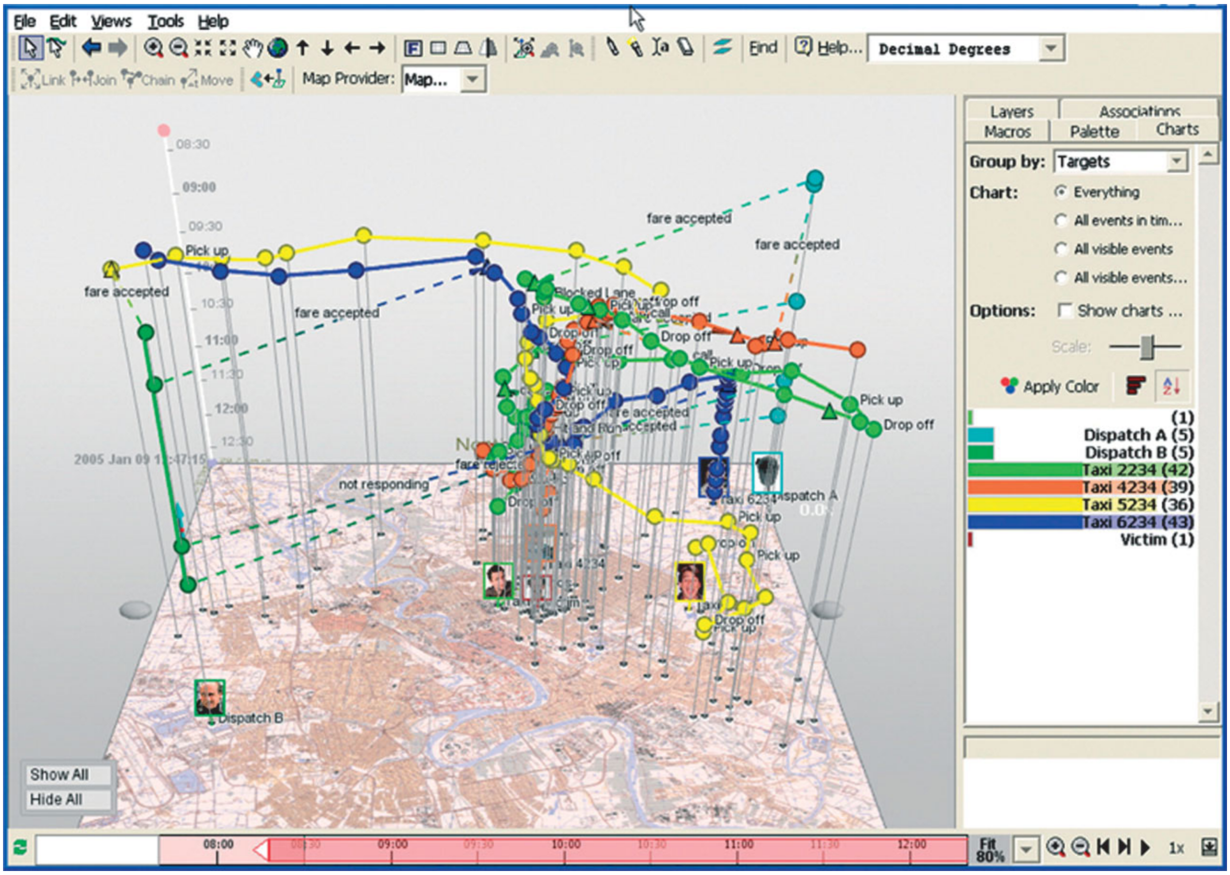

FIGURE 8 | A screenshot of GeoTime.

as our perception and cognition are concerned, the whole is more than the sum of parts. Most commonly known Gestalt principles are proximity, similarity, continuity, closure, figure and ground, and symmetry. A comprehensive explanation of these principles and a rich set of examples can be found in *How Maps Work*[41] in the context of cartography, that is, the design of geographically based thematic maps.

The proximity principle says that we tend to see groupings of individual items in a visual arrangement based on the proximity between these items. Items that are relatively close to one another tend to give us a sense of similarity. In other words, we see individual items in groups of some underlying similarity. This principle has been adapted by the information visualization community from the early stage. Algorithms that can arrange information items in this fashion tap into the proximity principle. Some interesting examples include Bead[42] and Information Mural.[43]

The similarity principle from Gestalt psychology says that visual attributes such as the shape, color, and texture are cues for us to group items, for example, all the circles in one group and all the triangles in another. The proximity and similarity principles can be used simultaneously to reinforce each other.

The Mantra of Visual Information Seeking

The most widely known visual information seeking mantra is given by Ben Shneiderman, University of Maryland: Overview first, zoom and filter, then details-on-demand.[44] This mantra insightfully summarizes the essential elements of interacting with graphically presented information.

Designers of visual overviews commonly capitalize on metaphors that can give users a sense of intuitiveness and familiarity. Naturally, metaphors of an information space are particularly popular, especially in 1990s, ranging from two-dimensional maps, three-dimensional landscape views and contours, to star fields and galaxies of information. An important function of an overview is to depict interrelationships among units of information. Units of textual information include words, sentences, documents, and collections of documents such as websites. Units of visual information include scenes, episodes, and libraries of videos.

Information space metaphors naturally invite navigational operations such as zoom, pan, tilt, and rotate. One of the earlier claims and design goals of information visualization is that good information visualization should present information to users intuitively. Many filtering operations have been adapted to enable users interact with dynamic information visualization, including brushing, linking, dynamic queries, and coordinated views.

In 1996, Shneiderman offered a taxonomy for visual information seeking.[44] The taxonomy divides general visual information seeking into seven data types and seven tasks. This taxonomy is one of the earliest and most influential contributions to the information visualization field.

Seven Data Types

- one-dimensional data;
- two-dimensional data;
- three-dimensional data;
- temporal data;
- multidimensional data;
- tree data;
- network data.

Seven Tasks

- overview;
- zoom;
- filter;
- details-on-demand;
- relate;
- history;
- extract.

The data type by task taxonomy has influenced a generation of information visualization researchers. Other notable efforts include the data state reference model.[3]

The Pursuit of Insights

Reflections on insight-centric evaluation are motivated by the increasing concern of how to establish the effectiveness of interacting with information visualization interfaces. On the one hand, it is almost a community-wide consensus that insight is the ultimate goal of information visualization. On the other hand, the definition of insight in the information visualization literature *per se* has been vague and ambiguous. The nature of insight has been extensively studied in the context of scientific discovery in cognitive science, psychology, and history of science. Few connections have been established so far between the study of insight in other disciplines and the field of information visualization. An intriguing introduction to some of the recent understanding of the brain activities that lead to insights can be found in a *New Yorker* article *The Eureka Hunt*.[45] *The Nature of Insight* is a comprehensive collection of studies of insight.[46]

In a recently developed explanatory and computational theory of scientific discovery, the nature of insight is characterized by a brokerage mechanism and a burst function of recognition.[47] The brokerage mechanism echoes what is described in the Eureka Hunt in that one arrives at insights by linking previously unconnected thoughts. The theory is computational and it is possible to formulate the search for insights as a problem of searching for the potential linkage between even the most unthinkable relations. Initial studies of transformative discoveries such as Nobel Prize winning discoveries are particularly promising. This approach is particularly relevant to visual analytics and insight-based evaluative studies because they can characterize insightful patterns in terms of structural and temporal properties.

Within the information visualization community, notable efforts on characterizing and measuring insights include exploratory approaches as opposed to benchmark-based experimental studies,[9] lessons learned from the first 3 years of InfoVis contests,[48] and more recent reflection in the context of visual analytics.[8] An interesting framework of evaluating interactive visualizations is proposed recently in Ref 49. The framework is built on top of a generic conceptual model in human–computer interaction, namely Don Norman's Seven Stages of Action.[50] According to the Seven Stages of Action, two stages of interacting with computer interfaces are particularly problematic: execution and evaluation. The gulf of execution and the gulf of evaluation are used to refer to these problematic stages. The gulf of execution, for example, should be narrowed so that users can accomplish their tasks smoothly and seamlessly. The gulf of evaluation should be narrowed so that users can judge their progress accurately.

Much of the discussions in information visualization on insights primarily address practical and methodological issues concerning how evaluative studies should be designed to capture the effectiveness of an information visualization design in terms of insights. The types of insights that are relevant to information visualization and evaluative studies have theoretical and practical implications. We found two meta-analysis studies of information visualization.[51,52] Given the growing calls for theoretical foundations in the field, this is expected to be a significant topic of research.

Theoretical Frameworks

The general consensus, as reported by a recent workshop and a few other public presentations, was that information visualization currently lacks adequate theoretical foundations.[53] As a result, many approaches are *ad hoc* in nature. A week-long seminar took place at Dagstuhl, Germany in mid-2007, for example, addressed four potential directions for developing new theories. The lack of theories becomes particularly prominent in information visualization courses and when designing empirical and evaluative studies.

The search for theoretical foundations increasingly introduces and adopts theories and conceptual frameworks from other fields and disciplines. For example, distributed cognition in human–computer interaction is seen as a potential candidate for a theoretical framework for information visualization.[54] Norman's Seven Stages of Action, also in human–computer interaction, provides a new insight into interacting with information visualizations, specifically on the gulf of execution and the gulf of evaluation.[49]

Many information visualizations lack a quantitative measure that could indicate the overall quality, uncertainly, novelty, and other evaluative metrics. The focus on gulfs of execution and evaluation, for example, has the potential to make progress in this direction.

TECHNICAL ADVANCES

Some of the recent developments in information visualization are worth noting. At the technical level, scalability issues remain to be a long-lasting challenge.[55] Some of the algorithms developed for clustering large-scale data sets in machine learning are particularly appealing, such as Refs 56,57 and one can expect these algorithms will soon find their ways to information visualizations.

Edge Bundling

Edge bundling is an emerging strategy to solve a common problem in visualizing a densely connected graph due to cluttered images caused by overlapping edges. Avoiding edge crossings has been long recognized as one of the constraints that could improve the clarity of resultant visualizations. Recently, an interesting strategy has emerged—that is the use of edge bundling techniques in a variety of graph visualizations to increase the clarity of visualized patterns. Bundling reduces visual clutter. Visualizations with bundled edges make it easier for viewers to see underlying patterns than non-bundled versions,[58] for example, as shown in Figure 9. Edge bundling is a generic technique in nature because it can be applied virtually to all node-and-link diagrams regardless the underlying layout algorithms. In this sense, it is similar to other generic display techniques such as fisheye views. A geometry-based edge bundling example appears recently, showing prominent patterns of migration in the USA[59] (Figure 10).

Constraint-Based Graph Drawing

Another trend originated from the graph drawing community is constraint-based graph drawing. Tim Dwyer et al. are the leading researchers in this research area.[60] Many graph visualization applications can benefit from the new development in this direction because of the generic and valuable role in establishing visual hierarchies and grouping (Figure 11).

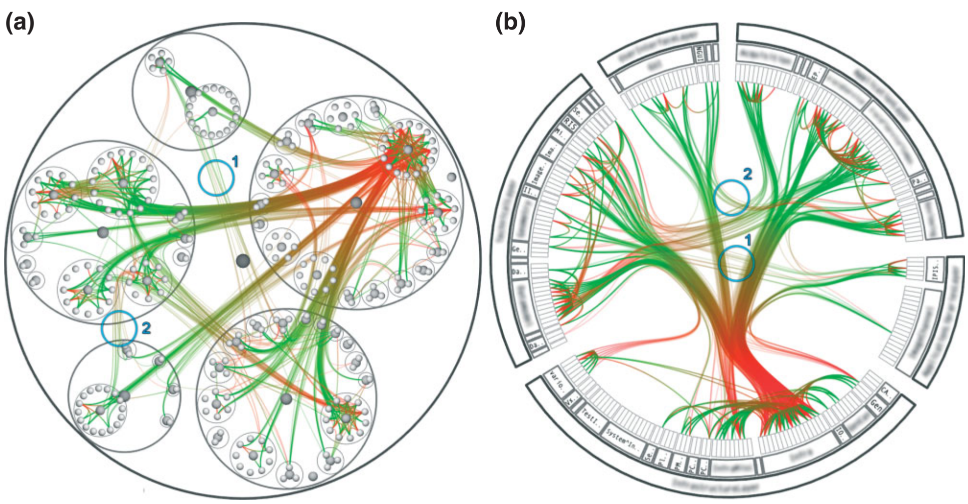

FIGURE 9 | Bundled edges in graph visualization.[58]

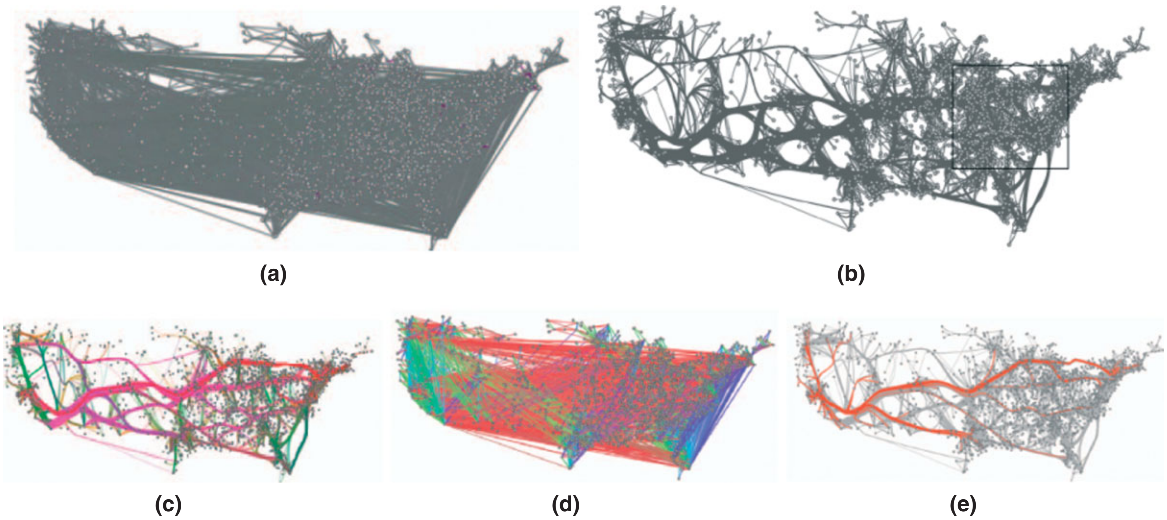

FIGURE 10 | Geometry-based edge bundling.[59]

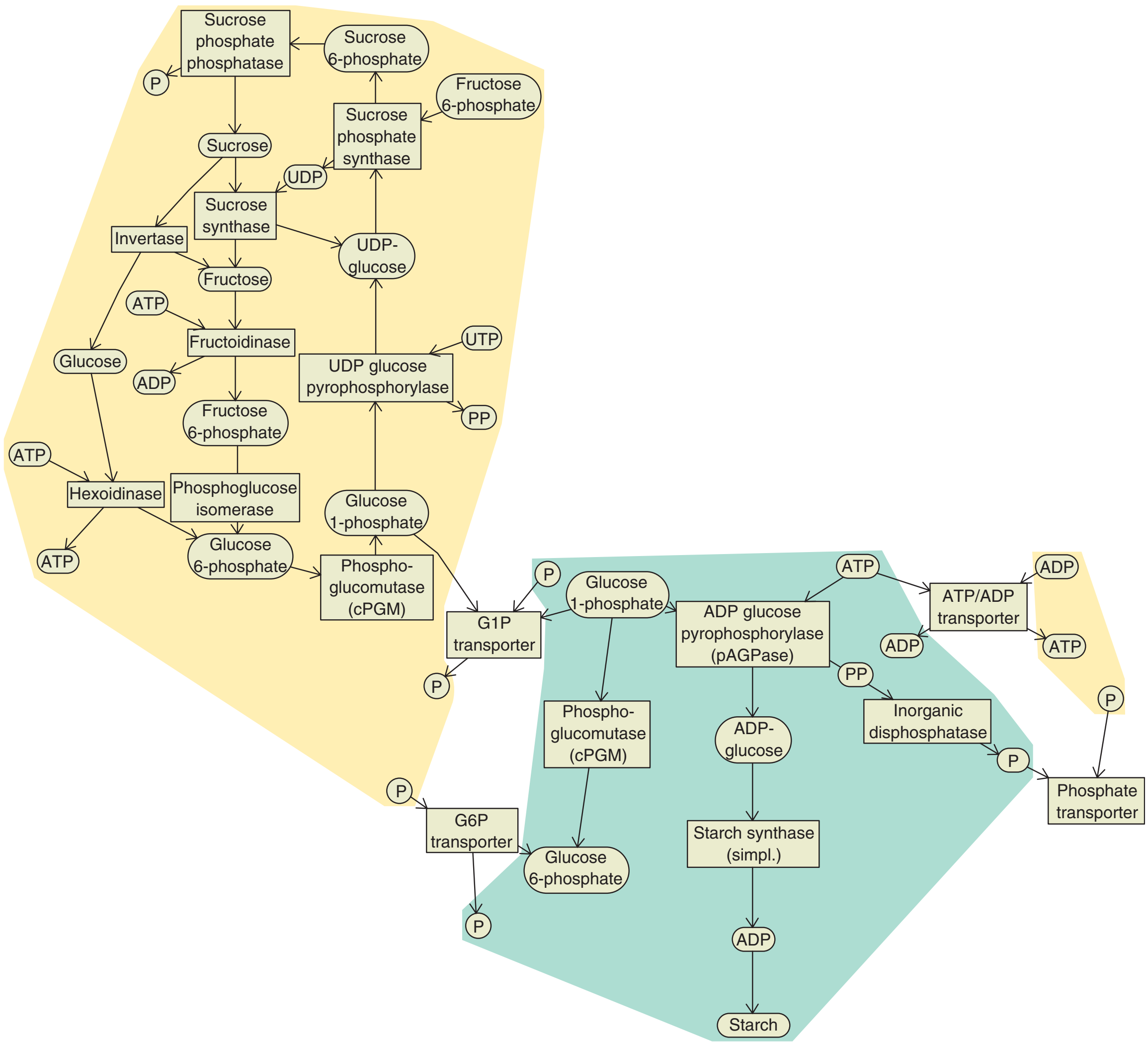

FIGURE 11 | Layout with constraints.[60]

Logarithmic Transformations

One of the problems identified earlier on by the information visualization community is the tension between showing more local details while maintaining users' contextual awareness. The problem is known as the focus + context problem. Many widely known techniques in information visualization were indeed developed originally to deal with such problems, notably including fisheye views[16] and hyperbolic views.[31] Along a similar vein, Figure 12 shows a logarithmic view.[61] Logarithmic transformations are commonly used by astronomers when they need to deal with multiple vast scales. The major advantage of a logarithmic view is its computational scalability. Like fisheye views, a logarithmic view also enlarges some areas of display at the expenses of other areas. Figure 13 illustrates the use of logarithmic transformations of the sky. Astronomical objects distributed across a wide span of multiple scales are depicted in the same single sky map. See video of mapping the universe with Sloan Digital Sky Survey.[e]

Other enabling and supporting techniques include fast point-feature labeling algorithms,[62] and fast network scaling algorithms that improve semantically desirable but computationally expensive algorithms such as Pathfinder network scaling.[63–66]

FIGURE 12 | Logarithmic view centered at the Capitol in Washington.[61] Points northwest of the capitol are mapped to a vertical line in the middle of the image. Points southeast are mapped to the very left and the very right.

EMERGING TRENDS AND FUTURE DIRECTIONS

Mixed-Initiative Interaction

Integrating perceptual guidelines from human vision with an AI-based mixed-initiative search strategy is a promising but challenging direction for information visualization.[67] Mixed-initiative interaction is motivated by the observation that even experienced designers cannot be expected to know everything about how to construct effective visualizations due to the diverse range of situated requirements. Furthermore, designers often repeatedly utilize the same basic design strategy. Consequently, the resulting visualization may not be the best possible design option. It is often more effective to be able to explore the same set of data from different perspectives through different visualization designs. Therefore, the goal of mixed-initiative interaction is to augment designers with an easy access to the existing body of knowledge of proven and effective visualization design options in a given scenario. The underlying principle is very similar to the concept of design pattern and design language in the field of human–computer interaction.