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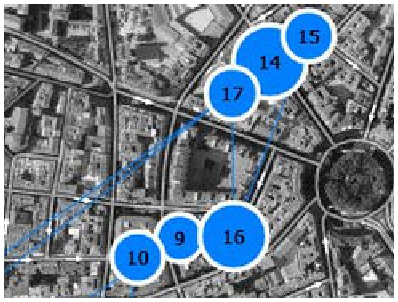

Visualizations

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Introduction

Visualizations, i.e., thinking in images internally in our minds, **or** externally expressing a concept via graphical means (documenting an observation in a hand-drawn or digital visuospatial sketch, or creating a visual output from data), have always been an integral part of scientific inquiry and communication. One might argue that the ‘graphy’ part of ‘geo**graphy**’ refers to visually and spatially[1] documenting the world around us. A significant part of human experience is shaped by sight for majority of people, and the human visual system occupies a large chunk of human cognitive processing capacity. Given that, one can speculate that comprehension and communication through visuospatial means could be ‘second nature’ to people. There is ample evidence to support this line of thinking: As opposed to written words or a large list of numbers, visualizations allow us to see patterns and anomalies quickly, sometimes even at a glance. However, the power of visualizations depends on a number of factors including the details of their **design**, abilities and background of the **human** viewing them, and the **context** in which a visualization is used. This power must also be critically viewed from an ethics perspective. We will elaborate on these three factors under various subsections below.

However, before we do, there is one fundamental question we need to ask: Is visualization a *product* or a *process*? The word visualization is commonly used as a noun for a visual product, *e.g.,* a map or a plot is a visualization. However, it is necessary to remember that the mental visualization is a cognitive process, and the term visualization was introduced into cartographic (and other scientific) discourse because people wanted to distinguish the new era where the dynamic displayed enabled visualization as a *process*. The process aspect is important to remember, because this is the key factor that distinguishes using visualizations to *explain what we already know* vs. *explore what we do not know*. With the latter thinking, visualizing things becomes a part of the scientific inquiry as an active tool that helps build hypotheses and thus facilitate thinking and reasoning, *besides* explaining what we already know. Whether the goal is to explain or to explore, the design and use of visualizations needs to be intentional and not accidental. To create and read visualizations intentionally, a certain level of *visual literacy* built on design, technology and knowledge of human visuospatial cognition is necessary. This manuscript identifies scholarly resources to help all scientists and aspiring scientists, especially those in spatial sciences, to build, refresh their knowledge of, learn or teach about visualizations.

[1] Visual and spatial information processing are often coupled, and referred to as *visuospatial*.

General overviews

The foundations of visualization in geography grew from the earlier work of statisticians, computer scientists, and graphic designers. The building blocks of graphics lie at the core of any visualization, and have been defined in terms of graphical variables (Bertin, 1967) as well as mathematical formulas (Wilkinson, 2005). What we know about human vision and how it perceives information from graphics can help us make smart design decisions and recognize potential limitations (MacEachren, 1995). The potential tasks that can be supported by visualization have been thoroughly explored in geographic as well as non-geographic contexts (Dykes et al. 2005; Andrienko & Andrienko, 2006; Munzner 2014). Distilled guidelines exist now to help visualization creators make better decisions about representations and interactivity (Heer, 2010; Munzner 2014; Field, 2018), and we have a theoretical base that frames visualization in geography as a cognitive and semiotic system (MacEachren, 1995). In spite of a great deal of scientific activity in this subfield of geography (Dykes et al. 2005; Noellenburg, 2006), key research challenges remain (Çöltekin et al. 2017).

Andrienko, N., & Andrienko, G. (2006). *Exploratory analysis of spatial and temporal data: a systematic approach*. Springer Science & Business Media.
Emphasizing the exploratory potential for visualization, this work is particularly strong in its explanation of a wide range of possible analytical task types and for defining visualization design principles that connect tasks to functional implementation in systems.

Bertin, J. (1967). Semiology of graphics: Diagrams, networks, maps. Redlands (2010)
Foundational work from 1967 (reprinted in 2010), on the ways in which graphics are constructed to represent information. Bertin introduced the concept of visual variables in this volume with the intention to help provide guidelines that can be generally applied for representing a wide range of data types.

Çöltekin, A., Bleisch, S., Andrienko, G., & Dykes, J. (2017). Persistent challenges in geovisualization–a community perspective. *International Journal of Cartography*, *3*(sup1), 115-139.
Based on expert inputs, the research challenges proposed in a number of previous research agenda articles are compared to what the geovisualization community believes are persistent problems in the field today. Three major areas emerged; the need to define geovisualization and its connection to allied fields, the need to develop a better understanding of human factors in geovisualization, and the need to develop practical guidelines for geovisualization design and implementation.

Dykes, J., MacEachren, A. M., & Kraak, M. J. (2005). *Exploring geovisualization*. Elsevier.
Spans the gamut of research in geovisualization, including core theoretical perspectives, computational frameworks, application areas, and evaluation methods. Also introduces key research challenges for the field, many of which remain relevant today.

Field, K. (2018). *Cartography*. Esri Press.
An extensively illustrated primer on map design, presented in a condensed format and dispensed in a non-linear, non-academic fashion. One of the easiest and most engaging ways to dive into cartographic design, and quite useful as a reference for experienced cartographers too.

Heer, J., Bostock, M., & Ogievetsky, V. (2010). A tour through the visualization zoo. *Communications of the ACM*, *53*(6), 59-67.

A concise and visual guide to visualization methods, including those commonly applied as well as those that are not typical but may be well-suited to particular situations. Written in a way to inspire the reader to learn the basics about each approach, its intent is to whet the appetite in a few pages rather than serve as a deep reference.

MacEachren, A. M. (2004). *How maps work: Representation, visualization, and design*. Guilford Press.
Recognized as a key work in the field, this monograph expands on MacEachren's earlier work to develop connections between cartography, cognition, and semiotics. It advances and develops a new theoretical framework for cartography as an engine of discovery beyond its use for communication.

Munzner, T. (2014). Visualization analysis and design: Principles, techniques, and practice. *AK Peters Visualization Series*.
Blends together principles for visualization design with core theoretical frameworks and synthesized results from perceptual studies to provide a comprehensive reference. A unique aspect compared to other references is that it also delves into motivations for visualization and offers helpful rules of thumb.

Nöllenburg, M. (2007). Geographic visualization. In *Human-centered visualization environments* (pp. 257-294). Springer, Berlin, Heidelberg.
Offers a broad overview of geovisualization, ranging from its development as a subdiscipline of cartography to its implementation in various systems and its intersections with human-centered computing.

Wilkinson, L. (2013). *The grammar of graphics*. Springer Science & Business Media.
Proposes a complete system whereby graphics can be constructed from mathematical and conceptual parts, including their aesthetic affordances as well. A particularly useful and general guide for anyone who seeks to implement visualizations in software.

Representation

Some of the persistent challenges in visualization research are issues related to *representation* which lies at the intersection of cognition, semiotics and philosophy (Morrison, 1977). Phenomena can be represented by means of a large range of abstraction systems such as in words, sounds, numbers, formulas, and importantly in the scope of this section, in visualizations (*e.g.,* sketches, graphs, pictures, maps). While all representations may not be visualizations, all visualizations are representations, even realistic images and photographs. A photograph captures a particular moment, and while doing that it distorts geometry, and the image of an object is clearly not the object itself. A well-known art piece on this very subject —perhaps a historical *meme*— is the "this is not a pipe" image by Magritte (Bowman 1985), for which he reportedly argued that if it cannot be stuffed and smoked, it is not a pipe. Since all visualizations are representations, visualization phenomena requires a number of big and small representation decisions (Fairbairn et al., 2001). In geographic and spatial sciences, a core discussion in relation to representation is on the levels of abstraction (or realism), often studied under the umbrella of *generalization* (Raposo, 2007; Weibel & Jones 1998) and visual complexity (Bjorke 1996). How closely should the representation resemble the object it represents? What is intuitive vs. what is effective; are they sometimes the same? Creating a language of symbols means having to learn these symbols, perhaps partly because of this, people seem to prefer visual realism (Smallman & John, 2005). However, visual realism, along with other ‘seemingly intuitive’ representations, can impair performance in some tasks (Hegarty et al., 2009). Decisions regarding levels of realism and use of symbols are traditionally guided by cartographic principles through *generalization*. Generalization can be conceptualized in graphic or semantic categories, and these are goverend by operators such as simplification, aggregation, smoothing, selection/elimination, typification, displacement, exaggeration, classification, etc. (Raposo, 2017). Generalization operators serve as ‘rule-of-thumb’ guidelines to designers (Fairbairn et al., 2001). As a key attention guiding method, in modern visualization systems, *highlighting* has been one of the ways people (re)use generalization principles (Liang & Huang 2010, Robinson 2012). Cartographic generalization and map design remain relevant and prove to be difficult to formalize, quantify and automate, even though various attempts do exist (Weibel & Jones 1998; Bjorke 1996).

Bjørke, J. T. (1996). Framework for entropy-based map evaluation. *Cartography and Geographic Information Systems*, *23*(2), 78-95.
Links attempts of formalizing and automatizing map design/generalization to Shannon’s information theory and proposes entropy and entropy-related measures to control automated processes.

Bowman, R. (1985). Words and images: A persistent paradox. *Art Journal*, *45*(4), 335-343.
This paper provides a discussion of photorealism and representation in arts. With references to art, design and philosophy, this piece may make an unusual reading piece for the geovisualization researcher, and will bring insights from another line of thinking.

Fairbairn, D., Andrienko, G., Andrienko, N., Buziek, G., & Dykes, J. (2001). Representation and its relationship with cartographic visualization. *Cartography and Geographic Information Science*, *28*(1), 13-28.
Provides a general overview of representation in cartography covering multiple perspectives including how underlying data, user interface, and cognition interact within this frame. Also importantly, this is a research agenda paper that provides insights into two-decade old challenges in this domain.

Hegarty, M., Smallman, H. S., Stull, A. T., & Canham, M. S. (2009). Naïve cartography: How intuitions about display configuration can hurt performance. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *44*(3), 171-186.
Demonstrates that the naive realism concept extends to cartography, including realism, animation, 3D. Provides empirical evidence from a series of experiments in support of this position.

Liang, J., & Huang, M. L. (2010, July). Highlighting in information visualization: A survey. In *2010 14th International Conference Information Visualisation* (pp. 79-85). IEEE.
Summarizes and classifies existing highlighting methods in information visualization and visual analytics.

Morrison, J. L. (1977). The science of cartography and its essential processes. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *14*(1), 58-71.
This paper brings forward strong arguments on cartography as a visual language and links this ‘language’ with the theories of design and cognition. It introduces the ‘cognitive realm’ of the map

maker and map reader and everything that happens in between. A communication model that has been cited many times and taught in classroom since 70s.

Raposo, P. (2017). Scale and generalization. *The Geographic Information Science & Technology Body of Knowledge,* 4th Quarter 2017 Edition, John P. Wilson (ed.).
This modern book section from the 'body of knowledge' efforts is a great entry point to scale and generalization in cartography. Follow the exercises and citations to get deeper insights.

Robinson, A. C. (2011). Highlighting in geovisualization. *Cartography and Geographic Information Science*, *38*(4), 373-383.
Color is the dominant visual variable used in highlighting. This paper examines the alternatives in the context of geovisualization, and proposes design criteria for them, including recommendations for combining them and research challenges.

Smallman, H. S., & John, M. (2005, September). Naive realism: Limits of realism as a display principle. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 49, No. 17, pp. 1564-1568). Sage CA: Los Angeles, CA: Sage Publications.
Argues for and defines the concept of 'naive realism', how people usually prefer realistic displays, but their performance does not match their preference.

Weibel, R., & Jones, C. B. (1998). Computational perspectives on map generalization. *GeoInformatica*, *2*(4), 307-314.
This editorial to a journal special issue on (map) generalization both introduces key terms, and identifies the early research challenges at the intersection of cartography and computer science.

Color

Among one of the most elusive of Bertin's (1967) visual variables to 'get it right', color has been a topic of research in cartography and visualization for decades (Olson, 1987), and continues to remain relevant today (Brychtová & Çöltekin, 2017). Color is difficult to manage from a number of perspectives; first of which is that it is not psychophysically fully-understood. Perceptually, color is not straightforward to model, as there are many individual differences. Perceptual mechanisms (or their failures) lead to many illusions, some of which can be a threat in visualizations (*e.g.,* a color surrounded by another color may appear different, or some colors may 'spread' causing the 'water color illusion'). Some of the individual differences also might mean color deficiencies, reported to be up to 8% in men (Ware, 2013; Olson & Brewer 1997). To counteract against color deficiencies and create an inclusive design, there are modern tools that simulate various forms of color deficiencies (*e.g.,* Jenny, 2020; colororacle.org). Even when there are no color deficiencies, people might struggle telling different shades of the same color apart (Brychtova & Çöltekin, 2017), or perceive the same color differently under different lighting conditions, or if they use different monitors or printers. Some of these 'mishaps' can be prevented by using *e.g.,* Brewer & Harrower's (2020) well-known colorbrewer2.org. Because we map so many data values using color, it is important to get the colors right. If the colors need to follow an 'order' (*i.e.,* if the darker color is supposed to be higher value), one clear advice is to avoid using the common software default "rainbow color scheme" (Light & Bartlein, 2004), and consult colorbrewer2.org!

Bertin, J. (1967). Semiology of graphics: Diagrams, networks, maps. Redlands (2010)
This seminal book (reprinted in 2010) has been featured in the earlier section 'general overviews'. Here we cite it again, because Bertin makes a point of distinguishing color value and color hue as

key visual variables (pages 85-92). This paved the way on how we characterize color schemes today.

Brewer, C., Harrower, M. (2020, February 29). Color Brewer 2.0, Color advice for cartography. Retrieved from [colorbrewer2.org.](colorbrewer2.org)
A web application developed by scientists informed by theories of vision and empirical evidence. It runs on a browser and it is very helpful in designing color schemes that are safe for color blind individuals and also otherwise informed by cartographic theories. The app has been integrated in the mainstream GIS software ArcGIS, and is very popular across interdisciplinary visualization communities.

Brychtová, A., & Çöltekin, A. (2017). The effect of spatial distance on the discriminability of colors in maps. *Cartography and Geographic Information Science*, *44*(3), 229-245.
This relatively recent paper provides a framework for discriminability of colors, including a literature review that may be of value to the readers of this subsection. Authors demonstrate also based on experiments that there a quantifiable threshold is possible for discriminating shades of the same color, even when they are physically separated from one another on a computer display.

Jenny, B. (2020, February 29). Color oracle, Design for the color impaired. Retrieved from [https://colororacle.org/.](https://colororacle.org/)
This amazing little piece of software that runs on common operating systems and simulates common color deficiencies and makes for a great 'quality check' of any visualization with colors, and an eye opening demo in color-related teaching.

Light, A., & Bartlein, P. J. (2004). The end of the rainbow? Color schemes for improved data graphics. *EOS, Transactions American Geophysical Union*, 85(40), 385-391.
This paper provides some recommendations of how one might use color in designing visualizations (aimed primarily at geoscientists), first making a point of graphical literacy, then reviewing the color deficiencies and providing a good account of early account of why rainbow color scheme does not work well.

Olson, J. M., & Brewer, C. A. (1997). An evaluation of color selections to accommodate map users with color-vision impairments. *Annals of the Association of American Geographers*, *87*(1), 103-134.
This may have been the paper that planted the seeds of the popular Color Brewer tool. Based on a controlled experiment, authors demonstrate that it is indeed possible to design maps that work for color blind users.

Olson, J. M. (1987). Color and the computer in cartography. In *Color and the Computer* (pp. 205-219).
This chapter gives a broad overview of using colors appropriately with digital media in its earlier days, especially thematic (statistical) maps, both from functional and aesthetics points of view.

Ware, C. (2020). *Information visualization: perception for design*. Morgan Kaufmann.
Connects representation in visualization to how the human eye-brain system operates. Fundamentals of perception are explained in the context of how visualization systems can be designed, synthesizing a long history of visual perceptual science and offering many compelling visual examples along the way, including color perception.

Interactivity

Visualization can support a user's thinking by enabling her to see multiple views of a data set (Cleveland & McGill 1988). Interactivity is needed to quickly generate these multiple views on-the-fly in response to new questions posed as part of that thinking process. However, these interactive visualizations need to be appropriately designed given the data's characteristics and the data exploration goals (Shneiderman 1996; Andrienko & Andrienko 1999). Failing to design interactivity appropriately so that users are most likely to see the most-task relevant information can lead to ineffective visualizations (Keehner, et al. 2008). But there is much that is still not known about how to best design interactivity in visualizations (Roth 2013a). This requires further scientific research to establish which combinations of tools and interactivity reduce "visualization effort" and improve the efficiency of discovering insights about datasets and problems (Dykes 2005). Task typologies and taxonomies can be helpful in designing these experiments (Crampton 2002; Roth 2013b).

Andrienko, G. L., & Andrienko, N. V. (1999). Interactive maps for visual data exploration. *International Journal of Geographical Information Science, 13*(4), 355-374.
Describes Descartes, an early web-delivered application designed to embed interactivity in maps with the aim of supporting visual thinking. This research was inspired by earlier work on developing interactive statistical graphics for exploratory data analysis. Descartes produced maps that changed in real-time in response to user manipulations of the maps and used expert cartographic design knowledge to choose and present appropriate representations of the data.

Cleveland, W. C., & McGill, M. E. (1988). *Dynamic graphics for statistics*. CRC Press, Inc..
Edited book that presents approaches for direct manipulation of statistical graphics by their users. The editors argued that manipulations that can be used to generate insight about statistical information as well as to communicate these insights to others. Many described manipulations are now common in modern visualization software. Early concerns identified here such as making interactions effortless and quick enough to not disrupt thinking are continuing themes in later research.

Crampton, J. W. (2002). Interactivity types in geographic visualization. *Cartography and Geographic Information Science*, *29*(2), 85-98.
Developed an early ranked typology of interactivity as it applies to geovisualization. This typology considered different types of interaction, ranking them by their utility (low-high); interaction with the data representation, interaction with the temporal dimension [of the data], interaction with the data, and contextualizing interaction. The typology can be used to compare and evaluate the success of types of interactivity implemented within different interactive mapping environments.

Dykes, J. (2005). Facilitating interaction for geovisualization. In *Exploring geovisualization* (pp. 265-291). Elsevier.
Introduces the concept of "visualization effort" as a way of measuring the efficiency of particular combinations of visualization tools that allow users to interact with data. Combinations that result in high levels of visualization effort are problematic for visual thinking because they slow thinking down. Flexible visualization tools and smooth transitions between different types of tools (*e.g.,* GUIs, scripting, code libraries, and system programming) can reduce total visualization effort.

Keehner, M., Hegarty, M., Cohen, C., Khooshabeh, P., & Montello, D. R. (2008). Spatial reasoning with external visualizations: What matters is what you see, not whether you interact. *Cognitive science*, *32*(7), 1099-1132.
Visualization augments cognition by distributing it between internal cognitive processes in the mind and perceptual-motor processes needed for interacting with the external world (*i.e.,* the visualization). Using experimental evidence, the authors argue that simply providing interactivity is insufficient for supporting effective inference. Interactivity only helps when users are able to use it to manipulate the visualization effectively so that they see the most task-relevant information within the visualization.

Roth, R. E. (2013a). Interactive maps: What we know and what we need to know. *Journal of Spatial Information Science*, *2013*(6), 59-115.
Presents a formal definition of cartographic interaction and an argument for why understanding it is increasingly important to cartographic practice. In so doing, it reviews research about cartographic interaction with the aim to answer questions such as why interaction is needed, when it should be provided, for whom it is beneficial, and where and how it should be provided within a map.

Roth, R. E. (2013b). An empirically-derived taxonomy of interaction primitives for interactive cartography and geovisualization. *IEEE Transactions on Visualization and Computer Graphics*, *19*(12), 2356-2365.
Used expert knowledge sourced from interactive map users and interactive map designers to develop a four-part taxonomy of cartographic interaction building blocks (goals, objectives, operators, operands). Unlike many other interaction taxonomies, its development drew on cartographic practice rather than primarily on theory although theory was used to guide the empirical study of interactive cartographic practice. Future scientific experimentation can use this taxonomy to identify effective cartographic interaction strategies.

Shneiderman, B. (1996, September). The eyes have it: A task by data type taxonomy for information visualizations. In *Proceedings 1996 IEEE Symposium on Visual Languages* (pp. 336-343). IEEE.
Presents a (now) frequently implemented approach to information visualization design that relies fundamentally on interactivity: “Overview first, zoom and filter, then details on demand”. This paper also developed an early task by data type taxonomy that could be used to explore design alternatives to select appropriate visual representations as well as user interactions to control exploration of information in the visual representations when building information visualizations.

Space-Time Visualizations

Most of the data we visualize — as fundamental physics dictates it, and as expressed in the classical model of geographic information science (GIScience)— can be conceptualized around the dimensions *space, time,* and *attribute*, i.e., *where, when* and *what* (Pequet 1994). Foci of most spatial analyses have been on 2D (or less frequently, 3D) space & attribute(s). This is partly because we do not always have temporal data, and partly because time adds another complexity in multivariate visualization which is already difficult to do well (Pequet 1994; Andrienko & Andrienko, 2008). One of the earliest temporal visualization ideas in geography was proposed by Hägerstrand in 1970: The ‘space-time cube’ (STC). In the STC, a three-dimensional visualization is used where two of the dimensions are spatial, and third dimension is temporal. One can then visualize attribute data as annotations in modern versions of the STC as well. The STC might take some getting used to (3D can be harder to read and interpret), but works well with few trajectories. If there are many trajectories, then the STC might get too cluttered to be useful. In such cases, one may consider using flows or densities (Demsar & Virrantaus, 2010). Another common mode of visualizing spatiotemporal data is through small-multiples or animation (DiBiase et al., 1992). Whether it is trajectories, flows or densities; one can show temporal change using these techniques. Besides the amount of data, deciding how to visualize the spatiotemporal data begins by the inherent differences in movement patterns: Birds and fish move in 3D space, humans mostly on terrain except if it is flight data, eyes move fast and 'jumpy', cars, bikes or trains may have other 'behaviors' (Dodge et al., 2008). Of course humans also move in urban areas based on the feelings of 'safety' or 'pleasantness' or 'attractiveness'. Analyzing and visualizing such patterns in connection to not only space but also time affords understanding more than the facts about how they are distributed, but why this may be the case (Kwan et al., 2007).

Andrienko, G., & Andrienko, N. (2008, October). Spatio-temporal aggregation for visual analysis of movements. In *2008 IEEE Symposium on Visual Analytics Science and Technology* (pp. 51-58). IEEE.
Provides an account of how to deal with 'too much' data that is being generated through smartphones and other GPS-enabled devices in the last two decades, with the main focus on aggregation methods. Includes considerations of visualization as well as interaction with movement data.

Demšar, U., & Virrantaus, K. (2010). Space–time density of trajectories: exploring spatio-temporal patterns in movement data. *International Journal of Geographical Information Science*, 24(10), 1527-1542.
This paper offers an approach to dealing with a cluttered space-time cube by creating a density map from the trajectories. The proposed algorithm is presented in the paper as well as a case study based on synthetic data to test the algorithm, and a real-world case study based on ship movements.

DiBiase D, MacEachren AM, Krygier JB et al (1992). Animation and the role of map design in scientific visualization. Cartography and Geographic Information Science 19: 201–214.
This manuscript extends the visual variables to dynamic displays (scene duration, order and rate of change), specifically, map animations. It also provides a brief critical perspective on the effectiveness of animation over *e.g.,* small multiples (this has been a subject of scientific debate in following decades and is not fully established when animations facilitate).

Dodge, S., Weibel, R., & Lautenschütz, A. K. (2008). Towards a taxonomy of movement patterns. *Information Visualization*, *7*(3-4), 240-252.
Through a systematic approach to classifying movement behavior and patterns (including a concise dendrogram) based on a literature review, this paper made its mark on the analysis and visualization of spatiotemporal data.

Kwan, M. P., & Lee, J. (2004). Geovisualization of human activity patterns using 3D GIS: a time-geographic approach. *Spatially Integrated Social Science*, *27*, 721-744.
Building further on the time geography concept, this book chapter demonstrates how one may use 3D geovisualization to understand spatiotemporal differences in behavior patterns of people of different ethnicity and gender based on diary data.

Peuquet, D. J. (1994). It's about time: A conceptual framework for the representation of temporal dynamics in geographic information systems. *Annals of the Association of American Geographers*, *84*(3), 441-461.
Pequet is one of the earliest researchers to point at the fact that we conduct analyses 'frozen in time', and proposes her well-known **'triad'** model in this paper that covers a phenomena from the three fundamental aspects or dimensions: What, where, and when. Paper draws links to many scientific disciplines, emphasizes the importance of including time in our thinking (and in GIS) and its importance for understanding and predicting change.

Torsten, H. (1970). What about people in Regional Science?. *Regional Science Association*, *24*(1), 6-21.
A classic from the 'father of time geography' from a social science perspective that introduces the space-time cube. Both time geography and the STC remained as influential concepts over the decades that followed, and this manuscript will be an excellent starting point to both.

Perception, Cognition, User-Centered Design

Whether a product or a process, or whether its aim is to facilitate visual thinking or visual communication; all visualizations are made for people (even if it is for you alone!). This simple fact has been historically somewhat neglected in technical communities, but today, relatively strong interdisciplinary research efforts on understanding human factors in visualization do exist. From the perspective of psychology, visualization research may benefit from cognitive and perceptual literature, and may also contribute towards these domains (Slocum et al., 2001, Hegarty 2011; Ware et al., 2013). This type of exchange also occurs with design research and usability (Haklay & Zafiri, 2008) and user-centered design perspectives (Roth et al., 2017; Sedlmair et al.). These efforts are also called human-centered approaches (Lloyd & Dykes, 2011), in which researchers ask questions on the user experience with visualizations, such as what makes them memorable (Borkin et al., 2013), or how individual and group differences can be characterized so that a display can be customized or personalized, or if maps can evoke emotions and what to do with such emotions (Pirani et al., 2019). Answering such questions allows rethinking design from the perspective of human information processing and pyschology, leading towards a much better understanding how people consume and interact with visuospatial information, as well as to much better informed display designs (Hegarty 2011).

Borkin, M. A., Vo, A. A., Bylinskii, Z., Isola, P., Sunkavalli, S., Oliva, A., & Pfister, H. (2013). What makes a visualization memorable? *IEEE Transactions on Visualization and Computer Graphics*, *19*(12), 2306-2315.
Asks the seemingly simple question expressed in the title of the paper (what makes a visualization memorable?) and examines more than 2000 static visualizations in an online study. Characterizing the user ratings gives some fairly consistent patterns: color, human recognizable elements, and an element of 'surprise' might be relevant for memorability.

Haklay, M., & Zafiri, A. (2008). Usability engineering for GIS: Learning from a screenshot. *The Cartographic Journal*, *45*(2), 87-97.
Introduces usability engineering and links it to GIS. Are there specific things to consider when a GIS is being evaluated? Can usability engineering routines be integrated into the regular GIS development routines in the 'wild' (in-situ). Authors then collect and present screenshots from 'real world' GIS users, and evaluate these in connection to usability engineering practices.

Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design. *Topics in Cognitive Science*, *3*(3), 446-474.

Based on a literature review, this paper classifies visuospatial displays into 'types' and explores whether they all amplify (and in which ways they may amplify) cognition.

Lloyd, D., & Dykes, J. (2011). Human-centered approaches in geovisualization design: Investigating multiple methods through a long-term case study. *IEEE Transactions on Visualization and Computer Graphics*, *17*(12), 2498-2507.
Presents a study that was conducted over three years based on observations and interactions with three domain specialists. On some level, the study questions the ecological validity of empirical observations and highlights the human factors such as trust and communication. Authors also review paper and digital prototypes as communication methods between domain specialists and geovisualization experts.

Pirani, N., Ricker, B. A., & Kraak, M. J. (2019). Feminist cartography and the United Nations Sustainable Development Goal on gender equality: Emotional responses to three thematic maps. *The Canadian Geographer/Le Géographe Canadien*.
As a relatively rare piece that examines emotions different map types might evoke, this text is both insightful and somewhat (we believe intentionally) provocative as it touches upon sensitive social, political and psychological issues.

Roth, R. E., Çöltekin, A., Delazari, L., Filho, H. F., Griffin, A., Hall, A., ... & van Elzakker, C. P. (2017). User studies in cartography: Opportunities for empirical research on interactive maps and visualizations. *International Journal of Cartography*, *3*(sup1), 61-89.
Provides a comprehensive research agenda for empirical user research that focuses on the interactive maps and visualizations, taking into account not only perceptual and cognitive factors, but also cultural and practical ones.

Sedlmair, M., Meyer, M., & Munzner, T. (2012). Design study methodology: Reflections from the trenches and the stacks. *IEEE Transactions on Visualization and Computer Graphics*, *18*(12), 2431-2440.
Based on 21 design studies and a comprehensive literature review, this paper might be the strongest 'meta paper' out there for those who would want to conduct design studies of their own. The authors cover definitions, methodological frameworks and even venture towards visualization design guidelines.

Slocum, T. A., Blok, C., Jiang, B., Koussoulakou, A., Montello, D. R., Fuhrmann, S., & Hedley, N. R. (2001). Cognitive and usability issues in geovisualization. *Cartography and Geographic Information Science*, *28*(1), 61-75.
A gemstone of a research agenda paper from nearly 20 years ago that contains challenges that are still unsolved, and might remain so for a long-time to come. Some of the issues this paper catches are inherently complex and requires understanding humans better first. Some of them (such as the role of virtual environments in visualization) are making a 'come back' every time there are technological leaps too.

Ware, C. (2020). *Information visualization: Perception for design*. Morgan Kaufmann.
We have cited this book already in the Color section. However because color is in essence a sub-topic to perception from a human-centered perspective, here this book needs to be revisited. It is one of the most interesting readings in information visualization to date that connects cognitive and perceptual sciences to visualization design and computer science.

Analytical Reasoning and Visual Analytics

Support for analytical reasoning is a key motivator for the design and implementation of visualization in Geography. Defining what constitutes analytical reasoning and how it connects to elements of visualizations has been a common thread in research for several decades. Early work sought to expand the affordances of maps beyond simple means of communicating known results to include hypothesis generation and knowledge creation (MacEachren & Ganter, 1990), and this work was later extended to consider multiple potential pathways for making discoveries (Gahegan, 2005). The era of visual analytics as a separable field apart from other forms of visualization began in the early 2000s (Thomas & Cook, 2005; Andrienko et al. 2007) and encouraged conscious efforts to support reasoning and reduce gaps in knowledge (Amar & Stasko, 2005) through visualization and computation. Visual analytics work requires a close focus on how users conceptualize problems, how they reason with spatiotemporal information, and how human perception couples with cognition to make decisions (Jones et al. 2009; MacEacren et al., 2004; Keim et al. 2010; Fabrikant et al. 2010).

Amar, R. A., & Stasko, J. T. (2005). Knowledge precepts for design and evaluation of information visualizations. *IEEE Transactions on Visualization and Computer Graphics*, *11*(4), 432-442.
Defines a set of potential analytical goals and results for information visualizations. This work proposes so-called knowledge and rationale gaps that information visualizations might be used to remedy. These precepts can be in turn used to help design new systems and to evaluate their utility.

Andrienko, Gennady, Natalia Andrienko, Piotr Jankowski, Daniel Keim, M-J. Kraak, Alan MacEachren, and Stefan Wrobel. "Geovisual analytics for spatial decision support: Setting the research agenda." *International Journal of Geographical Information Science* 21, no. 8 (2007): 839-857.
Building on the then-recent development of visual analytics as a research area, Andrienko et al. defined a research agenda that focused more specifically on how geographic information science and visual analytics could be combined. As a result, this work helped launch the concept of geovisual analytics as a subfield of visual analytics.

Fabrikant, S. I., Hespanha, S. R., & Hegarty, M. (2010). Cognitively inspired and perceptually salient graphic displays for efficient spatial inference making. *Annals of the Association of American Geographers*, *100*(1), 13-29.
Explores the relationship between visualization design choices and their ability to support cognition. Fabrikant et al. evaluate two weather map designs with novices before and after they receive training on weather principles. Using eye tracking and task performance measures, they find that without an analytical basis for reasoning, users make fast decisions and choose poorly. However, after training they improve significantly and focus on the relevant portions of each map.

Gahegan, M. (2005). Beyond tools: Visual support for the entire process of GIScience. In *Exploring Geovisualization* (pp. 83-99). Elsevier.
Expanded previous work on the role of visualization in GIScience to include multiple methods for hypothesis generation, including induction, deduction, and abduction. Geovisualization is cast here as a method that can support a wide range of inquiries and forms of communication across every stage of scientific investigation.

Jones, C. E., Haklay, M., Griffiths, S., & Vaughan, L. (2009). A less-is-more approach to geovisualization–enhancing knowledge construction across multidisciplinary teams. *International Journal of Geographical Information Science*, *23*(8), 1077-1093.

Explores the potential for simplified geovisualizations to provide improved support for analytical introspection and collaborative decision making. Jones et al. show how a task-oriented design that results in a tool with limited forms of interactivity and representation may actually be helpful compared to approaches that provide a wide range of representational and interactive options.

Keim, E. D., Kohlhammer, J., & Ellis, G. (2010). *Mastering the information age: Solving problems with visual analytics*, Eurographics Association.
Edited collection resulting from a multi-year research project engaging EU visualization researchers with industry partners to solve problems using visual analysis. Explores the connections between analytical reasoning and the components needed to craft a visual analytics solution and provides concise guidance for designers and developers to employ.

MacEachren, A. M., Gahegan, M., Pike, W., Brewer, I., Cai, G., Lengerich, E., & Hardistry, F. (2004). Geovisualization for knowledge construction and decision support. *IEEE Computer Graphics and Applications*, *24*(1), 13-17.
Demonstrates how geovisualization approaches can be used in a variety of domain areas, including crisis management, epidemiology, and environmental analysis. Focuses on how discoveries can be made in these domains via map-centric interactive interfaces, and is written for a more general audience that may not have much prior knowledge about academic cartography.

MacEachren, A. M., & Ganter, J. H. (1990). A pattern identification approach to cartographic visualization. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *27*(2), 64-81.
Proposed the use of cartographic visualizations for the construction of knowledge and for the purposes of making discoveries, bucking the then-dominant communication paradigm of cartography which suggested that maps are primarily used to convey known information. Made linkages to cognitive theories of pattern recognition that are triggered by visual inputs.

Thomas, J., & Cook, K. A. (2005). Illuminating the path: The R&D agenda for visual analytics national visualization and analytics center. *National Visualization and Analytics Center*.
The first work to introduce the concept of visual analytics, this edited collection brought together a wide range of experts from computer science, information visualization, and other related fields to define a swath of new research challenges. This work helped set in motion a new line of research focused on analytical reasoning with visualization that branched off from the fields of information and scientific visualization.

Design Patterns

The technological implementation of visualization in Geography has transitioned from its initial era of hard-coded and inflexible designs to the contemporary age where flexibility and modularity are commonplace. Early approaches to making visualization modular and reconfigurable focused on crafting component libraries in which multiple predefined visualizations could be selected and combined to create an interactive application that works in a desktop or web environment (Takatsuke & Gahegan, 2002; Van Ho et al, 2012). Contemporary visualization frameworks have focused more exclusively on supporting visualization in the browser, and have sought to create reusable and reconfigurable code elements that are more generic and can afford a higher degree of control to support creative combinations than predefined visualization components would allow (Heer et al. 2005; Bostock & Davies, 2013). A common element across all of these frameworks is that views in visualization are usually coordinated such that interactions are visible in multiple representations and selection/filtering propagate from one view to all of the others (Roberts, 2007).

Bostock, M., & Davies, J. (2013). Code as cartography. *The Cartographic Journal*, *50*(2), 129-135.
Demonstrates how contemporary web mapping is enabled by scripting that controls data, projections, and symbolization. Simple examples are implemented and presented using D3.js, currently the most popular framework for implementing web geovisualizations.

Heer, J., Card, S. K., & Landay, J. A. (2005, April). Prefuse: a toolkit for interactive information visualization. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 421-430).
The precursor to today's widely-used D3.js scripting library for implementing web visualizations, Prefuse provided a collection of connectable components that can be combined to craft interactive visualization systems. Unlike most previous visualization frameworks which offered pre-made visualization components with defined attributes, Prefuse provided abstracted methods for data handling, representation, and interactivity that could be flexibly modified and combined.

Roberts, J. C. (2007, July). State of the art: Coordinated & multiple views in exploratory visualization. In *Fifth International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV 2007)* (pp. 61-71). IEEE.
Defined patterns of coordination between multiple representational views in a visualization environment. Coordinated view systems offer the ability for users to interact with one view and see how data observations are visualized in other views at the same time through a linked highlighting effect.

Takatsuka, M., & Gahegan, M. (2002). GeoVISTA Studio: A codeless visual programming environment for geoscientific data analysis and visualization. *Computers & Geosciences*, *28*(10), 1131-1144.
An early example of a toolkit intended to support the design (and flexible redesign) of interactive geovisualizations, GeoVISTA Studio made it possible for users to wire together visualization components on a virtual canvas and supported coordinated selection and highlighting across all views.

Van Ho, Q., Lundblad, P., Åström, T., & Jern, M. (2012). A web-enabled visualization toolkit for geovisual analytics. *Information Visualization*, *11*(1), 22-42.
Building on the concept of a connectable component library for geovisualization pioneered by CommonGIS, GeoVISTA Studio, and others, Van Ho et al. designed and implemented a framework based on ActionScript for web-enabled geovisualization. Explicit support for storytelling is a notable feature of this work.

Data Quality and Uncertainty Representation

As noted in the introduction to this chapter, visualization can be conceptualized as both process and product, supporting visual thinking and visual communication, respectively. Couclelis 2003 argues that we must accept the existence of uncertainty because we will never be able to fully eliminate it, and makes the case for learning how to effectively communicate it to geospatial knowledge users. The question of how we can best achieve this goal, however, is still far from unanswered, as Kinkeldey, et al. 2014 demonstrate in their systematic review of user studies that have evaluated the ability of different visual representations to communicate geospatial uncertainty. Early attempts to consider which visual variables might best communicate uncertainty MacEachren 1992 married simple uncertainty typologies with visual variables to derive design possibilities. Later research extended these typologies, and systematically tested the intuitiveness and effectiveness of symbols derived from them (MacEachren, et al. 2012). Despite the fact that Kinkeldey, et al. 2014 showed that we are still far from being able to prescribe which symbols to use to communicate uncertainty, by comparison even less is confidently known about how understanding uncertainty affects geospatial decision-making outcomes (Kinkeldey, et al. 2017). Both decision-making contexts and the details of how best to build visual representations of uncertainty can be fiendishly complex given the number of variables that affect the success of the visualizations, making it challenging to derive general principles that can be applied to their design. A good example of this can be seen in a study that examined the 3D decision-making task of locating a geological exploration well's drilling location (Viard, et al. 2010). This study showed that less-than-optimally designed visualizations of uncertainty can impair decision making. Despite these challenges, experimenting with new ways to visually represent uncertainty can be fruitful. Slingsby, et al. 2011 described an evaluation of a set of visualizations they designed to help demographic experts to understand and more effectively work with the outputs of a geodemographic classifier. The visual communication of uncertainty in their visualization environment supported domain experts to explore how the classifier worked and how uncertainty in the input data varied between attributes and across space.

Couclelis, H. (2003). The certainty of uncertainty: GIS and the limits of geographic knowledge. *Transactions in GIS*, *7*(2), 165-175.
A philosophical treatment of uncertainty in the geospatial domain that investigates its role across three different modes of geospatial knowledge production, each with its own limitations: data, method and product. Visualization can be considered both a type of geospatial knowledge product and a method. A key argument is that because we cannot eliminate uncertainty, effectively communicating it to knowledge users of all kinds (experts and laypersons) is crucial.

Kinkeldey, C., MacEachren, A. M., Riveiro, M., & Schiewe, J. (2017). Evaluating the effect of visually represented geodata uncertainty on decision-making: Systematic review, lessons learned, and recommendations. *Cartography and Geographic Information Science*, *44*(1), 1-21.
Reviews recent geospatial uncertainty visualization user studies that focused on decision making. A key finding is that there is no existing conceptual framework for making sense of the findings of decision-making studies. They suggest the ability to compare and generalize from these studies will improve when using an uncertainty visualization typology, a typology of categories of reasoning tasks, and knowledge of what kinds of decisions require consideration of geospatial uncertainty.

Kinkeldey, C., MacEachren, A. M., & Schiewe, J. (2014). How to assess visual communication of uncertainty? A systematic review of geospatial uncertainty visualisation user studies. *The Cartographic Journal*, *51*(4), 372-386.
Reviews geospatial uncertainty visualization user studies undertaken since the 1990s, systematically describing studies of techniques for communicating uncertainty visually using three dimensions: coincident-adjacent, intrinsic-extrinsic, static-dynamic. A key finding is that the ad-hoc nature of many studies leads to difficulties in comparing results. They suggest future studies should be guided by uncertainty visualization typologies and that these typologies include at least three high-level task categories: communication, analysis, and exploration.

MacEachren, A. M. (1992). Visualizing uncertain information. *Cartographic Perspectives*, (13), 10-19.
A seminal paper on visualizing geospatial information uncertainty. This early paper on this topic presents a typology of uncertainty as it applies to geospatial information and considers how both Bertin's visual variables as well as additional visual variables such as symbol focus (fog/blur) can be used to represent uncertainty. Different methods of combining uncertainty with attributes (map pairs, sequential presentation, and bivariate maps) are considered as potential visualization strategies.

MacEachren, A. M., Roth, R. E., O'Brien, J., Li, B., Swingley, D., & Gahegan, M. (2012). Visual semiotics & uncertainty visualization: An empirical study. *IEEE Transactions on Visualization and Computer Graphics*, *18*(12), 2496-2505.
Develops an extended typology of categories of data uncertainty (*e.g.,* accuracy, consistency, subjectivity, etc.) and how each interacts with spatial, temporal or attribute components of information. Syntactical relationships between these components and visual variables were investigated empirically to understand the intuitiveness and effectiveness of different visual representations of uncertainty for point symbols. Iconic symbols were generally more intuitive and similarly effective as abstract symbols, but took longer to read.

Slingsby, A., Dykes, J., & Wood, J. (2011). Exploring uncertainty in geodemographics with interactive graphics. *IEEE Transactions on Visualization and Computer Graphics*, *17*(12), 2545-2554.
Statistical classifiers such as geodemographic classifiers reduce the dimensionality of population data. Uncertainty in both input variables and the classification itself can vary spatially and this can affect the reliability of inferences made from the classifier. Exploratory visualization tools incorporating multiple linked maps and statistical graphics helped expert users increase their understanding of the classifier as well as of heterogeneity in the input data and its uncertainties.

Viard, T., Caumon, G., & Lévy, B. (2011). Adjacent versus coincident representations of geospatial uncertainty: Which promote better decisions?. *Computers & Geosciences*, *37*(4), 511-520.
Extends empirical evaluation of a visual representations of attribute uncertainty from more commonly studied 2D applications to a typical 2.5D geological decision-making scenario, choosing the drilling location for an exploration well. The experiment demonstrated that participants using well designed coincident uncertainty visualizations outperformed those with adjacent uncertainty visualizations for the most difficult task. They speculated this was due to the additional cognitive load of integrating two displays mentally.

Big Data & Visualizations

One of the common reasons people who work with data (spatial or otherwise) turn to visualizations is that the data is too 'big' (Keim et al., 2013; Robinson et al., 2017). Some of the statistical methods do not scale, and one does not even know where to begin discovering what is in the data (Li et al., 2015). When the study is hypothesis-driven, the goals are often clear already before the data collection, and researchers often know what they would like to summarize, compare and cross-check. However, there are hidden patterns even in these well-planned data sets that may lead to new hypotheses; and as importantly, there are many data sets that are collected as a byproduct of people using social media, GPS enabled devices or countless sensors being installed all around the world for monitoring things (*e.g.,* animal movements, people's usage patterns of roads/stations/services, airborne monitoring of water or air pollution, energy use, etc.) (Guo & Zhu, 2014). Many of these are not intentionally "designed" scientific data collections but can be used (and be extremely useful) at the service of science in studying important social and environmental issues (Robinson et al., 2017; MacEachren, 2017). To discover patterns and anomalies in such large data sets, an ideal software environment is where researchers can have computation and visualization equally powerful and interact with each other, such as in visual analytics environments (Keim et al., 2013; Li et al., 2015). Besides multiple-linked views that visual analytics software offers, explorations on how to visualize big data led to considerations of larger displays (such as tiled visualization walls). Also, *immersive analytics* was born at least partly due to the needs to explore large data sets; in which the analyst can 'walk' in their data using virtual reality or superimpose it onto a relevant physical space using augmented/mixed reality and inspect the patterns and anomalies on an unusual scale, which may potentially lead to new insights (Reda et al., 2013).

Guo, D., & Zhu, X. (2014). Origin-destination flow data smoothing and mapping. *IEEE Transactions on Visualization and Computer Graphics*, *20*(12), 2043-2052.
Provides a great example of analyzing 'big' geographic mobility data that is turned into visualizations, specifically generalized flow maps based on density estimations captured based on the patterns found in the data.

Keim, D., Qu, H., & Ma, K. L. (2013). Big-data visualization. *IEEE Computer Graphics and Applications*, *33*(4), 20-21.
This piece is an editorial of a special issue on big data visualization, which the reader may find interesting to read as an entry point, and follow up with the papers included in the special issue. It is a computer science perspective on big data visualization, thus has a wide interdisciplinary approach to the topic.

Li, S., Dragicevic, S., Castro, F. A., Sester, M., Winter, S., Coltekin, A., ... & Cheng, T. (2016). Geospatial big data handling theory and methods: A review and research challenges. *ISPRS Journal of Photogrammetry and Remote Sensing*, *115*, 119-133.
This review and research challenges paper takes a more data-centric look at the big data from a geospatial lens. It contains issues of not only high-dimensional attribute data but spatio-temporal and image data too. Has a specific visualization section too.

MacEachren, A. M. (2017). Leveraging big (geo) data with (geo) visual analytics: Place as the next frontier. In *Spatial Data Handling in Big Data Era* (pp. 139-155). Springer, Singapore.
An interesting example of what human geographers and other social scientists can do with big data in collaboration with the GIScientists or computer scientists: Paper argues that one can attempt formalizing *place* instead of studying space, which is more typical in quantitative approaches.

Reda, K., Febretti, A., Knoll, A., Aurisano, J., Leigh, J., Johnson, A., ... & Hereld, M. (2013). Visualizing large, heterogeneous data in hybrid-reality environments. *IEEE Computer Graphics and Applications*, *33*(4), 38-48.
Brings a relatively old idea brought to new light: What if we can see our spatial or non-spatial data in room/street scale, and literally walk in it? This paper offers an approach to implementing this

idea, as a solution to visualizing large and multivariate data sets that may come from different sensors and modes of data collection.

Robinson, A. C., Demšar, U., Moore, A. B., Buckley, A., Jiang, B., Field, K., ... & Sluter, C. R. (2017). Geospatial big data and cartography: research challenges and opportunities for making maps that matter. *International Journal of Cartography*, *3*(sup1), 32-60.
Provides a focus on how cartography should respond to challenges of working with big data, and identifies a set of research challenges which may be specifically relevant to readers from the cartography and geovisualization domains.

Visualization Context, 3D and Extended Reality

Technological changes shape the design possibility space for visualization designers, in terms of both affordances and constraints. Visualizations are no longer found only in the pages of books, but on the Internet, on mobile devices in apps, and in large-scale electronic displays such as virtual reality environments. This expansion in activities and environments in which we use visualizations and in the media for which visualizations can be designed has led to the need to understand more about what design principles apply no matter the design context, and those that are context-sensitive (Griffin, et al. 2017). We can distinguish between visualization use situations that are dynamic, such as when a mobile device user might use a visualization while they are moving from place to place, and those that are (relatively) more fixed, such as those in which a visualization is displayed in an immersive virtual environment, such as in a company or university lab. Nevertheless, visualization approaches like augmented/mixed reality blur the lines between visualizations designed for mobile devices and those designed for laboratory or office spaces (Çöltekin, et al. 2020). A key concept informing mobile map design is context modeling. While quite a few different models of context have been proposed, Reichenbacher 2003 presented one of the first, along with an example of how a context model might helpfully inform design. Other recent work on mobile mapping has extended thinking about design to account for cases where visualizations in mobile device apps are not only consumed by their users, but also produced when their users contribute data, such as in apps designed for collecting volunteered geographic information (VGI) (Ricker, et al. 2014). Visualizations designed for use by people in virtual environments have undergone many changes over the past two decades. The ready availability of massive amounts of data, some generated in real time or near-real time, and at high spatial resolutions across the whole planet has changed what we can show and the questions we can ask and answer in virtual environments (Goodchild, et al. 2012). Immersive virtual environments may be one way for a visualization platform to help visualization users cope with this data flood (Chandler, et al. 2015).

Chandler, T., Cordeil, M., Czauderna, T., Dwyer, T., Glowacki, J., Goncu, C., ... & Wilson, E. (2015). Immersive analytics. In 2015 Big Data Visual Analytics (BDVA). In *IEEE, September* (pp. 1-8).
Describes the nascent field of immersive analytics, wherein multisensory user interfaces are used to provide visualization users with a more engaging experience that allows them to be immersed in their data. The authors contend that if people encounter engaging visualization systems then they will be more likely to adopt these tools. Presents several use cases for immersive analytics and research questions that need answers to move the field forward.

Çöltekin, A., Griffin, A. L., Slingsby, A., Robinson, A. C., Christophe, S., Rautenbach, V., ... & Klippel, A. (2020). Geospatial Information Visualization and Extended Reality Displays. In *Manual of Digital Earth* (pp. 229-277). Springer, Singapore.
Critically reviews the current state-of-the-art in geovisualization and extended reality visualizations and assesses their contribution(s) to achieving Gore's Digital Earth vision. Provides a more recent overview of the current visualization capabilities than does Goodchild, et al. 2012, but has a broader focus than the former contribution on virtual globes. It includes discussion of broadly visualization-related concepts such as human factors and visual analytics.

Goodchild, M. F., Guo, H., Annoni, A., Bian, L., De Bie, K., Campbell, F., ... & Lewis, A. J. (2012). Next-generation digital earth. *Proceedings of the National Academy of Sciences*, *109*(28), 11088-11094.
Assesses the visualization capabilities of virtual globes by the early 2010s against Al Gore's 1998 vision. Shows that virtual globes have been helpful in improving communication of science to the general public because they are easy to interact with and produce compelling visualizations, but identifies key limitations. Presents a vision for next-generation virtual globe functionality as multiple connected infrastructures to edge closer to achieving Gore's vision.

Griffin, A. L., White, T., Fish, C., Tomio, B., Huang, H., Sluter, C. R., ... & Picanço, P. (2017). Designing across map use contexts: A research agenda. *International Journal of Cartography*, *3*(sup1), 90-114.
Increasing diversity in map use situations means designs that work for one situation may not work for others. This paper proposes design transferability as a concept that might help visualization designers understand what kinds of redesigns are necessary for visualizations to work in multiple contexts. It identifies research challenges and opportunities related to understanding when and how designs transfer across contexts.

Reichenbacher, T. (2003, August). Adaptive methods for mobile cartography. In *Proceedings of the 21st International Cartographic Conference* (pp. 1311-1322). Durban, South Africa.
Presents an early model of context for visualizations, especially those used on mobile devices. This context model includes components such as the user, technology, information, activities, and situation. The author proposes that three components of visualizations can be adapted to different contexts: geoinformation, user interface, and cartographic representation. The approach is demonstrated using a small scenario, which highlights the existence of tradeoffs between privacy and utility.

Ricker, B., Daniel, S., & Hedley, N. (2014). Fuzzy Boundaries: Hybridizing Location-based Services, Volunteered Geographic Information and Geovisualization Literature. *Geography Compass*, *8*(7), 490-504.
Critically reviews literature relevant to designing location-based mobile apps, in which visualizations are a key application component. Draws a distinction between productive (active) and consumptive (passive) use of geoinformation from mobile maps and the role that visualization plays in facilitating the development of geographic understandings from each use context.

Critical Reflections on Visualization, Ethics

Mapping has always invoked issues of power and ethics, and the rise of visualization techniques has in turn prompted scholars to critique it from a variety of perspectives (Leszczynski, 2019). Data are not value neutral, and neither are the maps and visualizations that are made. Uncertainty and dynamism are intertwined with all problem contexts (Gould, 1995) and how a visualization is interpreted is never exactly the same amongst its viewers. Today we see an increasingly diverse range of potential geographic data sources to visualize (Elwood, 2009), authored more often by non-experts than experts, and in some cases authored by entirely automated means (Crampton et al. 2013). The ways we visualize these data can be shaped by what we know about human perception in order to make a technically-correct visualization. However, one can question what technically correct means *e.g.,* what are the implications of using 3D in visualization? (Shepherd, 2008). Besides the perceptual and technical concerns, there are political and power-related issues we cannot ignore. In fact, what we are able to visualize is often heavily influenced (if not outright controlled) by the handful of people who make decisions regarding which data are captured, how they are described, and how they are made available to others (Thatcher, 2014).

Crampton, J. W., Graham, M., Poorthuis, A., Shelton, T., Stephens, M., Wilson, M. W., & Zook, M. (2013). Beyond the geotag: situating 'big data'and leveraging the potential of the geoweb. *Cartography and Geographic Information Science*, *40*(2), 130-139.
Demonstrated new ways in which geospatial social media can be evaluated apart from simplistic representations of point locations from geotags. Five approaches were proposed, including the use of implicit geography, focusing on spatiotemporal change, augmented concepts of proximity, examining bot-generated content, and using external sources of media to complement findings.

Elwood, S. (2009). Geographic Information Science: new geovisualization technologies—emerging questions and linkages with GIScience research. *Progress in Human Geography*, *33*(2), 256-263.
Characterizes the rise of heterogeneous forms of geospatial media on the web and posits that new methodological combinations will be needed in order to analyze and understand them, and suggests that the practices associated with generating these new data should motivate new research as well.

Gould, P. (1995). Sources of Error in a Map Series, or Science as a Socially Negotiated Enterprise. *Cartographic Perspectives*, (21), 30-48.
Powerful example showing how an animated series showing the spatio-temporal spread of AIDS in the United States evolves in form and interpretation after its initially drafted. As science and society change—so does the map, and uncertainty will always persist despite the willingness of a map audience to accept it as-is.

Leszczynski, A. (2019). Digital methods II: Digital-visual methods. *Progress in Human Geography*, *43*(6), 1143-1152.
Proposes three lines of inquiry that employ the use of visual artifacts and visual methods in human geography; evaluating the political and social implications of visual artifacts, creating new visual artifacts through novel combinations and reinterpretations of visual platforms, and using visualization to explore and characterize research data. Emphasizes qualitative and critical approaches to these three areas, highlighting recent examples in the literature.

Shepherd, I. D. (2008). Travails in the third dimension: A critical evaluation of three-dimensional geographical visualization.

Critique of the many issues associated with using 3-dimensional representation of geographic data. Analytical and perceptual issues with showing thematic data in 3D are summarized and demonstrated through graphical examples.

Thatcher, J. (2014). Big data, big questions| Living on fumes: Digital footprints, data fumes, and the limitations of spatial big data. *International Journal of Communication*, *8*, 19.
Critiques data driven geospatial research by exploring the ways in which algorithms, database structures, and data observations developed by small groups of programmers define the inputs that are used by researchers and thereby have a significant impact on the production of geospatial science.

Application Examples

Visualization can be used to a very wide range of application areas, for example, ecology (Demšar, et al. 2015), journalism (Gray, et al. 2012), disaster management (Liu and Palen 2010, MacEachren, et al. 2011), planning services in cities (Wood, et al. 2011), and disease outbreak investigation (Maciejewski, et al. 2007), among others. The practice of visualization is used to support different aims including communicating information to others, exploring and analyzing scientific data, understanding the current state of systems (*e.g.,* McArdle and Kitchin 2016), and operational decision-making. Research about visualizations also has a range of goals, including developing novel visual representations (Demšar, et al. 2015, Dorling 2012); evaluating the utility, efficiency and usability of a specific visualization toolset for a particular use context (Johansson, et al. 2017, Savelyev and MacEachren 2018); and selecting optimal combinations of visual representations, including how they can be used together with computational and statistical methods (Maciejewski, et al. 2007, MacEachren, et al. 2011).

Demšar, U., Buchin, K., van Loon, E. E., & Shamoun-Baranes, J. (2015). Stacked space-time densities: A geovisualisation approach to explore dynamics of space use over time. *GeoInformatica*, *19*(1), 85-115.
Demonstrates a new use of the space-time cube to show temporal changes in how animals use and move through space with stacked volumetric space-time densities. The method can help to identify areas that are frequently visited by an animal and whether there are distinct temporal patterns to these visits, which may or may not change over time. When applied to bird movement data, the method identified differences in bird behaviour.

Dorling, D. (2012). *The visualization of spatial social structure*. John Wiley & Sons.
This monograph draws its foundations from visualizations originally designed for the author's 1991 PhD dissertation, and includes a revised text. The principal argument of the monograph is that maps designed to represent physical geography can conceal important social structures, thus new forms of visualization are needed for representing social geographies. The monograph presents several (for the 1990s) novel visualization techniques, including what is now known as the Dorling cartogram.

Gray, J., Chambers, L., & Bounegru, L. (2012). *The data journalism handbook: how journalists can use data to improve the news*. " O'Reilly Media, Inc.".

Describes how visualization can be used in the reporting (*i.e.,* research) and communication (*i.e.,* storytelling) phases of journalistic practice. Chapter 6 in particular offers a wealth of suggestions about how visualization can be used to explore datasets and offers a curated list of visualization tools that the editors find helpful in their own journalistic practice.

Johansson, J., Opach, T., Glaas, E., Neset, T. S., Navarra, C., Linnér, B. O., & Rød, J. K. (2016). VisAdapt: A visualization tool to support climate change adaptation. *IEEE Computer GraphicsaAnd Applications*, *37*(2), 54-65.
Reflects on the creation of a single-webpage-based interactive visualization designed for the general public (*i.e.,* individual homeowners) to show predicted climate change impacts to support decision making about climate change adaptation measures. It also provides a discussion of user-centred design's iterative cycle of design prototyping, user studies, and redesign, which identified a need to reduce interface complexity and increase constraints on user attention through careful sequencing of information views.

Liu, S. B., & Palen, L. (2010). The new cartographers: Crisis map mashups and the emergence of neogeographic practice. *Cartography and Geographic Information Science*, *37*(1), 69-90.
Explores how visualizations have been hybridized to draw upon both professional and participatory geotechnologies, either by formalizing (initially) informal cartographic practices or including informal practices within formal ones. The authors argue that hybridization can be the foundation for improved cartographic literacy and can more broadly distribute both the production and consumption of maps, which is particularly important when maps need to be generated and consumed quickly, as in crisis situations.

MacEachren, A. M., Jaiswal, A., Robinson, A. C., Pezanowski, S., Savelyev, A., Mitra, P., ... & Blanford, J. (2011, October). Senseplace2: Geotwitter analytics support for situational awareness. In *2011 IEEE conference on Visual Analytics Science and Technology (VAST)* (pp. 181-190). IEEE.
Develops a visual analytics environment that can be used to make sense of geolocated social media feeds to develop situational awareness for crisis management activities. The environment implements a place-time-entity conceptual framework that can be used with visual and computational tools to query and explore the social media data by filtering on one framework component. It also implements overview-detail methods that can be applied to both place and time.

Maciejewski, R., Tyner, B., Jang, Y., Zheng, C., Nehme, R. V., Ebert, D. S., ... & Glickman, L. T. (2007, October). Lahva: Linked animal-human health visual analytics. In *2007 IEEE Symposium on Visual Analytics Science and Technology* (pp. 27-34). IEEE.
Describes a visual analytics environment designed to facilitate identification of disease outbreaks or environmental contamination incidents. It links multiple datasets (*e.g.,* human and animal disease) to support identification of potential outbreak- or incident-related clusters visually and statistically and explore potential causal explanations. It examines case study scenarios using the tools, demonstrating that they can be used successfully to detect anomalous spatiotemporal patterns that might indicate an outbreak or incident.

McArdle, G., & Kitchin, R. (2016). The Dublin Dashboard: Design and development of a real-time analytical urban dashboard. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-4/W1, 19-25, An early paper describing a city dashboard that pulls together a multiplicity of real-time data streams. Dashboards are visualizations that are used for operational decision making or integrating data from multiple custodians. The dashboard described here aimed to provide an overview of the city's state at any given point in time. It used open-source technologies and was designed to be easily extensible to allow ingestion of different types of data.

Savelyev, A., & MacEachren, A. M. (2018). Augmenting geovisual analytics of social media data with heterogeneous information network mining—Cognitive plausibility assessment. *PloS One*, *13*(12).
Provides evidence that visualization is helpful for assisting visual analytics application end users to understand how a heterogeneous information network mining approach can be applied to exploring messy geolocated social media to help end users (in the case scenario, journalists) look for relevant and informative social media posts when doing research to develop newspaper coverage of environmental hazard events.

Wood, J., Slingsby, A., & Dykes, J. (2011). Visualizing the dynamics of London's bicycle-hire scheme. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *46*(4), 239-251.
Presents a visualization environment that is capable of producing insightful visualizations of large numbers of origin-destination movements to support the use and management of an urban bicycle hire operation. The complementary visualizations include curved flow maps, gridded hierarchical spatial treemaps of docking stations that enable space-time pattern exploration, and origin-destination maps. The tools preserved key city landmarks and included animated transitions between geographic and gridded views to support spatial orientation.