for better ways to measure uncertainty.

### 14.2.1 Qualitative Studies

Alternatively visualisation research could shift away from the accuracy concept all together ask questions that allow for open ended responses. This method can enlighten authors as to *how* the uncertainty information was used by the participants. Hofmann et al. (2012) tried to capture this by asking participants why they considered a particular plot to be more “right shifted”, however this qualitative assessment does not seem to have made it into the final paper. Daradkeh (2015) presented participants with ten investment alternatives and asked participants “from among available alternatives, which alternative do you prefer the most”, and were asked to think aloud and consider the uncertainty in their decision making. The experimenters goal was to observe and organise the methods people use when making decisions in the face of uncertainty. This study was an excellent example in a useful experimental design. They highlighted the specific aspects of uncertainty that participants typically considered, such as the range of outcomes that are above/below a certain threshold, minimum and maximum values, the risk of a loss, etc, and mapped where in the decision making process participants made these considerations. Data visualisation is commonly utilised as a tool in data exploration, so it is not uncommon for a data analyst to make a plot with only a vague goal and pull out a large number of adjacent observations. This experimental framework could replicate this process.

### 14.2.2 Just noticeable signal

It could be argued that a well done uncertainty visualisations should have an imperceptible signal unless the signal would be identified with a hypothesis test, almost like a reverse line up protocol, but this idea also has some issues that should be considered. The reject or do not reject concepts in hypothesis testing do not offer a complete image of uncertainty, and exploration of uncertainty visualisation largely stems from a desire to move away from this binary framework.

Additionally, setting up an uncertainty visualisation where the participants are expected to notice the signal once the data behind the visualisation passes a hypothesis test implies the signal *is* noticeable to a human at that level. (Patrick2023?) compared people ability to recognise patterns in a residual plot to typical statistical tests and found human viewers looking at a plot were less sensitive than the typical residual tests. These experiments utilised the line-up protocol which has been suggested as a method to check if perceived patterns are real or merely the result of chance (Buja et al. 2009; Wickham et al. 2010; Chowdhury et al., n.d.). This concept bears similarity to the goal of uncertainty visualisation, but it is not quite the same. fig-hypvs shows the conceptual difference between the line-up protocol and uncertainty visualisation.



## 14.3 Other elements of uncertainty visualisations

- Things that are true for both normal visualisation and uncertainty, but of particular interest for uncertainty

### 14.3.1 Heuristics

Additionally, these heuristics and biases can change depending on the larger scope of the graphic and the population we are communicating with (Spiegelhalter 2017; Kinkeldey, MacEachren, and Schiewe 2014).

Heuristic checks are useful because they look at unknown pitfalls that might exist in interpretation of current plots. Since the hypothesis for these experiments are usually quite specific, e.g. “do people perceive a an outcome that is within the bar as more likely than one outside it, even if both outcomes are the same distance from the mean?”. This means they are less likely to fall into the trap of trying to answer questions that are *far* too broad to be answered with a single experiment (e.g. “is a scatter plot better at showing uncertainty than a box plot”). This work also provides useful insights for experiments by highlights pitfalls participants might fall into when they review the results of evaluation experiments (Hullman 2016). Newman and Scholl (2012) found that participants were more likely to view points within the bar as more likely than points outside of the bar in bar charts with error bars. Similar effects have been identified in other types of uncertainty displayed. L. M. Padilla, Ruginski, and Creem-Regehr (2017) found that points that were on an outcome of an ensemble display were perceived as more likely than points not on an outcome, even when the point that was not on a specific outcome of the ensemble was closer to the mean of the uncertainty distribution. The sine illusion can cause the confidence interval of a smoothed sine curve to seem wider at the peaks than the troughs, causing us to underestimate uncertainty associated with changing values (Vanderplas and Hofmann 2015).

## 14.4

In a similar vein, experiments that verify smaller aspects of plot design might be more useful to the field in the long run because it helps contribute to a larger working theory of “how do we see visualisations”. Many visualisation experiments try to compare two plots with several differences, but do not seem to be interested in the mechanisms by which we extract information from visualisations. Small perceptual tasks that seek to answer small but highly relevant questions (for example, if colour hue and colour value can be perceived as a single signal suppressed variable) would be useful to the field.

## 15 Future work

This paper has identified gaps in the uncertainty visualisation literature that could be filled to progress the field.

*Each new development should be accompanied by a mathematical definition of the uncertainty being addressed.* Ideally, a mathematical definition of uncertainty that allows us to combine these components would be developed, but in the absence of that, authors should be more specific about what aspect of “uncertainty” they are covering with their visualisation.

*The concept of uncertainty should be formalised within the grammar of graphics.* This formalisation would allow uncertainty visualisation authors to have a clear understanding of what is or is not an uncertainty visualisation. Additionally placing uncertainty visualisation in the framework that is used to understand existing information visualisation research would help authors understand when existing methods can be used to explain their results. Incorporating uncertainty into the grammar of graphics will also give a more precise concept of the information contained within a plot. Other fields of science employ marginal changes when designing experiments to ensure it is well understood *what* aspect of their experiment is contributing to their results, and a better sense of what “marginal” is in the case of uncertainty visualisation would greatly help the field. (*XXX Is data pipeline connected with the grammar of graphics? Should this be a recommendation?*)

*Experimental practices on uncertainty visualisation need to be standardised.* If we are going to consider uncertainty as noise, not signal, there needs to be a way to identify this signal suppression in an experimental design. As the literature currently exists, there is no way to combine papers to get a meaningful sense of how uncertainty information is understood by a viewer. There is also the possibility that uncertainty visualisation evaluations will need to swap to a qualitative methodology where participants are allowed to freely comment on what they notice in graphics until we establish how the existence of noise can be observed.

If an uncertainty visualisation researcher would prefer to perform experiments rather than formalise methods, there are options there too. It would be interesting to know if any perceptual tasks that can be mapped to two different visual tasks condense into a single dimension when looking for overarching signal in a plot. Alternatively, the task dependency many authors in uncertainty visualisation mention would be a useful direction to consider. It is clear that the number of potential tasks that can be performed on a visualisation increases with the number of observations. A single observation is limited to value extraction, two observations can be compared, multiple observations allow for shapes or global statistics to be extracted. The interaction between sample size and task is of particular interest to the uncertainty visualisation community, as uncertainty can be expressed through multiple observations using a sample, or through a single value using an error. Of course, this is limited by the fact that there also isn’t a definition for what is a “task” and given the mess created by the lack of formalisation in uncertainty visualisation, it may be wise to formalise that concept before performing these experiments. Amar, Eagan, and Stasko (2005) suggested a taxonomy for

information visualisation based on the types of tasks we use visualisations for and suggest 10 “analytical primitives” that we can then map to visualisations, which could be a good starting point. Regardless, these are directions of research would be fruitful to the uncertainty visualisation community even if it appears on the surface to be research that is only beneficial to the “normal” visualisation community. (XXX Not sure what this paragraph is recommending?)

- Amar, Robert, James Eagan, and John Stasko. 2005. “Low-level components of analytic activity in information visualization.” *Proceedings - IEEE Symposium on Information Visualization, INFO VIS*, 111–17. <https://doi.org/10.1109/INFVIS.2005.1532136>.
- Anscombe, F. J. 1973. “Graphs in Statistical Analysis.” *The American Statistician* 27 (1): 17–21. <https://www.tandfonline.com/doi/abs/10.1080/00031305.1973.10478966>.
- Begg, Steve H., Matthew B. Welsh, and Reldar B. Bratvold. 2014. “Uncertainty vs. variability: What’s the difference and why is it important?” *SPE Hydrocarbon Economics and Evaluation Symposium*, no. May: 273–93. <https://doi.org/10.2118/169850-ms>.
- Benjamin, Daniel M., and David V. Budescu. 2018. “The role of type and source of uncertainty on the processing of climate models projections.” *Frontiers in Psychology* 9 (MAR): 1–17. <https://doi.org/10.3389/fpsyg.2018.00403>.
- Blenkinsop, Steve, Pete Fisher, Lucy Bastin, and Jo Wood. 2000. “Evaluating the perception of uncertainty in alternative visualization strategies.” *Cartographica* 37 (1): 1–13. <https://doi.org/10.3138/3645-4v22-0m23-3t52>.
- Boone, Alexander P., Peri Gunalp, and Mary Hegarty. 2018. “Explicit versus actionable knowledge: The influence of explaining graphical conventions on interpretation of hurricane forecast visualizations.” *Journal of Experimental Psychology: Applied* 24 (3): 275–95. <https://doi.org/10.1037/xap0000166>.
- Boukhelifa, Nadia, Anastasia Bezerianos, Tobias Isenberg, and Jean Daniel Fekete. 2012. “Evaluating sketchiness as a visual variable for the depiction of qualitative uncertainty.” *IEEE Transactions on Visualization and Computer Graphics* 18 (12): 2769–78. <https://doi.org/10.1109/TVCG.2012.220>.
- Boukhelifa, Nadia, Marc Emmanuel Perrin, Samuel Huron, and James Eagan. 2017. “How data workers cope with uncertainty: A task characterisation study.” *Conference on Human Factors in Computing Systems - Proceedings 2017-May* (May): 3645–56. <https://doi.org/10.1145/3025453.3025738>.
- Buja, Andreas, Dianne Cook, Heike Hofmann, Michael Lawrence, Eun Kyung Lee, Deborah F. Swayne, and Hadley Wickham. 2009. “Statistical inference for exploratory data analysis and model diagnostics.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 367 (1906): 4361–83. <https://doi.org/10.1098/rsta.2009.0120>.
- Carlin, John B., and Margarita Moreno-Betancur. 2023. “On the uses and abuses of regression models: a call for reform of statistical practice and teaching.” <http://arxiv.org/abs/2309.06668>.
- Carr, Daniel B., Anthony R. Olsen, and Denis White. 1992. “Hexagon Mosaic Maps for Display of Univariate and Bivariate Geographical Data.” *Cartography and Geographic Information Systems* 19 (4): 228–36. <https://doi.org/10.1559/152304092783721231>.

- Cheong, Lisa, Susanne Bleisch, Allison Kealy, Kevin Tolhurst, Tom Wilkening, and Matt Duckham. 2016. "Evaluating the impact of visualization of wildfire hazard upon decision-making under uncertainty." *International Journal of Geographical Information Science* 30 (7): 1377–1404. <https://doi.org/10.1080/13658816.2015.1131829>.
- Chowdhury, Niladri Roy, Dianne Cook, Heike Hofmann, Mahbubul Majumder, Eun-Kyung Lee, and Amy L Toth. n.d. "Using Visual Statistical Inference to Better Understand Random Class Separations in High Dimension, Low Sample Size Data."
- Cleveland, William S., and Robert McGill. 1984. "Graphical perception: Theory, experimentation, and application to the development of graphical methods." *Journal of the American Statistical Association* 79 (387): 531–54. <https://doi.org/10.1080/01621459.1984.10478080>.
- Correll, Michael, and Michael Gleicher. 2014. "Error bars considered harmful: Exploring alternate encodings for mean and error." *IEEE Transactions on Visualization and Computer Graphics* 20 (12): 2142–51. <https://doi.org/10.1109/TVCG.2014.2346298>.
- Correll, Michael, Dominik Moritz, and Jeffrey Heer. 2018. "Value-suppressing uncertainty Palettes." *Conference on Human Factors in Computing Systems - Proceedings* 2018-April: 1–11. <https://doi.org/10.1145/3173574.3174216>.
- Daradkeh, Mohammad. 2015. "Exploring the use of an information visualization tool for decision support under uncertainty and risk." *ACM International Conference Proceeding Series* 24-26-Sept. <https://doi.org/10.1145/2832987.2833050>.
- Fischhoff, Baruch, and Alex L. Davis. 2014. "Communicating scientific uncertainty." *Proceedings of the National Academy of Sciences of the United States of America* 111: 13664–71. <https://doi.org/10.1073/pnas.1317504111>.
- Grewal, Yashvir, Sarah Goodwin, and Tim Dwyer. 2021. "Visualising Temporal Uncertainty: A Taxonomy and Call for Systematic Evaluation." *IEEE Pacific Visualization Symposium* 2021-April (April): 41–45. <https://doi.org/10.1109/PACIFICVIS52677.2021.00013>.
- Griethe, Henning, and Heidrun Schumann. 2006. "The Visualization of Uncertain Data: Methods and Problems." *Proceedings of SimVis '06* vi (August): 143–56. <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+Visualization+of+Uncertain+Data:+Methods+and+Problems#0>.
- Gschwandtnei, Theresia, Markus Bögl, Paolo Federico, and Silvia Miksch. 2016. "Visual Encodings of Temporal Uncertainty: A Comparative User Study." *IEEE Transactions on Visualization and Computer Graphics* 22 (1): 539–48. <https://doi.org/10.1109/TVCG.2015.2467752>.
- Hofman, Jake M., Daniel G. Goldstein, and Jessica Hullman. 2020. "How Visualizing Inferential Uncertainty Can Mislead Readers about Treatment Effects in Scientific Results." *Conference on Human Factors in Computing Systems - Proceedings*. <https://doi.org/10.1145/3313831.3376454>.
- Hofmann, Heike, Lendie Follett, Mahbubul Majumder, and Dianne Cook. 2012. "Graphical Tests for Power Comparison of Competing Designs." <http://www.public.iastate.edu/>.
- Hullman, Jessica. 2016. "Why evaluating uncertainty visualization is error prone." *ACM International Conference Proceeding Series* 24-October: 143–51. <https://doi.org/10.1145/2993901.2993919>.
- . 2020. "Why Authors Don't Visualize Uncertainty." *IEEE Transactions on Visu-*

- alization and Computer Graphics 26 (1): 130–39. <https://doi.org/10.1109/TVCG.2019.2934287>.
- Hullman, Jessica, and Andrew Gelman. 2021. “Designing for Interactive Exploratory Data Analysis Requires Theories of Graphical Inference.” *Harvard Data Science Review*, 1–70. <https://doi.org/10.1162/99608f92.3ab8a587>.
- Hullman, Jessica, Matthew Kay, Yea Seul Kim, and Samana Shrestha. 2018. “Imagining Replications: Graphical Prediction Discrete Visualizations Improve Recall Estimation of Effect Uncertainty.” *IEEE Transactions on Visualization and Computer Graphics* 24 (1): 446–56. <https://doi.org/10.1109/TVCG.2017.2743898>.
- Hullman, Jessica, Xiaoli Qiao, Michael Correll, Alex Kale, and Matthew Kay. 2019. “In Pursuit of Error: A Survey of Uncertainty Visualization Evaluation.” *IEEE Transactions on Visualization and Computer Graphics* 25 (1): 903–13. <https://doi.org/10.1109/TVCG.2018.2864889>.
- Hullman, Jessica, Paul Resnick, and Eytan Adar. 2015. “Hypothetical outcome plots outperform error bars and violin plots for inferences about reliability of variable ordering.” *PLoS ONE* 10 (11). <https://doi.org/10.1371/journal.pone.0142444>.
- Ibrekk, Harald, and M. Granger Morgan. 1987. “Graphical Communication of Uncertain Quantities to Nontechnical People.” *Risk Analysis* 7 (4): 519–29. <https://doi.org/10.1111/j.1539-6924.1987.tb00488.x>.
- Kale, Alex, Matthew Kay, and Jessica Hullman. 2019. “Decision-making under uncertainty in research synthesis: Designing for the garden of forking paths.” *Conference on Human Factors in Computing Systems - Proceedings*. <https://doi.org/10.1145/3290605.3300432>.
- Kale, Alex, Francis Nguyen, Matthew Kay, and Jessica Hullman. 2018. “Hypothetical Outcome Plots Help Untrained Observers Judge Trends in Ambiguous Data.” *IEEE Transactions on Visualization and Computer Graphics* 25 (1): 892–902.
- Kinkeldey, Christoph, Alan M. MacEachren, and Jochen Schiewe. 2014. “How to assess visual communication of uncertainty? a systematic review of geospatial uncertainty visualisation user studies.” *Cartographic Journal* 51 (4): 372–86. <https://doi.org/10.1179/1743277414Y.0000000099>.
- Kuhnert, P. M., D. E. Pagendam, R. Bartley, D. W. Gladish, S. E. Lewis, and Z. T. Bainbridge. 2018. “Making management decisions in the face of uncertainty: A case study using the Burdekin catchment in the Great Barrier Reef.” *Marine and Freshwater Research* 69 (8): 1187–1200. <https://doi.org/10.1071/MF17237>.
- Locke, Steph, and Lucy D’Agostino McGowan. 2018. *datasauRus: Datasets from the Datasaurus Dozen*. <https://CRAN.R-project.org/package=datasauRus>.
- Lucchesi, Lydia, Petra Kuhnert, and Christopher Wikle. 2021. “Vizumap: an R package for visualising uncertainty in spatial data.” *Journal of Open Source Software* 6 (59): 2409. <https://doi.org/10.21105/joss.02409>.
- MacEachren, Alan M. 1992. “cartographic perspectives Visualizing Uncertain Information.” *Cartographic Perspectives*, no. 13: 10–19.
- Maceachren, Alan M., Robert E. Roth, James O’Brien, Bonan Li, Derek Swingley, and Mark Gahegan. 2012. “Visual semiotics & uncertainty visualization: An empirical study.” *IEEE Transactions on Visualization and Computer Graphics* 18 (12): 2496–2505. <https://doi.org/10.1109/TVCG.2012.2205898>.

- [org/10.1109/TVCG.2012.279](https://doi.org/10.1109/TVCG.2012.279).
- Manski, Charles F. 2020. “The lure of incredible certitude.” *Economics and Philosophy* 36 (2): 216–45. <https://doi.org/10.1017/S0266267119000105>.
- Meng, Xiao Li. 2014. “A trio of inference problems that could win you a nobel prize in statistics (if you help fund it).” *Past, Present, and Future of Statistical Science*, 537–62. <https://doi.org/10.1201/b16720-52>.
- Ndlovu, Akim, Hilson Shrestha, and Lane T Harrison. 2023. “Taken by Surprise? Evaluating How Bayesian Surprise & Suppression Influences Peoples’ Takeaways in Map Visualizations.” In *2023 IEEE Visualization and Visual Analytics (VIS)*, 136–40. IEEE.
- Newman, George E., and Brian J. Scholl. 2012. “Bar graphs depicting averages are perceptually misinterpreted: The within-the-bar bias.” *Psychonomic Bulletin and Review* 19 (4): 601–7. <https://doi.org/10.3758/s13423-012-0247-5>.
- North, Chris. 2006. “Toward measuring visualization insight.” *IEEE Computer Graphics and Applications* 26 (3): 6–9. <https://doi.org/10.1109/MCG.2006.70>.
- O’Neill, Onora. 2018. “Linking Trust to Trustworthiness.” *International Journal of Philosophical Studies* 26 (2): 293–300. <https://doi.org/10.1080/09672559.2018.1454637>.
- Olston, C., and J. D. Mackinlay. 2002. “Visualizing data with bounded uncertainty.” *Proceedings - IEEE Symposium on Information Visualization, INFO VIS 2002-Janua*: 37–40. <https://doi.org/10.1109/INFVIS.2002.1173145>.
- Otsuka, Jun. 2023. *Thinking About Statistics: The Philosophical Foundations*. 1st ed. New York: Routledge. <https://doi.org/10.4324/9781003319061>.
- Padilla, Lace M., Ian T. Ruginski, and Sarah H. Creem-Regehr. 2017. “Effects of ensemble and summary displays on interpretations of geospatial uncertainty data.” *Cognitive Research: Principles and Implications* 2 (1). <https://doi.org/10.1186/s41235-017-0076-1>.
- Padilla, Lace, Matthew Kay, and Jessica Hullman. 2022. “Computational Statistics in Data Science.” In, 405–26. John Wiley & Sons.
- Pang, Alex T., Craig M. Wittenbrink, and Suresh K. Lodha. 1997. “Approaches to uncertainty visualization.” *Visual Computer* 13 (8): 370–90. <https://doi.org/10.1007/s003710050111>.
- Pham, Binh, Alex Streit, and Ross Brown. 2009. “Visualization of information uncertainty: Progress and challenges.” In *Advanced Information and Knowledge Processing*, 36:19–48. Springer-Verlag London Ltd. [https://doi.org/10.1007/978-1-84800-269-2\\_2](https://doi.org/10.1007/978-1-84800-269-2_2).
- Potter, K., J. Kniss, R. Riesenfeld, and C. R. Johnson. 2010. “Visualizing summary statistics and uncertainty.” *Computer Graphics Forum* 29 (3): 823–32. <https://doi.org/10.1111/j.1467-8659.2009.01677.x>.
- Potter, Kristin, Paul Rosen, and Chris R. Johnson. 2012. “From quantification to visualization: A taxonomy of uncertainty visualization approaches.” *IFIP Advances in Information and Communication Technology* 377 AICT: 226–47. [https://doi.org/10.1007/978-3-642-32677-6\\_15](https://doi.org/10.1007/978-3-642-32677-6_15).
- Refsgaard, Jens Christian, Jeroen P. van der Sluijs, Anker Lajer Højberg, and Peter A. Vanrolleghem. 2007. “Uncertainty in the environmental modelling process - A framework and guidance.” *Environmental Modelling and Software* 22 (11): 1543–56. <https://doi.org/10.1016/j.envsoft.2007.02.004>.
- Sanyal, Jibonananda, Song Zhang, Gargi Bhattacharya, Phil Amburn, and Robert J. Moor-

- head. 2009. “A user study to compare four uncertainty visualization methods for 1D and 2D datasets.” *IEEE Transactions on Visualization and Computer Graphics* 15 (6): 1209–18. <https://doi.org/10.1109/TVCG.2009.114>.
- Smart, Stephen, and Danielle Albers Szafr. 2019. “Measuring the separability of shape, size, and color in scatterplots.” *Conference on Human Factors in Computing Systems - Proceedings*, 1–14. <https://doi.org/10.1145/3290605.3300899>.
- Spiegelhalter, David. 2017. “Risk and uncertainty communication.” *Annual Review of Statistics and Its Application* 4: 31–60. <https://doi.org/10.1146/annurev-statistics-010814-020148>.
- Thomson, Judi, Elizabeth Hetzler, Alan MacEachren, Mark Gahegan, and Misha Pavel. 2005. “A typology for visualizing uncertainty.” *Visualization and Data Analysis 2005* 5669 (March 2005): 146. <https://doi.org/10.1117/12.587254>.
- Vanderplas, Susan, Dianne Cook, and Heike Hofmann. 2020. “Annual Review of Statistics and Its Application Testing Statistical Charts: What Makes a Good Graph?” <https://doi.org/10.1146/annurev-statistics-031219-041252>.
- Vanderplas, Susan, and Heike Hofmann. 2015. “Signs of the Sine Illusion — Why We Need to Care Signs of the Sine Illusion — Why We Need to Care” 8600. <https://doi.org/10.1080/10618600.2014.951547>.
- Walker, W. E., P. Harremoes, J Rotmans, J. P. Van Der Sluijs, M. B. A. Van Asselt, P Janssen, and M. P. Kraye Von Krauss. 2003. “Defining Uncertainty.” *Integrated Assessment* 4 (1): 5–17. <https://www.narcis.nl/publication/RecordID/oai:tudelft.nl:uuid:fdc0105c-e601-402a-8f16-ca97e9963592>.
- Wallsten, Thomas S., David V. Budescu, Ido Erev, and Adele Diederich. 1997. “Evaluating and combining subjective probability estimates.” *Journal of Behavioral Decision Making* 10 (3): 243–68. [https://doi.org/10.1002/\(sici\)1099-0771\(199709\)10:3%3C243::aid-bdm268%3E3.0.co;2-m](https://doi.org/10.1002/(sici)1099-0771(199709)10:3%3C243::aid-bdm268%3E3.0.co;2-m).
- Wickham, Hadley, Dianne Cook, Heike Hofmann, and Andreas Buja. 2010. “Graphical inference for infovis.” *IEEE Transactions on Visualization and Computer Graphics* 16: 973–79. <https://doi.org/10.1109/TVCG.2010.161>.
- Wickham, Hadley, and Heike Hofmann. 2011. “Product plots.” *IEEE Transactions on Visualization and Computer Graphics* 17 (12): 2223–30. <https://doi.org/10.1109/TVCG.2011.227>.
- Wilkinson, Leland. 2005. *The Grammar of Graphics (Statistics and Computing)*. Berlin, Heidelberg: Springer-Verlag.
- Zhang, Sam, Patrick Ryan Heck, Michelle Meyer, Christopher F Chabris, Daniel G Goldstein, and Jake M Hofman. 2022. “An Illusion of Predictability in Scientific Results.”
- Zhao, Jieqiong, Yixuan Wang, Michelle V. Mancenido, Erin K. Chiou, and Ross Maciejewski. 2023. “Evaluating the Impact of Uncertainty Visualization on Model Reliance.” *IEEE Transactions on Visualization and Computer Graphics* PP (X): 1–15. <https://doi.org/10.1109/TVCG.2023.3251950>.