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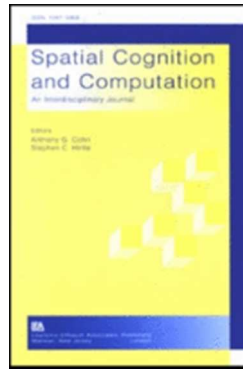
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**Introduction to the Special Issue on Visually-Supported
Spatial Reasoning with Uncertainty**

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Introduction

Uncertainty is ubiquitous in spatial data ([Couclelis, 2003](#); [Hope & Hunter, 2007](#)). With more data and sophisticated tools available for exploring and analyzing them, additional research is imperative to address and develop ways to advance the understanding of how humans reason and make decisions under spatial uncertainty. While research on uncertainty and decision-making have a long history across several disciplines, recent technological developments producing new open data sources compels researchers to rethink how to best address and understand uncertainty inherent in data and models. One such approach is to use visualization techniques proposed by the geographic visualization and information visualization communities. When decisions are made from visualized geospatial data without the uncertainty explicitly mentioned or depicted with the dataset, it can lead to an inaccurate or misleading understanding of spatial patterns and processes. [Hunter and Goodchild \(1993\)](#) state that without proper attention to uncertainty, outcomes can result in the “use of wrong data, in the wrong way, to arrive at the wrong decision” (p. 55). Thus, recent efforts have attempted to support the decision-maker through integration of uncertainty in data visualization. For a comprehensive overview of research in this area, see [Kinkeldey, MacEachren, Riveiro, and Schiewe \(2015\)](#).

In research, the large number of current uncertainty visualization techniques draw mostly upon existing cartographic methods using standard visual variables (e.g., [MacEachren et al., 2012](#)), however less research focuses on the impact this has on reasoning and decision-making ([Kinkeldey et al., 2015](#)). This is largely due to the lack of comprehensive and generalizable empirical studies across the entire domain of uncertainty visualization. Additionally, while progress has been made, results are scattered across different disciplines ([MacEachren et al., 2005](#)) and various contexts without enough communication and interdisciplinary work. This lack of comprehensive and generalizable empirical testing may partially be due to the conflicting and numerous definitions of uncertainty ([Aerts, Clarke, & Keuper, 2003](#); [Pang, Wittenbrink, & Lodha, 1997](#)). For instance, [Deitrick and Edsall \(2008\)](#) find that the term uncertainty is an issue across multiple disciplines often defined through numerous terms: data quality, accuracy,

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3 precision, error, vagueness, ambiguity, etc. This disagreement makes this topic both complex
4 and difficult to research, understand, and visualize.
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9 Beyond having mixed terminology among researchers focusing on uncertainty, [Aerts et al.](#)
10 [\(2003\)](#) point out that there is still only a small amount of literature and research addressing
11 perceptual and cognitive questions as well as the effectiveness of visualizing uncertainty among
12 various approaches. In many instances, we may be prematurely attempting to create
13 uncertainty visualizations that may not appropriately take users and their heuristics, biases,
14 experiences, and abilities into account. For example, researchers have identified that heuristics,
15 or experience-based approaches aiding in reasoning, play a key role for reasoning under
16 uncertainty ([e.g., Tversky & Kahneman, 1974](#)). Heuristics are strategies that people use in order
17 to simplify a difficult judgment or decision such as understanding probabilities through a rule of
18 thumb or common sense. In this special issue, Ruginski et al. used a think aloud exercise to
19 disentangle their results and found several heuristics that users employ in order to reason
20 about potential damage to an oil rig. Some potential issues arising from the use of heuristics
21 and prior experience is that individuals have several types of systematic errors, or biases, that
22 affect our judgment capabilities ([Tversky & Kahneman, 1974](#)). This presents a unique problem
23 in the case of uncertainty visualization. Since both experts and non-experts apply heuristics and
24 biases when they only have partial or uncertain information, it is also likely that this
25 characteristic of human decision-making will apply when interacting with spatial visualizations
26 like maps containing uncertainty. Thus, uncertainty visualization researchers must understand
27 and face this issue and develop methodologies that will help users overcome these biases and
28 make better-informed decisions. Additionally, researching how other differences including prior
29 experience, knowledge, and abilities relevant to the context and uncertainty visualization may
30 impact the outcome (including decisions, comprehension, etc.) are important to support the
31 data visualization users.
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54 Understanding how and when users utilize uncertainty to assist reasoning and decision-making
55 is of extreme importance in research. To begin with, quantifying uncertainty so that the result is
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3 of relevance to the decision maker is a necessary first step. In this special issue, Salap –Ayca and
4 Jankowski calculate uncertainty to aid in the selection and decision for agricultural lands to be
5 placed in conservation and crop reserve. Aside from quantifying uncertainty, one must also
6 question whether uncertainty should always be presented to the data visualization user. In the
7 empirical work from [Aerts et al. \(2003\)](#), more than 70% of participants agreed that the
8 visualization of uncertainty enhanced their analysis and decisions. The feedback from
9 participants in their study and another from [Leitner and Buttenfield \(2000\)](#) was mostly positive,
10 where users felt that the incorporation of uncertainty visualization clarified the geospatial data
11 rather than making it more complicated. Similarly, [Bisantz, Marsiglio, and Munch \(2005\)](#) found
12 that visualizing uncertainty enhanced the decisions of users, where decisions were most
13 impacted during times of greater uncertainty. In this special issue, Riveiro discovered that even
14 with uncertainty, experts reported high levels of confidence and significantly more than the
15 novices. It should be noted, however, that the inclusion of uncertainty ([Van Oort & Bregt, 2005](#))
16 can in some cases decrease user confidence and make the data appear less reliable and
17 unfavorable. Moreover, some research finds that users may explicitly attempt to ignore
18 uncertainty ([Hope & Hunter, 2007](#)) because, for example, they are not aware of it, they do not
19 understand it, do not know what to do with it, it makes the data appear less reliable or valid
20 ([Slingsby, Dykes, & Wood, 2011](#)), it is too difficult to investigate, or it makes a decision too
21 complicated. Based on these findings, it would appear that successful visualization of
22 uncertainty is highly dependent on the context, task, and individuals or groups interacting with
23 it.
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45 This special issue arises from the continuing need and support for more research on Visually-
46 Supported Spatial Reasoning with Uncertainty. While research on uncertainty visualization to
47 support spatial reasoning and decision-making have been prominent and important topics over
48 the past few decades, calls for papers, workshops, research groups, and grants continue to
49 appear in GIScience. The following research avenues show the prominent role uncertainty
50 continues to play. At the 2016 AAG conference, several sessions have sent out calls for papers
51 to include research on uncertainty and its visualization. A workshop on “visualization for
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3 decision making under uncertainty” and several papers on uncertainty visualization were
4 presented at the VIS 2015 conference. The National Center for Geographic Information and
5 Analysis ([NCGIA, 2015](#)) is a consortium that was established in 1988 and mainly funded from
6 the National Science Foundation with members from the University of California, Santa
7 Barbara, the University at Buffalo, and the University of Maine. The first area they undertook
8 was accuracy and uncertainty in spatial data and they continue to research this important topic.
9 Another collaborative project ("[Modeling, Display, and Understanding Uncertainty in](#)
10 [Simulations for Policy Decision Making," 2015](#)) is underway between groups from the University
11 of Utah, the University of Washington, Clemson University, and University of California, Santa
12 Barbara. The National Institutes of Health has an open funding opportunity for Spatial
13 Uncertainty: Data, Modeling, and Communication to include ways to visualize and
14 communicate spatial uncertainty beginning in 2015. With this continued demand for research
15 on the topic, this special issue is responding to this need and is the logical extension to two
16 successful and well-received workshops some of the editors held at the Conference on Spatial
17 Information Theory in 2013 and GIScience in 2014.

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34 The following articles in this special issue present research in the area of visually-supported
35 spatial reasoning with uncertainty. We have used a visual summary graphic developed by
36 [Mason, Retchless, and Klippel \(in revision\)](#) to provide an overview of each paper. This visual
37 summary applies a graphic typology with various domains of uncertainty visualization research.
38 Shaded regions show those domains that each paper employs in their research. This typology
39 has framed uncertainty visualization research as comprising three major domains: User effects,
40 visualization techniques, and stimulus effects. User effects are characteristics an individual user
41 has which will ultimately affect the way they interact with a visualization of uncertainty. These
42 include individual differences, prior knowledge and experience. Visualization techniques refer
43 to the various ways in which uncertainty can be visualized, organized, and evaluated. This
44 includes the type of data used, intrinsic or extrinsic representations, coincident or adjacent
45 displays, etc. The final domain, stimulus effects, encompasses the various effects that the
46 stimulus, or an uncertainty visualization, can have on the user. For instance, a visualization may
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3 impact the decisions a user makes, how they comprehend uncertainty, or elicit some sort of
4 emotional response. There are numerous other sub-domains of which we will discuss as each
5 paper covers them.
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11 In the article by Salap-Ayca and Jankowski, the authors explore the uncertainty in land
12 allocation criteria weights from multi-criteria evaluation models to assist in identifying
13 agricultural land that should be placed for land conservation and crop reserve. Upon running
14 Monte Carlo simulations, they have created maps of average suitability and uncertainty and
15 further ran a sensitivity analysis. The authors employ both global and local methods to
16 ascertain how the local spatial heterogeneity impacts the criteria weights. In order to visualize
17 the uncertainty of the suitability map, sensitivity maps were created focusing on the average
18 and standard deviation of the weights. This decision making model offers a look into the
19 uncertainty for each of the watersheds in Southwest Michigan showing both the average
20 suitability and the standard deviation (or uncertainty) in each. Combinations of high and low
21 suitability with high and low standard deviation shows how the uncertainty in the suitable areas
22 can affect final decisions. The approach taken by the authors offer alternative options to
23 support decision makers and providing them with multiple scenarios and their associated
24 uncertainty. Figure 1 presents the visual summary of the aforementioned article. This article
25 presents visualization techniques utilizing the polygon and field (raster) data, a coincident
26 display method, and intrinsically visualizes uncertainty.
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44 Figure 1. Visual Summary of Salap-Ayca and Jankowski (2016)
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48 Ruginski et al. compare how different visualizations of the uncertainty for a hurricane track
49 impact decision-making for non-experts in a controlled experiment. The five visualizations
50 include: the traditional “cone of uncertainty” map as often presented by the National Hurricane
51 Center, a cone without the center track line, a center line without the outer cone, a fuzzy-
52 boundary without the center track, and an ensemble of potential tracks. Other factors included
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3 varying the hurricane, temporal points, and oil rig locations. The study then asked participants
4 to estimate damage to the oil rig and in a later task follow a think aloud protocol and discuss
5 their reasoning and decision-making strategies which were coded into various heuristics. The
6 findings of the think aloud protocol yielded a high inter-rater reliability for Cohen's Kappa,
7 revealing that these participants used similar heuristics when reasoning and making decisions
8 about the hurricane. Figure 2 reveals the different topics that the presented research covers:
9 intrinsic and extrinsic visualization methods, line and polygon uncertainty data, coincident
10 display method, and an evaluation of the visualization techniques which implicitly ascertain
11 whether users comprehend the various visual components presented on the maps. This
12 research contributes both quantitative and qualitative methods to better understand how
13 reasoning and decision-making heuristics interplay while interacting with various visualizations
14 and with different factor conditions (i.e. the hurricane forecast, temporal points, oil rig
15 locations). The authors have importantly focused on non-experts, the major consumers of these
16 visual products who are potentially affected by hurricanes and have to make decisions from a
17 variety of sources, including maps with uncertainty like those presented in the study, to
18 ultimately make decisions about their well-being and property.
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37 Figure 2. Visual Summary of Ruginski et al. (2016)
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41 The study by Riveiro focuses on user expertise to assess the threat of targets in an air traffic
42 control simulation. Both sets of participants (all military officers) have some training in this
43 area, however their domain expertise varies in the length of time they had practical experience
44 (either a maximum of 3 years for novice or more than 10 years for expert in air surveillance and
45 risk assessment). Each participant was tasked with protecting a radar station from various
46 targets and upon using an interactive system and map, look at various information (i.e. altitude,
47 distance, speed, etc.) and their uncertainties to make decisions about their potential threat and
48 the priority of each (low, medium, and high) to be sent to the next in command. Overall,
49 experts have more confidence with the additional uncertainty information than the novice
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3 users and performed better at correctly determining targets in the simulations. Figure 3 shows
4 the comprehensive nature of this research in the uncertainty visualization field. As reflected in
5 the visual summary, Riveiro evaluates how context (background related to the mapping
6 context. i.e. novice and expert domain expertise) affects decisions and comprehension of
7 intrinsic and extrinsic uncertainty in an animated and interactive coincident display of both
8 points and lines. By including the entire user effects, visualization techniques, and stimulus
9 effects, Riverio obtains a comprehensive picture of the entire process of a user interacting with
10 a visual display of uncertainty.
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21 Figure 3. Visual Summary of Riveiro (2016)
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26 Outlook

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28 Upon viewing these visual summaries, the reader will find that each of these articles covers
29 different topics in the uncertainty visualization domain, offering complementary research in
30 this field. Understanding this uncertainty and its impact on users is a puzzle that we are now
31 actively trying to understand. Uncertainty visualization will continue to be an important field of
32 research as uncertainty plays an increasing role in data analysis and practical human decisions
33 with the increasing amount of data and combination of various data sources. With the large
34 and expanding utilization of geospatial data and its visualization, a largely ignored component
35 in many analyses and visualizations is the uncertainty interwoven throughout the data. In many
36 cases, this may cause user misinterpretation and poor reasoning and decision-making behaviors
37 because users do not fully grasp the complexity of the different uncertainties arising from data
38 collection, manipulation, analyses, visualizations and our human cognitive capacities and
39 biases. Decision-making under uncertainty is a process that many users among numerous
40 domains must face. Visualization of uncertainty for geospatial data is a promising mode for
41 presenting this attribute to support these various researchers and people who make decisions
42 and reason about their data. The large knowledge gap in this area is the application and
43 extension of research on individual differences, prior experience, and conceptualization of
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3 uncertainty in other research areas and how they might apply in designing effective uncertainty
4 visualizations to support reasoning and decision-making. Furthermore, extending this body of
5 research and finding new ways to explore how these visualizations may help or hinder the
6 analytical and reasoning process of humans continues to be a necessary step towards better
7 knowledge and decisions taking into account all available evidence.
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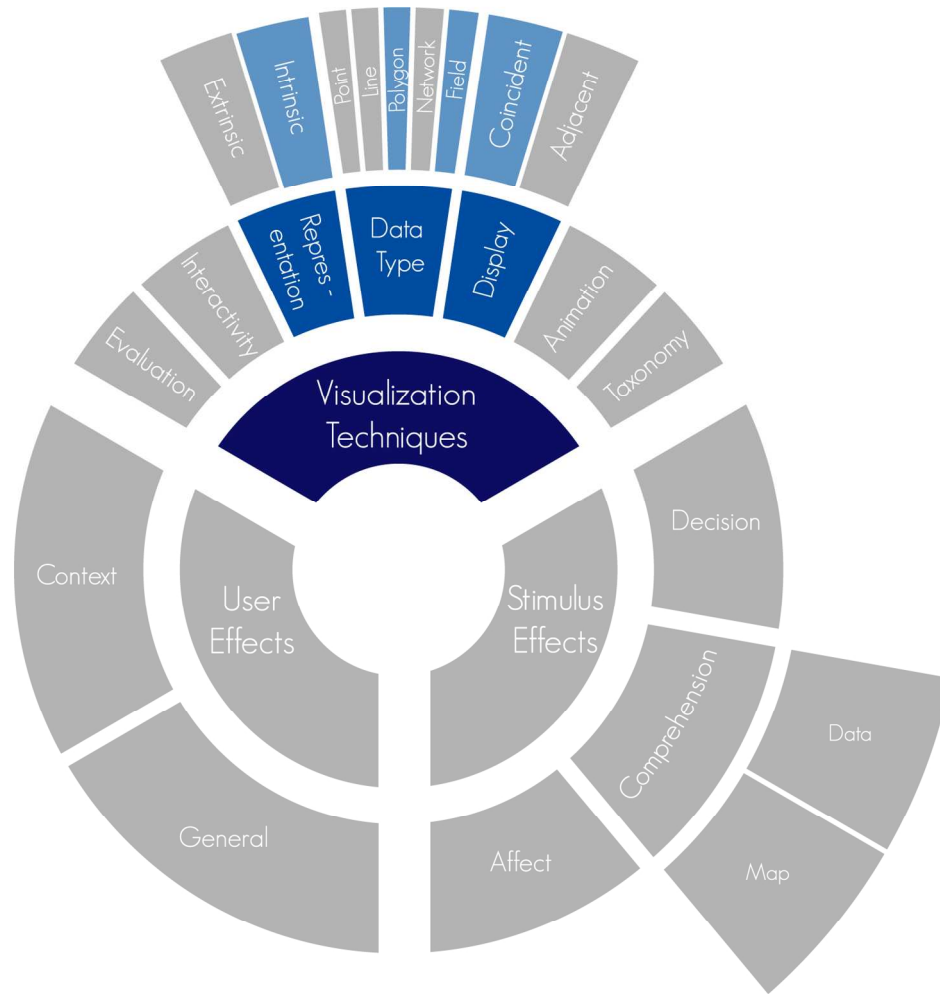


Figure 1. Visual Summary of Salap-Ayca and Jankowski (2016)
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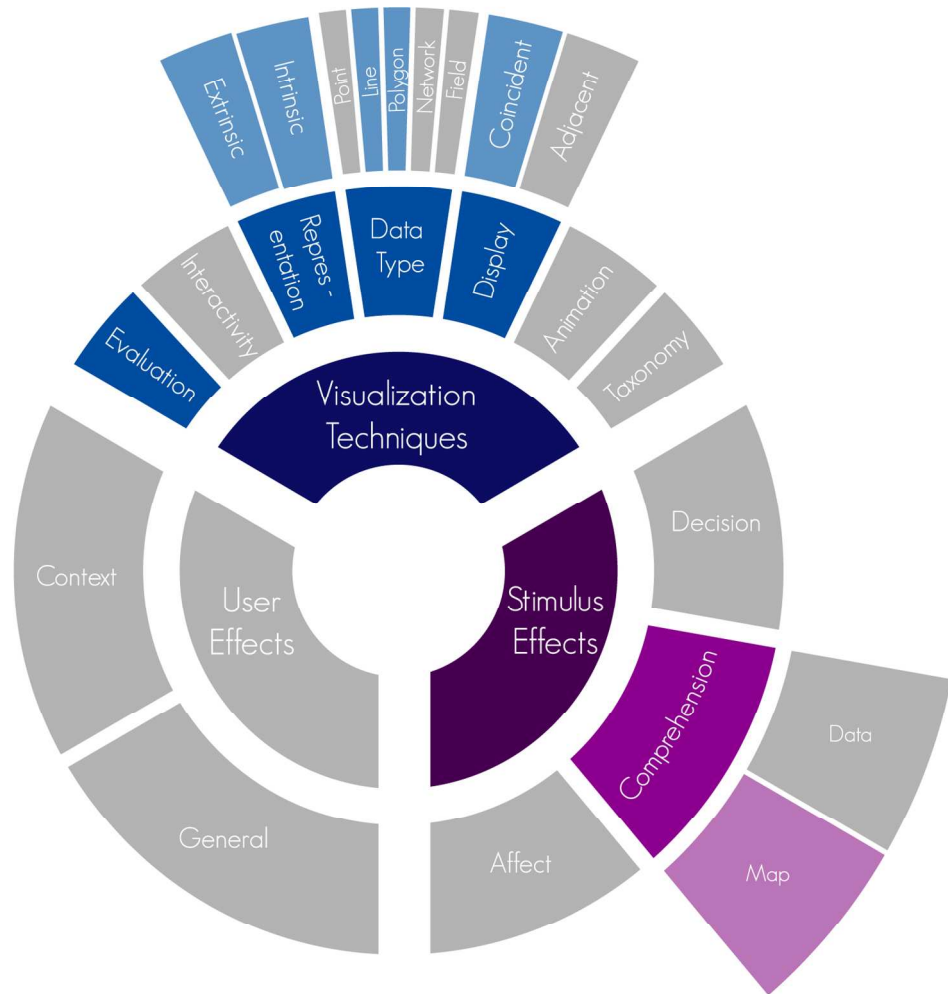


Figure 2. Visual Summary of Ruginski et al. (2016)
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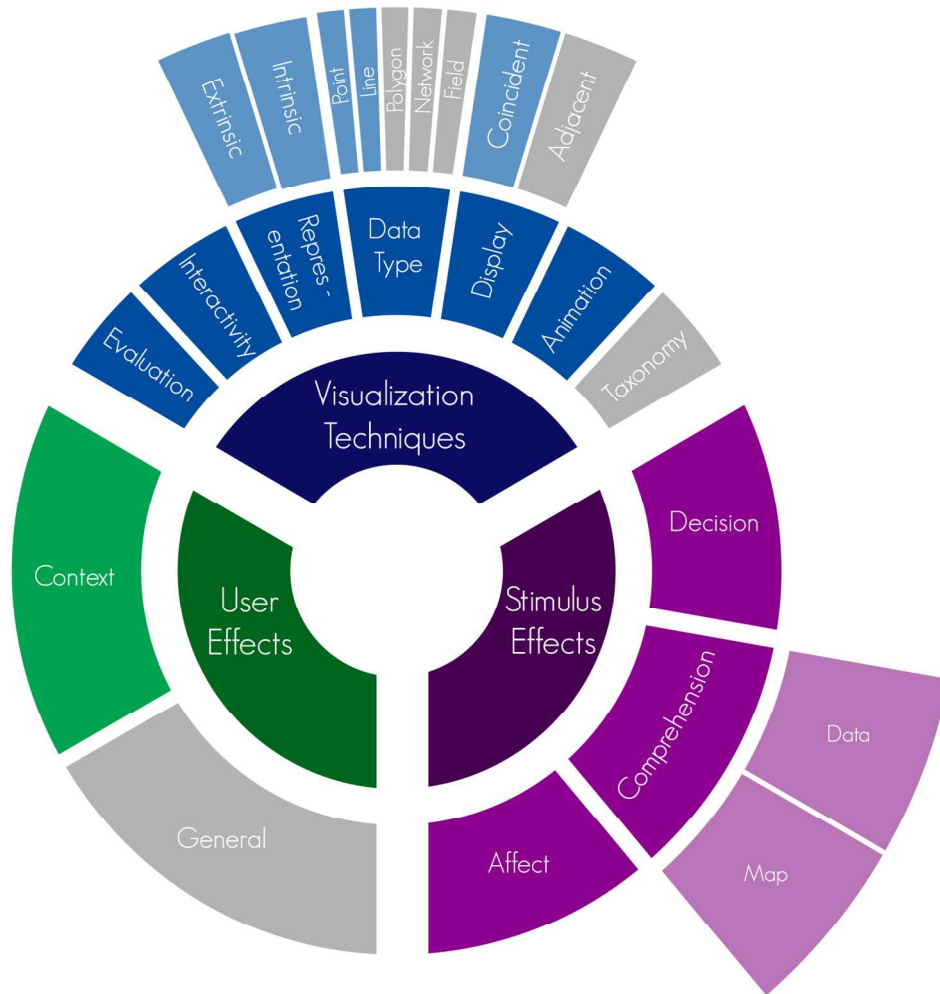


Figure 3. Visual Summary of Riveiro (2016)
139x146mm (300 x 300 DPI)

