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Many types of design needed for effective visualizations

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Abstract

For effective visualizations, there are many types of design to consider. Visualization design focuses on core theory of tasks, data and visual encodings. Workflow design, user interface design and graphic design all contribute to a successful visualizations. All design aspects range from initial design exploration to iterative design refinement. Guidelines can help, but have limitations. Examples illustrate visualization issues arising from missing domain knowledge, facilitating alternative designs, refining labeling, layouts to aid workflow, frankenvis, 3D timeseries, and ineffective design collaboration.

CCS Concepts

• ***Human-centered computing*** → ***Visualization design and evaluation methods;*** *Field studies; Information visualization;*

1. Introduction

While there are many gaps between research and industry, there is a significant design skills gap. Training in academic visualization is not necessarily suited for design needs for industry applications: design needs extend beyond visualization theory; accepted research may not be applicable to expert domains; and the scientific method is not suited to complex, multi-faceted, potentially conflicting requirements with multiple valid solutions.

The design of an effective visualization used in real-world applications has many considerations:

- **Visualization design**: i.e. the visual encodings and interactions of data into effective representations to aid analysis and comprehension, plus associated legends, labels, interactions, etc.
- **Workflow design**: so that the visualization fits within a larger analytical process allowing the user to complete their objective through a series of tasks using the visualization(s) and associated interactions.
- **User interface design**: to create the appropriate combination of user interface elements following reasonably expected design patterns that also fit the target user community.
- **Graphic design**: so that color, layout, organization, etc., of individual components and all components are logically grouped, harmonious and facilitate conceptualization of the system.

Each of these design tasks can be addressed throughout the design lifecycle, from:

- **Design space exploration**: Early in the design process, the range of potential designs must be broadly explored, so that better potential designs are considered prior to locking in on a specific design direction.
- **Design refinement**: Later in the design process, there are many improvements and enhancement feasible to make a design more effective for the target use cases, which may also evolve through the design process.

Further, all the above design tasks must be understood with regards to all stakeholders in the system:

- **Objectives design**: Goals may not be well-defined, and initial design tasks may require clarifying objectives of the target system as each participant may have varying goals.
- **Design facilitation**: may be required, as casual end-users, expert end-users, managers, technical systems staff (e.g. I.T., dev ops) have deep expertise, but unlikely have expertise in visualization nor design.

In the computer sciences, broader design is often minimally addressed. Human-computer interaction based approaches often consider a few close variants, evaluate, and create guidelines, which are then followed by practitioners. Visualization design guidelines and texts are focused on a narrow scope of assessing user tasks and creating an appropriate visual encoding based on perceptual abilities (e.g. Munzner's four levels of validation [**?**]) or even more narrow to focusing only on the data-type to visualization-type correspondence (e.g. data-to-viz.com). In real-world solutions, visualizations are part of a larger, complex system, and pre-existing guidelines may not be available for the target system, may be too narrow for the broader workflows required, may mismatch the workflow of the target system, or may not meet the skills and needs of expert users. The visualization computer-scientist may be able to create code and studies to evaluate new alternatives, but does not have a robust design education and may not consider the importance of iterating through design alternatives, prior to studies. The computer-scientist may be aware of the importance of graphic design and user-interface design (e.g. Norman's *The Design of Ev-*

eryday Things [Nor13]), however, with little formal training in design, may be unaware of various design considerations in design mockups and coded prototypes, nor collaborative and iterative design sessions with a variety of stakeholders ranging across casual end-users, expert end-users, managers, and technology staff.

Alternatively, designers from the graphic arts and design community have typically trained in environments where design iteration requires creating many different variants of target designs. Considerations such as information hierarchy, composition, organization, layout, spacing, alignment and typography are harmonized to facilitate comprehension of a unified user experience. Design education often focuses on iterative design, refinement and feedback (e.g. critique, research-through-design), thereby allowing for a more-thorough exploration of the design space at design time. However, designers may have low exposure to software development, technical constraints, visualization research, and learnings from HCI: designers may risk overly focusing on the surface-layer of the target system and miss effective workflows to facilitate easy task completion.

The primary contribution of this paper is to identify these gaps and provide examples on the above based on actual experience.

2. Background

While interactive information research may be a young field, there is a long history of information graphics and related fields.

2.1. Visualization design space exploration

In visualization and HCI, it is known that design spaces can be large and thus require suitable exploration of the design space so that poor designs are not chosen [Mun09]. Techniques for exploring the visualization design space are excellent starting points for novice non-designers, such as Five Sheet Design method [RHR15]. Furthermore, iterative exploration of design ideas is known in HCI as a means to make designs more effective [Bux10].

The design method is important because these design spaces are big - there may be nearly infinite possible solutions - e.g. to the layout of a user interface, or a workflow to complete a task. These methods of design exploration are common in the undergraduate education of art and design, with many projects, across many courses, each with many iterative feedback loops. Given a project, there are complex, overlapping and competing requirements. Many valid designs are created and critiqued as a means of probing designs to assess them and make them better. Designers learn this design method across widely varying projects over 4 years.

On the other hand, computer scientists follow the scientific method. Many questions may have a narrow design space - such as code efficiency or whether an algorithm is NP-complete. The notion of exploration of many different possibilities, each with many different potentially conflicting requirements, is difficult to approach with the scientific method - there are far too many permutations to test and qualitative tradeoffs between choices. One or two HCI courses can only introduce the notion of the design method with little time to develop skills with the method.

Within the context of visualization design, the core of visualization theory is expressed in perception and visualization grammar e.g. [Ber67, Wil99, WNP16]. However, there is a breadth of visualization types beyond the grammars which visualization designers may be unaware of:

- *Diverse visualization:* The breadth of potential visualization is wider than infovis grammars. For example, Venn diagrams, flow charts, and some cartographic techniques, can be addressed in part by wider theories such as VisDNA.com [Ric84, Ric23]; textvis, e.g. textvis.lnu.se or [Bra20]; cartography e.g. [Mac95, Bör15]; and the context of historic examples as compiled in Tufte [Tuf83, Tuf90, Tuf96], or Friendly and Wainer [Wai05, FW21].
- *Domain visualization:* Many domains have specialized visualization techniques, with which their users are deeply familiar but the techniques are not widely known in the visualization community, such as: financial timeseries charts (e.g. point-and-figure chart, Figure 1 left); industrial monitoring visualizations (e.g. SCADA line displays); linguistic visualizations (e.g. parse trees); maps (e.g. cartographic relief shading); and so on. Each of these domains are documented, for example, in overview sections on Wikipedia, and detailed in domain documentation, such as many books on financial timeseries visualization [DT33, Nis01, Nis09, Ass21].
- *Un-recognized visualization:* Novice visualization designers may have the equivalent of change blindness [SL97]: by focusing on visualization articulated in recent visualization literature and theory, they may miss other recognizing other examples of visualization. For example, modern code editors use a wide variety of visualization techniques (markup techniques, overview/focus techniques, details on demand, word-scale glyph visualizations, etc), but not recognized as a visualization (e.g. much pioneering work in code visualization occurred in the 1980's, e.g. [BM86]). Or, maps use a wide variety of encoding techniques, such as textures or narrow gradient fills that follow the boundary of an area mark as shown in Figure 1 right [RMM*95, Tyn12]. These techniques, being unrecognized by the designer, are rarely used in information visualization.

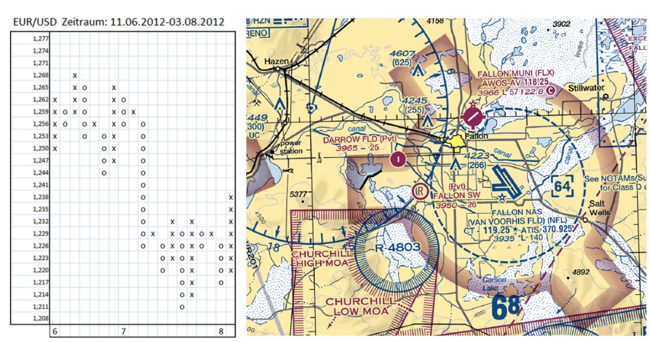

Figure 1: *Domain-specific charts: point-and-figure (left), aeronautic chart (right).*

2.2. Design refinement

After broad design decisions, there are still many design refinements to be done (e.g. see Buxton's Sketching the User Interface [Bux10]). At the level of broad user-interface this may include providing an information hierarchy to aid the user to differentiate between high-level tasks (e.g. search vs. export output) and low-level tasks (e.g. selection and identification). This may include the notion of a harmonious design system, so that consistent use or color, typography, layout and spacing aids transfering learning from one part of the interface to others. Assembling a visual analytics system out of ready-made visual analytic components with inconsistent styles risks creating a Franken-system: functionally capable but difficult to learn and use.

At a lower-level, such as individual visualization components, there are many nuances. For example, the visualization expert:

- *should* know that pie charts don't express negative values;
- *might* know that label placement around the perimeter of a pie chart is important, for ease of perception as opposed to relying on a legend (e.g. [SPCF61, FPS*22]); and
- *may not* know that effective label placement has many nuances with regards to tick marks, label justification, positioning, leading and so forth.

These small design cues may be important factors to the successful use of a system. Design refinement of visualizations is very different from early conceptual visual design, which focuses more on the high-level problem and broad configuration of the visualization. Design refinement is focused on improving a visualization, for example, with efficient use of space, enhancing readability, aiding interpretation, and avoiding potential confusion. All of these can ease cognitive load on the end-user. Resources to facilitate design refinement can include critiques and guidelines to tweak visualizations [Tuf83, Hol84, WWP*96, Won13, Sch21, Fun], guidelines for scientific illustration, e.g. [Hod03], and reviewing the fine-tunings created by designers of past visualizations, e.g. [Ren12, Ren14] or the documented design process, e.g. [BW21].

Graphic design training and resources are also important to design refinement, for example, tuning layout, color and type. Resources ranging from elementary introductions to graphic design (e.g. [Don74, Leb06]), to graphic design history (e.g. [Cra10, MP12]), and graphic design texts and resources. Closely related to graphic design is the use of typography: at a minimum, some fonts are designed for use at small sizes (e.g. book fonts or caption fonts), others are intended to be used at large sizes (e.g. display fonts). There are many typographic resources, [Lup04, CSB06, SWF06] are good staring points for using type; [Bei12] for type perception and design. Color is an interesting and endless topic of discussion across stakeholders: engineers may be uncomfortable picking colors; visualization designers may rely on resources such as Color Brewer or Viz Palette [HB03, ML22]; whereas graphic designers may have a background in color theory and pick more aesthetic colors such as Colorizer and harmonious colors e.g. [Mut20].

In should be noted that within a design based education, having many examples of prior work become important for a designer to familiarize themselves with the design space, analyze different design approaches to particular problems, assess various design refinements used across variants and use this context to aid in their synthesis of potential solutions. Thus, the designer will typically have a large collection of bookmarked visualization collections and blogs e.g. scimaps.org, informationisbeautiful.net, malofiejgraphics.com, davidrumsey.com; or access to a large library of example visualizations such as broad collections of infographics e.g. [NuWM30, Her81, Hol93, KEBT10, Byr13, Ren14], collections of visualizations with respect to a specific topic, e.g. timelines, radial visualizations, graphs, statistical maps [RG13, Hel06a, Lim13, Che99], or monographs such as [Osl69, Hel06b, NK09, Ren18, Sch22].

2.3. Visualization Guidelines

Visualization guidelines may be a quick way for non-designers to avoid common mistakes. Guidelines may be useful (e.g. [Mid20]), but designers should be wary of absolute pronouncements, as successive research or user observation may show the guidelines do not hold for all situations, e.g.:

- *Rainbow color scales* can be problematic [BI07] yet they remain common in practice and can be used effectively for diverging color scales [GÇ20].
- *Decluttering of visualizations* is generally recommended (e.g. [Tuf83]), yet some degree of grid lines, tick marks, etc., can improve performance and or the addition of effects such as 3D or pictorial imagery may improve memory of the data and message (see [FPS*22] for discussion.)
- *Dual axis charts* are recommended against (e.g. [IBDF11]), yet are prevalent in the financial domain and are required for some timeseries comparison tasks [BHS20].
- *Parallel coordinate charts* are recommended over their polar equivalents (i.e. radar chart) [PWH20]. In practice, this author has seen low acceptance and low usage of parallel coordinates over radar charts.

More generally, designers should be attuned to their users' familiarity with different visualization techniques. An oft cited quote in typography is *"Readers read best what they read most."* [Lic90]; which may explain popularity of pie charts, radar plots, rainbow color scales and so forth. The author has seen techniques recommended by guidelines dismissed out-of-hand. This could be remedied with simple training [BL13], however, retraining hundreds of thousands users may be difficult and may not achieve significant improvement if users are well adapted to effectively working with these other techniques.

Many design problems are not easily resolved. For example, a linked-views visualization can show many different visualizations of the same dataset all linked through interaction, but requires cognitive load to integrate relationships across views; whereas, a single view visualization with many data encodings into glyphs may integrate many values but have significant cognitive load for the user to learn and retain the encodings [War00] - there is unlikely to be a singular guideline to resolve these across use cases.

2.4. Author's Background

The author of this paper is uniquely suited to provide the critique of this gap. The author has 25 years practice in the design of visualization systems in government and private enterprise. Visualization projects range from tiny teams at startups to large teams at global corporations. The author has worked with more than 100 engineers and designers creating visualizations and visual analytics systems ranging from wall-sized ambient displays, desktop and mobile. Users have ranged from deep analytical experts who use visualizations throughout every day, to expert-users unfamiliar with visualization but need to derive high-value decisions, to casual Internet users who are non-committal to visualizations which may accompany additional content, e.g. [Bra13, MB13, BJ15, BHS20].

3. Examples

This section will provide a variety examples illustrating visualization issues arising from different design areas.

3.1. Diverse Chart Types: Design Knowledge Gaps

In one project, the author redesigned a domain-specific visualization chart using stacks of letters to form distributions as shown in Figure 2 top. The redesigned chart replaced text with bars, to allow scaling to smaller sizes and to increase accuracy (e.g. [CM84, HB10]), plus variants with stronger preattentive encodings (e.g. [HE11]) such as ordered colors instead of ordered letters. The thousands of users did not adopt the revised design.

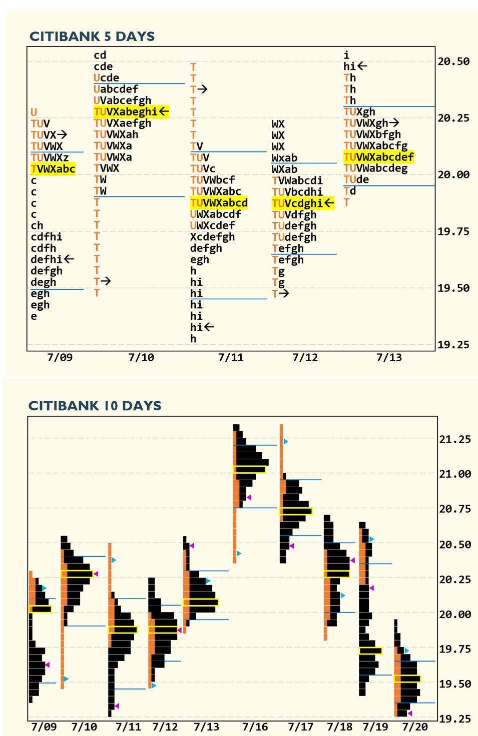

Figure 2: *Top, domain-specific chart showing daily distributions with letters indicating time periods. Bottom, redesigned chart with same distributions as bars - able to show more days – but not adopted by end-users.*

Since then, the author has also created charts in expert domains using the domain conventions – including conventions that are recommended against within the visualization community. When attempting to publish and subsequently present these non-conforming visualizations at a major visualization conference, a few critics have been dismissive. Comments include "this will never work", and "what you are doing is very dangerous and should not be recommended." Some researchers are willing to follow prior research, and may be inflexible when confronted with evidence of visualizations in broad use by thousands of users daily but do not follow conventionally accepted research.

This implies that existing visualization guidelines from visualization research may not extend to expert domains, and further research is required particularly with regards to expert users and domain conventions.

3.2. Country Stats: Vis Design Alternates & Facilitation

For a given dataset, there may be many applicable visualizations. Bertin famously creates 90 different visualizations for a dataset of occupations in France [Ber67]. The appropriate visualization depends on the task, the user, technical constraints, etc., but these may be vaguely defined. Until some designs are visible with some sense of the unique data and UX needs, each stakeholder may have a different conceptualization of the objective and tasks. Munzner indicates the importantance of exploring the design space so that a more appropriate visualization can be selected [Mun09]. The design space exploration also helps stakeholders to better understand their objectives, clarify their goals and define their constraints. In practice, users may not be able to articulate their needs, and the task decomposition may be non-obvious from user observations.

In one project, the design goal was to present four key metrics for industrialized countries around the world; for an *at-a-glance* display at a small size as shown in Figure 3. The visualization needed to readily convey the values and provide multiple workflow paths (e.g. drill-down to underlying data regarding the country, inspect metadata, see a historical timeseries for that country, add that country to a user-defined model, etc). There were multiple stakeholders and the needs ill-defined. These needs were refined through multiple iterations of design. For example:

- *Cross tabulations*. A few cross-tabulations were mocked up, e.g. a matrix of countries vs. metrics, with each cell containing a small chart such as a range bar (A) or sparkline (B). If each chart is independently scaled, it will be difficult to visually compare magnitudes across the matrix. When all the charts share a common scale per metric, an outlier in any one chart will make the data in all other charts compressed to a narrow range - two countries with small ranges were both nearly flat lines and not comparable to each other.
- *Map variants*. Choropleth maps were dismissed as many industrialized nations are relatively small and difficult to see on a small global map. Instead, star-glyphs set on a cartogram were considered (C), and this was also dismissed. Similarly, a variant on a equal area cartogram (G) was dismissed (with one participant saying "this looks like a map from a Commodore 64"). What was essentially discovered was that geospatial relationships between countries was irrelevant to the task.

- *Stacked bar*. A line-up chart [GLG*13] (D) was briefly considered but was dismissed. From this it was learned that the aggregate of the four metrics was not important to the task.
- *Scatterplots*. A grid of scatterplots (E) can be used to show one metric in each plot. Within each plot, one axis indicates the metric, the second axis indicates the change in the metric. This generated positive discussion reqarding the importance of the change.
- A large *timeseries chart* (F) was designed, such that all timeseries can appear, outliers are immediately obvious, any subset can be selected with the extents immediately rezoomed. While a promising design idea, upon further inspection of the data, some of the component metrics were more stable while others were more volatile. This means that the more volatile metrics will dominate the display (extreme values in the timeseries) while other metrics would be squashed at the center, and interaction requiring too much effort for at a glance.
- *Ranked tiles*. The design ultimately accepted after multiple design cycles was a set of independently ranked columns (H), each tile colored by the change to the period as compared to the prior 20 periods. The biggest movement in each metric appear at the top, with color indicating the magnitude of the difference compared to prior history. Each column can have very different ranges of data.

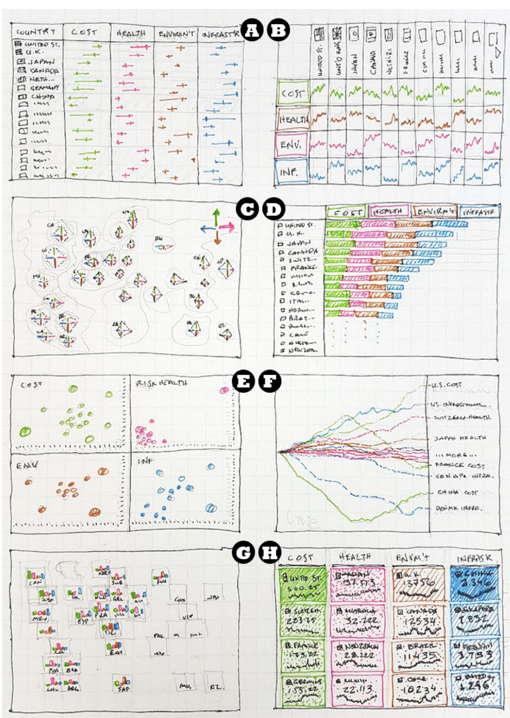

Figure 3: *Possible visualizations for 4 metrics per industrialized country.*

The accepted design was entirely non-obvious at the start of the design process as the requirements were successively revised with each design iteration. By creating designs, exploring sample data, and iterating through successive issues and narrowing requirements with users, ultimately a design solution was found. However, it is important to note that one of the designers on this particular project came from a computer science background - they were convinced that one of the early designs that they had created was optimal, and were devastated when their clever design was rejected. A computer science background does not prepare an engineer for design rejection or the need to potentially iterate in a design phase many times. In practice, this situation has occurred many times, with engineers and sometimes with designers.

Note that libraries such as D3.js and ggplot2 and tools such as Charticulator [RLB18], can facilitate design space exploration, with the caveat that all exploration tools only cover a portion of the design space.

3.3. Pie Labels: Vis Design Refinement

Designing and implementing labels on visualizations to be legible, readable and fit within the available space is a non-trivial effort. Labels are highly required in real-world visualizations in industry: while interactions such as tooltips could be used to indicate information, users may not be inclined to interact (e.g. in casual applications, [Tse16]), users may not be able to interact (e.g. hardcopy or screenshot), or may not have time to interact (e.g. control-room display - where response time is critical and effective legible labels an absolute requirement). In practice, our teams have sometimes spent more development time on label layouts than on the actual visual encoding of the data.

Consider the hierarchical pie charts in Figure 4. On the left side, the chart uses simple labels with codes, but the codes are non-obvious to the non-American viewer, and there may be insufficient space to display a label on thin wedges. On the right side, there are a) full labels, b) justified left or right depending on the chart side, c) set on leader lines, d) which in turn are nudged at top and bottom so that labels do not overlap and adjust label position appropriately. Further, e) labels near the center may require word wrap and hyphenation; and f) the overall visualization has been reduced in size so that both visualization and labels fit in the available space. Inner labels have g) letter spacing to compress/extend text based on space available, and h) adjustable label color (black/white) based on background color. Further tweaks may be needed for i) very long labels (eg. ellipsis), j) handling across multiple languages, and other potential considerations.

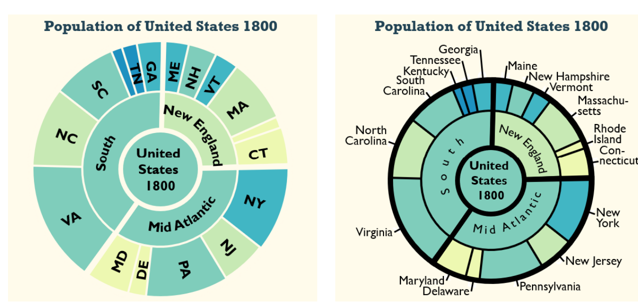

Figure 4: *Two hierarchical pies, very different labels.*

3.4. Visualization Hierarchy: UX Design

Visualizations co-exist with other content, UX and other visualizations. The layout of the user interface can aids the users' mental model and facilitate problem solving. A simple example is shown in diagrammatic representation in Figure 5. The solution required multivariate analysis across a dataset with many dimensions (i.e. categoric variables) and many metrics (i.e. quantitative variables). A *linked views* approach enabled explorative analysis so that any selection of data points in any one of the visualizations filtered and updated all other visualizations.

In the first implementation, (top image), six panels provide common visualizations. Any panel can be reconfigured to any of the visualizations through local menus and buttons. Any analytic objective can be accomplished by choosing the appropriate combination of visualizations and data selections. There are many problems:

- *Conceptualizing the required visualizations*. A casual user has difficulty formulating which visualizations are needed to complete the required objective.
- *Too many clicks*. To get to the target combination of visualizations, too many clicks are required, even with reasonable defaults across the panels.
- *Where to look*. Even more challenging for a novice user is where to focus attention. All visualizations are presented equally sized. As such there are no visualization which suggest it should have more attention. In terms of task completion, some visualizations are used to simply profile and filter the data (e.g. univariate visualizations such as bars, pies, lines, distributions) and visualizations are more granular (such as scatterplots) or show relationships (e.g. geographic, cross-tabulations, graphs, etc).

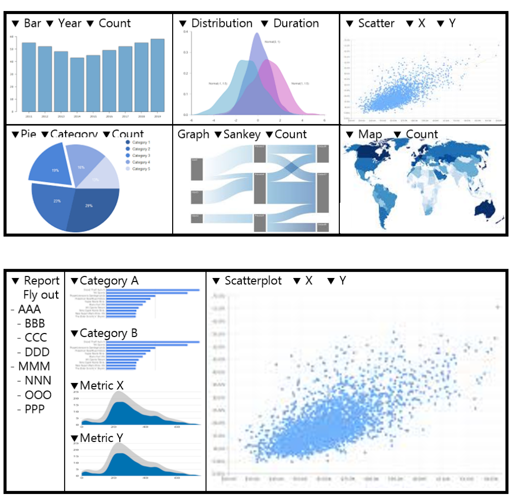

Figure 5: *Same analyses, different layouts.*

Instead, the second implementation (bottom image) shows a clear hierarchy:

- *Ready-made starting points*. The left side panel shows a hierarchy of analyses: choosing any analysis sets all the visualization panels to a pre-configured starting point. The panel prompts the user with many analytical tasks, rather than the viewer needing to formulate the task.
- *The thin visualization panel* (center) provides small univariate visualizations to easily profile and filter data, but otherwise do not use much space.
- *The large visualization panel* (right) indicates that it is the primary focus by its large size. It contains more complex multivariate visualizations central to the analysis of interest.

Note that second implementation required refining the design of the univariate visualizations: the initial implementations had much chart decoration (axes, ticks, tick labels, axes labels, gridlines) that required a fair bit of space and needed to be streamlined for a smaller space. For example, bars were rotated 90 degrees to better fit long labels, bar widths became narrower, axes and tick marks dropped or minimized, etc.

While both solutions allow the same functional task completion, the layout and ready-made starting points provide far greater ability for the user to consider potential analyses and easily begin to explore each. The success is not dependent on the individual visualization designs nor the interactions, rather the design of the layout and UX aid the user's workflow to complete the tasks.

3.5. FrankenVis: Vis Graphic Design

Visualizations can be readily assembled from ready-made visualization components, such as maps, graphs, charts, and so forth. When these visualizations come from different sources, the styles and interactions can be different. For example, a) different color palettes and color encodings may be used; b) marks in one visualization may be styled differently but not meaningfully convey data differences; b) fonts may differ in sizes and styles, but the differences do not encode data; c) ticks, axes and gridlines may differ is size, density and units drawing attention to them; d) simple interactions, such as tooltips, may contain different contextual information; e) alignment of elements such as titles, toolbars, and labels may use different layouts; and so on (e.g. Figure 6). The result can be a Frankenstein-like stitching of visualizations into a system.

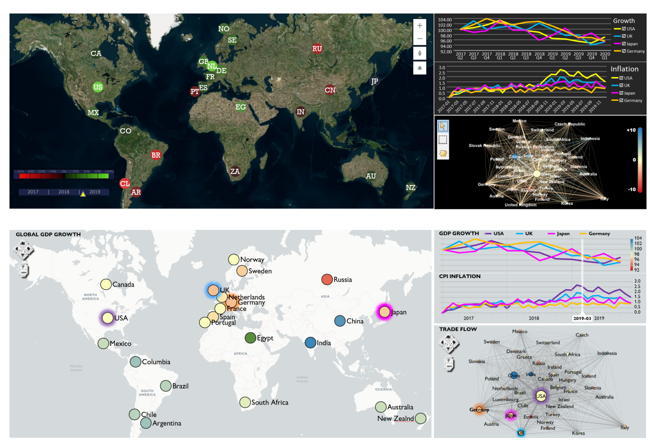

Figure 6: *Top visualization components stitched together with different labels (codes, full), color themes, button/legend placement, etc. Bottom, revised visualization with consistent encodings, interaction controls, alignment.*

Without modifying the default styles, differences hinder applying learning from one visualization to another. The resulting inconsistencies impact the visual cues that may hinder seeing patterns across visualizations and increase cognitive load. Graphic design training and resources can help, see some of the resources in the previous section.

3.6. 2D and 3D Timeseries: Interaction Design

In one project, a 3D visualization had been previously created for timeseries analysis, but it was difficult for users to interpret and did not provide obvious affordances for interaction (it depicted multiple timeseries in 3D polar coordinates which stakeholders called a tubmbleweed). Discussions with senior stakeholders established critical requirements that the visualization be easily recognizable and obvious interactions.

A review of financial chartbooks revealed a variety of 2D charts which do not depict timeseries data, such as histograms, scatterplots and yield curve charts (Figure 7 left). Furthermore, when users attempted to extend these 2D charts to include time, the representations became too cluttered to decipher (middle). The redesigned visualization starts with a familiar 2D chart, such as a bar chart or scatterplot in the front plane, which then rotates to a 3D viewpoint to show additional timeseries datapoints (right). Interactive elements are explicitly made to look interactive, such as chevrons and shaded buttons.

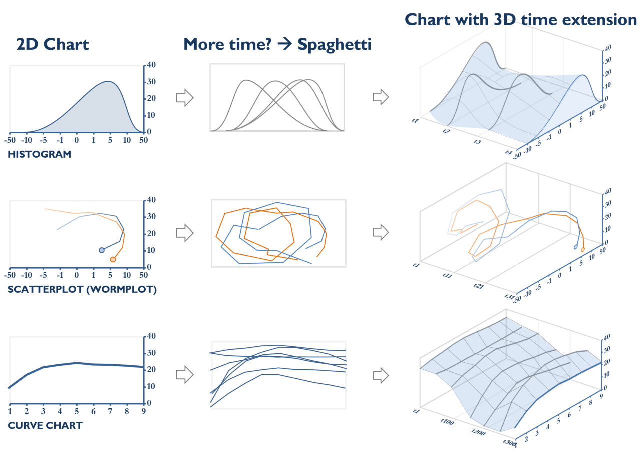

Figure 7: *Left: 2D charts without time. Middle: additional time periods overlaid. Right: Timeseries extending in the third dimension.*

3.7. Effective or Ineffective Design Collaboration

As the range of design skills to create effective visualizations is very broad, the design process can be improved by collaboration among designers with different design backgrounds and design skills. For example, designers from a graphic design background often excel at designing harmonious color palettes, effectively using of typography to create an information hierarchy, and creating style guides that unify an entire application. These design tasks may be difficult for designers from other backgrounds.

On the other hand, multiple designers can produce design tweaks and modifications that result in reducing the effectiveness of the overall design. In one project, an initial visualization design team created a state transition visualization as shown in Figure 8 left. Later in the project, a well-meaning graphic design team wished to reduce the messiness of the visualization and introduced edge-bundling (right). However, critical edge information was lost: transitions from one state to another became difficult to identify. Maintaining design intent requires engagement of designers throughout the full software lifecycle.

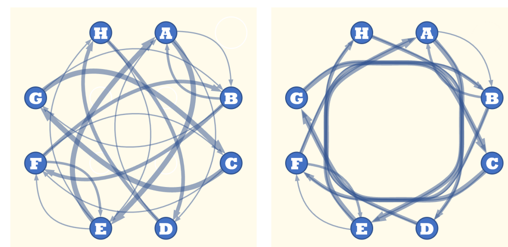

Figure 8: *State transition visualization. Left: original is messy but informative. Right: revised with nice edge bundling but ineffective for understanding point-to-point flows.*

3.8. Data Issues and Design Refinement

Data may not be perfect, resulting in a wide variety of issues with the visual display. Data may have null values, timeseries may have gaps, outliers may make a well designed visualization difficult to use (e.g. a single outlier can compress most of the points in a scatter into a corner). In one application, we used pie charts to indicate market share, as pie charts were frequently used in reports in the domain. We were surprised with occasional real-world data with negative market share: market share was defined on revenue, and a company may provide new products at a loss to gain a foothold in a market. As negative values do not work well in pie charts, the chart was replaced with a bar chart.

3.9. Checklists vs. Guidelines

While guidelines are useful, we have sometimes used checklists as means for assessing visualizations throughout the design process. Early design may include validating the business objective, whether the visual encoding matches the task, and so forth. Mid stage design may include assessing robustness under data conditions; whether expected visual patterns are salient with real data; whether labels, axes, ticks, numerical formats are appropriate for the task; whether selection and tooltips are broadly available and consistent; and what forms of incremental user feedback have been collected. Late design may include refinement of legends, alignment across components; ability of novice users to easily understand the visualization on first use; and any training or tours that might help.

4. Conclusion

If the academic visualization community is concerned about teaching design of visualization for industry, then the teaching of design is critically important. Design is a broad issue, not easily addressed within a single lecture or single course. Graphic design, UX design, visualization design, workflow design - all from a conceptual level down to a refinement level - require a diverse set of skills, all necessary to creating effective interactive visualizations. When a design problem is loosely constrained, these skills are better delivered through design methods, and visualization courses and curricula need to find ways to integrate these, for example, through collaboration with design faculties or design studio courses integrated into computer science, perhaps via HCI/d (human computer interaction + design). Even without a design-based education, there is a requirement to raise awarenesss of the breadth of the design space - beyond vis theory - such as the many resources herein. It is a disservice to the field of visualization to publish visualization research without appropriately addressing and citing relevant prior work across the broader spectrum and history of relevant visualizations across 500 years rather than only recent research from visualization conferences.

Furthermore, this paper has focused on the core of interactive visualizations: there are additional layers of design depending on the use of the visualization. For example, visualizations for communication have additional design requirements for storytelling [McG10, BCG11, RHDC18].

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