Picturing Science: Design Patterns in Graphical Abstracts

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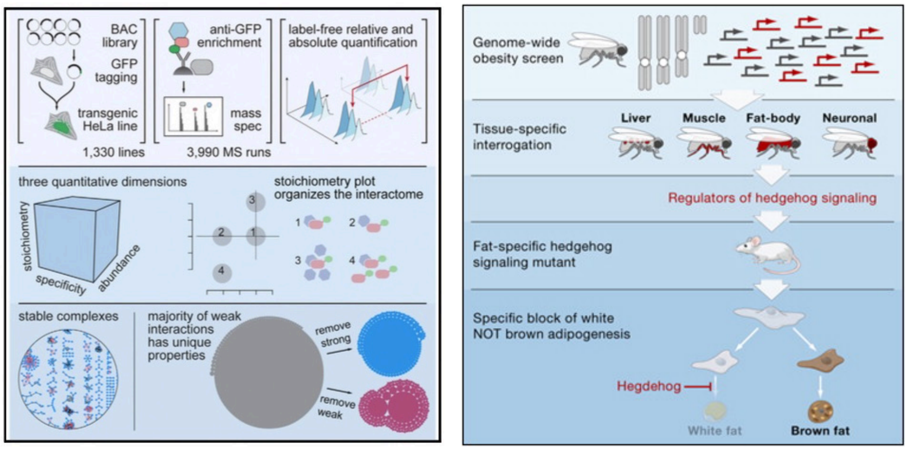
Abstract. A graphical abstract (GA) provides a concise visual summary of a scientific contribution. GAs are increasingly required by journals to help make scientific publications more accessible to readers. We characterize the design space of GAs through a qualitative analysis of 54 GAs from a range of disciplines, and descriptions of GA design principles from scientific publishers. We present a set of design dimensions, visual structures, and design templates that describe how GAs communicate via pictorial and symbolic elements. By reflecting on how GAs employ visual metaphors, representational genres, and text relative to prior characterizations of how diagrams communicate, our work sheds light on how and why GAs may be distinct. We outline steps for future work at the intersection of HCI, AI, and scientific communication aimed at the creation of GAs.

Keywords: graphical abstract, diagram, information visualization

1 Introduction

The overwhelming scale of scientific publishing—partly accelerated though digital publishing [15]—increases the number of articles that must be consulted in the research process. In an effort to make it easier for readers to grasp the gist of publications, multiple scientific publishers have mandated that authors prepare a graphical representation of their primary findings. This form of Graphical Abstract (GA) represents a single, concise, pictorial and visual summary of the main findings of the article [5] (Figure 1). By leveraging the efficiency of visual communication for portraying the essence of complex information, the assumption is that GAs will make scientific publications more accessible and understandable for in- and out-of-domain researchers as well as ”lay” audiences like students, journalists, or members of the public.

Graphical abstracts are becoming more common, either as a requirement or suggestion, among journals spanning scientific domains. Several scientific journals have been publishing GAs for nearly a decade [24]. However, relatively little is known about what visual and textual mechanisms GAs employ, and how, to express scientific research. While prior studies of diagrammatic communication can inform understanding of GAs (e.g., [8,9,10,36,33,34]), GAs are unique based on their focus on communicating scientific contributions specific to single publications. GAs can be thought of as a specific form of overview figure—a summative diagram used to aid readers in deciphering



(a) (b)

Fig. 1. Examples of layouts in GAs. *(a)*: GA using a zigzag layout with illustrations and data visualizations to depict a research method for studying protein interactions. *(b)*: GA combining elements of a unidirectional and a forking layout to illustrate findings about the fly genome.

research contributions and methods across many scientific and empirical disciplines. Consequently, a deeper understanding of GAs is beneficial outside the specific cases in which they are required. The fact that scientists—who are not typically trained in graphic communication—are responsible for creating GAs means that a better understanding of the design space of these diagrams could lead to important contributions to design support. More specific design guidelines can be proposed than the high level suggestions currently provided by publishers [25,5,41] (e.g., "emphasize the new finding from the paper" [25]). Additionally, better authoring tools for GA design could help address the huge body of existing publications that lack GAs and better support the needs of those creating them. Techniques from automated and mixed-initiative graphic design (e.g., [23,22]) could be adapted to support the unique needs of scientists as designers.

We are interested in identifying a repertoire of common structures and patterns in GAs. We believe that many GA authors arrive at patterns (e.g. choice of layout) without necessarily understanding how a given pattern relates to their communication goals. By surfacing common patterns, our work can contribute to helping authors of GAs to make more informed decisions in the future. We contribute the findings from a qualitative analysis of a sample of 54 GAs drawn from a range of scientific disciplines. Our primary contribution is an analysis of the pictorial, symbolic, and textual elements used in GAs. Our analysis characterizes design patterns associated with common GA design choices including the use of spatial layout, the type of picture or visual representation, how time is visualized, and how text is incorporated. We identify underlying design dimensions, including the linearity of spatial layouts, the degree of iconicity in picture types, and the degree to which text stands for versus narrates content. We describe how our results confirm, as well as problematize, prior conceptions of how scientific diagrams convey meaning. We reflect on how the unique status of scientists as graphic designers may impact the effectiveness of GAs, and present a set of design recommendations based on our study results. We conclude by motivating a research and development agenda for promoting the more effective design and use of GAs. We contrast the current state of GAs with a set of possible (imagined) functions of GAs as a form of scientific communication. We describe how research in Human-Computer-Interaction (HCI), Artificial Intelligence (AI), and science communication can be applied to facilitate the creation of effective GAs across disciplines.

2 Related Work

As a first step toward understanding the design of GAs, Yoon and Chung [42] recently examined the frequency and forms of GA use in the social sciences. Their coding process ("tagging") differentiated the scientific discipline, basic form of the GA (e.g., tables, charts (data visualizations), and diagrams), the content of the GA (e.g., the background, method, or results of the research), and whether the GA content was newly created or taken from an existing visualization in the publication. Their analysis surfaces patterns in overall forms of representations used and their relation to the content of the GA. Namely, schematic diagrams were most commonly used for presenting methods, background, or overviews of research, while data-driven charts were slightly more common than diagrams for depicting research results. Based on the prevalence of diagrams, our work takes a deeper look at the rich pictorial and symbolic space of GAs, which we find often transcends simple notions of representational genre (e.g., a large space of possible image schemas can be utilized within a diagrammatic GA). We also analyze a sample of GAs that includes a larger range of scientific disciplines.

The study of diagrammatic communication can inform our reading of how basic visual structures convey meaning in GAs. At a high level, diagrams schematize thought, using place and forms in space to convey both concrete and abstract meanings [34]. Certain "privileged symbols (arrows, lines, boxes, crosses, and circles) and dimensions of the page (horizontal, vertical) are commonly used to convey meaning in diagrammatic contexts [33,36]. For example, arrows have been found to strongly imply the functional (as opposed to the structural) organization of mechanical systems (e.g., the temporal, dynamic, and causal aspects) [10]. Graphic space itself is described as naturally conveying relations being elements, including nominal, ordinal, and interval and ratio relations [32]. Temporal information has been found to be more commonly mapped to the horizontal dimension [35]. The prevalence of temporal processes in scientific methods makes techniques and interpretive models of diagrammatic depictions of change such as Arnheim's notion of implied motion [1] relevant.

More generally, a number of visual metaphors, or image schemas, have been identified by cognitive psychologists and others [2,11,14]. Image schemas, such as "more is up, less is down," center-periphery, or containment are apparent in language as well as visual communication [14]. Image schemas are thought to metaphorically structure our thinking pre-conceptually [14]. As a result, space is "not neutral", even to children [31]. Understanding the "logic" of these schema is critical to effectively using them in visual compositions like GAs to convey complex concepts. We are interested in more specific conventions in the use of spatial layout and other schematizing elements used to convey the contributions of single publications, as a point of comparison to prior studies of graphical communication focused on textbooks or other educational diagrams [32,38].

Another goal of our work is to identify how research on automated and mixed-initiative (i.e., human in the loop) design at the intersection of AI and HCI could be applied to support the design of GAs. Prior work in automated construction of diagrams visualizing scientific research has focused on producing a high level representation ideas in papers [27]. Approaches to representing individual research documents like PDFs include thumbnails of extracted images [4], or summary graphics that incorporate key terms and important images extracted from the paper [28]. However, these approaches rely on combining existing imagery from the publication, and cannot create a new, synthesizing representation.

3 GA Sample and Coding Process

As an initial step toward characterizing how GAs communicate scientific findings, we gathered a convenience sample of 54 GAs. Our goal was to build a sample that included some diversity in the visual structures employed, so as to serve our goal of demarcating a design space. We found that writing and guidelines about GAs often referenced examples that captured such diversity. We therefore seeded our sample with examples cited in prior writings about GAs, including examples included in design guidelines for GAs from scientific publishers [25,5] (20 GAs), examples contained in editorials about GAs [26] (1 GAs), and an example GA for a prior article about GAs (1, from [42]). As a secondary concern, we wanted to include GAs from varying disciplines. We added examples from papers retrieved through Google and Google Scholar searches on “graphical abstract” (14 GAs) and by browsing journal archives that require GAs (18 GAs), continuing to select examples that were diverse in visual structures and discipline.

We employed an open coding approach [17] informed by past analysis of graphical abstracts [42], visual semiotics [18], and visual structures common to diagrams and metaphor [2,10,11,14,33,34,36]. Each author first independently analyzed a subset of the sample (6 GAs), making notes of the visual structures, text, and other elements used in the GA, and what higher level dimensions best described distinctions between GAs. For context, we read the research publication associated with each GA. Through discussion, we arrived at an initial set of codes related to the spatial composition or layout of GAs and their use of symbols, pictorial elements, and text. Through further parallel coding of a new subset (10 GAs) and subsequent discussion, we refined these codes. We merged categories that seemed redundant and creating new categories to capture emerging dimensions of the design space. We repeated this process three more times until our scheme stabilized around four high level design aspects, each of which was associated with 4 - 9 individual codes. We then divided the GAs and each author independently coded half in a final coding. All codes were discussed and agreed upon.

4 The GA Design Space

At a high level, our coding scheme acknowledges the way in which GAs employ graphical entities and text to communicate features of the research content at various levels of abstraction. Prior work describes how diagrams can convey both functional and structural information [10]. How the space of a diagram is used (structure), and the reader’s

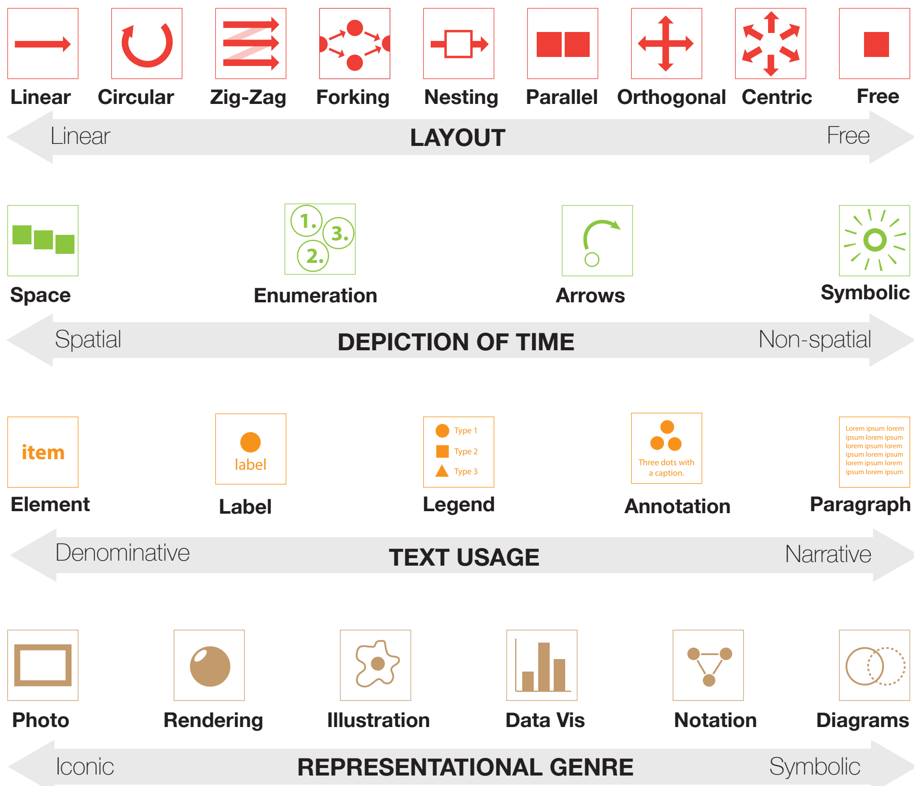


Fig. 2. Design patterns organized into four aspects: layout, depiction of time, text usage, and representational genre.

eye is guided in a sequential way (function), are often strongly influenced by the content being depicted. However, authors of diagrams also face a number of more arbitrary choices about how abstractly they wish to communicate their content. For example, text is highly abstract in how it refers to meanings, whereas photographs are highly concrete.

Our coding scheme operationalizes these aspects of both content and communication style by defining four *design aspects* to capture the diversity of visual mechanisms that GAs employed in our sample (Figure 2):

- **Layout** describes the organization of graphical elements in the 2D space of the GA. Layouts vary in the degree to which they imply a reading order (*linear* to *free*). Layout result from symbols (e.g., arrows), spatial mappings (e.g., organizing visual elements to extend from the center of the composition outward), or other implied relationships between elements (e.g., nesting one picture inside another).
- **Depiction of time** describes how the GA conveys a temporal process, a common function we observed in many GAs. With layout, depiction of time tends to be influenced by the scientific content that a GA is intended to communicate.
- **Text usage** differentiates ways of incorporating text in GAs, such as labels, paragraphs, or annotations (*denominative* to *narrative*). Most GAs we observed com-

bined text with visual elements. The choice of whether to use text versus visual means of communication is also relatively independent from the scientific content being expressed than choices related to layout or time depiction.

- **Representational genre** describes types of representations that comprise a GA. These can vary in their degree of abstraction and style, and include photographs and screenshots, illustrations, scientific visualizations, abstract data visualizations, and schematic diagrams (*iconic* to *symbolic*). Representational genres can be correlated with the content of the research displayed in a GA in some cases (e.g., microscopy-based studies will more often present images in a GA). However, in many cases representational genre is relatively independent from the content being displayed.

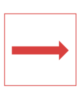
Codes were not mutually exclusive: a GA could demonstrate multiple codes (design patterns) associated with the same aspect (e.g., layout, time). The frequency of each design pattern in our sample is indicated in the respective section.

5 Design Patterns

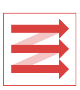
We describe the results of our analysis in terms of sets of *design patterns* we observed: standard solutions employed to solve a specific design problem. We identified distinct sets of design patterns associated with the design aspects of layout, depiction of time, text usage, and representational genre. We include example GAs and provide references to additional GAs in our sample which we include as supplemental material (*SM*[3], [4]).

5.1 Layout

Layout design patterns describe ways in which an author can use the graphic space of a GA to represent relations between pictures and concepts. As the fundamental means of organizing the space of a GA, layout is critical: prior work describes how cognitively, space is ”not neutral”, even to children [36]. How scientists choose to use layout sets up the implied “logic” that a GA conveys about a piece of research, whether intentionally or accidentally. The layouts we observed can be organized along a continuum, from *linear* layouts that convey an explicit reading order, to *non-linear* layouts that can be read in various orders (Figure 2 top). Whether a GA layout is more linear or parallel is a function of how the layout uses common symbols (e.g., arrows or boxes) as well as spatial schemas (e.g., center-periphery, linear) to relate the components of the GA.



LINEAR: (19 GAS, 35%) At the linear end of the spectrum, we observed simple linear layouts that used arrows or other visual cues to designate a clear reading order.



ZIG-ZAG (3 GAS, 5.5%): Some layouts imply reading order through the use of both horizontal and vertical space. A zig-zag layout (e.g., Figure 1(a)) consists of multiple rows, each of which implies the same horizontal reading order. Typically these layouts are designed to be read left-to-right and top-to-bottom [39].

[3] http://faculty.washington.edu/jhullman/GA_Sample_Images_Source_Info.pdf
[4] http://faculty.washington.edu/jhullman/GA_Table.pdf

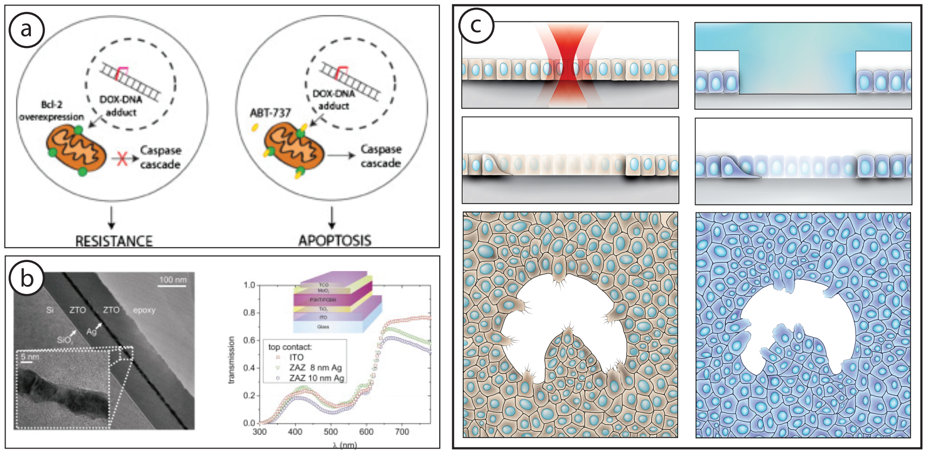
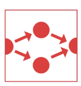
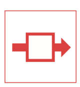


Fig. 3. GAs showing *parallel* (a and b), *orthogonal* (c), and *nested* (a) layouts.

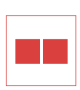


FORKING (10 GAS, 18.5%): Other layouts include both cues to a linear reading order and cues that break the implied linearity. For example, we observed multiple GAs using forking layouts, where entities or nodes are connected with paths (typically arrows) (e.g., Figure 1(b), bottom half). In a forking layout, the process being represented branches in multiple directions at least once, such that it is not strictly linear.

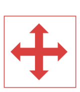


NESTING (16 GAS, 29.6%): Nesting is a common layout strategy that can also conflict with cues to linear reading order. Nesting in GAs is analogous to footnoting in text, where a nested frame within the larger GA composition contributes additional contextual information that would not otherwise have appeared. For example, nesting can be used to emphasize an intermediate step in a process by relegating it to a separate frame than the rest of the depiction (e.g., *SM#51*).

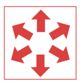
A common use of nesting is to incorporate representations that vary the scale or level of detail. The difference in scale is depicted by a boundary around the nested frame(s) using either color, borders, or other visual differentiation (e.g., dotted circles in Figure 3(a)). When used to vary scale or level of detail, nesting can problematize an otherwise clear reading order, by adding ambiguity about which level of detail should be examined first.



PARALLEL (20 GAS, 37%): Layouts that used nesting could also fall near the parallel end of the spectrum, such as when several frames were juxtaposed, each with a nested component (e.g., Figure 3(a)). Parallel layouts consist of side-by-side or vertical juxtapositions of multiple alternatives (which might be structures, processes, outcomes, etc.) for comparison, or multiple different representations juxtaposed without a clear indication of reading order (e.g., Figure 3(b)).



ORTHOGONAL (9 GAS, 16.6%): Similar to parallel layouts, orthogonal layouts do not always indicate one clear reading order, but map different information to both the horizontal and vertical dimensions of the GA (e.g., Figure 3(c)). Orthogonal layouts impose a grid on the space of the GA, which, in the absence of indicators of reading order, is analogous to the anti-narrative effect of grids in modern art [13]. Visual cues as to the hierarchy of the four quadrants may counteract the ambiguity, and conventional reading orders based on culture may compel readers to adopt certain orders. However, the lack of explicit order indicators in the GA design nonetheless subtly implies the equivalence and non-temporal relationships among the information being depicted.



CENTRIC (4 GAS, 7.4%): Centric layouts are have ambiguous reading orders. A centric layout divides the space of the GA into a center and a periphery, typically mapping elements to both types of position such that it is unclear which direction should be examined after the center.

SINGLE (8 GAS, 14.4%): Finally, some GAs used a single layout, consisting of a picture that was not clearly differentiable into sub-pictures. We observed single diagrams (e.g., *SM#4*), single data visualizations (e.g., *SM#37*), and single photographs (e.g., *SM#41*).

Vertical Versus Horizontal Dominance Prior work describes how graphical displays in the sciences tend to be remarkably constrained in their use of space, relying most heavily on vertical space unless a neutral dimension like time is shown. For instance, a prior analysis of scientific diagrams in textbooks provided quantitative evidence of the dominance of vertical arrays over horizontal. Only 2 out of 48 charts (4%) found in biology, geology, and linguistics textbooks in the Stanford Undergraduate Library used the horizontal dimension as the primary organizing direction [32]. We compared the frequency with which GAs in our sample utilized the vertical, horizontal, or both dimensions for comparison. Only three of the 17 GAs in our sample that relied on a single dimension used the vertical dimension. Two of these GAs used vertical layout to depict a non-evaluative dimension, including to display several alternative models and several graphical representations of results. Of the much larger proportion of GAs in our sample that utilized both vertical and horizontal layout (28/54 or 52%), several used visual cues to prioritize the vertical dimension while using the horizontal dimension to show alternative views as might be predicted by the prior work. However, three of these 28 GAs used vertical layout to depict time, which prior work suggests is typically mapped to horizontal layout [32]. The 14 GAs that used only horizontal layout were, on the other hand, more likely than not to use space for a neutral dimension like time or to show alternatives.

5.2 Depiction of Time

A majority of GAs (83%) depicted processes, including both natural processes like cellular division or engineered processes like technical pipelines. Processes are by definition temporal, requiring strategies for representing time in the 2D graphical plane. Of all 54 GAs in our sample, only 9 (17%) did not represent any temporal information. We observed GAs employing several specific strategies to depict temporal information spanning symbolic and spatial approaches. The most prevalent depictions of time used arrows (72%); however, arrows necessarily involve a spatial mapping as well. Spatial mappings (without additional schematics to convey time) were also prevalent, with 54% of GAs using space.

SPATIAL (29 GAS, 53.7%): To map time to space is to essentially "unfold" a temporal process onto the 2D space of the GA. The steps in a process or temporal snapshots of a system can be represented in pictures like visualizations, schemas, or photographs, and laid out with a specific reading ordering. The implicit reading order in western culture is left-right and top-down, though the presence of other visual cues such as arrows can change the implied order. These types of spatial mappings can use any of the linear layouts described in Section 5.1.

Prior work suggests that the horizontal dimension is more frequently used to depict time in diagrams [35], as an example of a more general convention of using the horizontal to depict neutral, as opposed to evaluative, dimensions [32]. Among those 29 GAs that used space to convey a temporal process, 13 GAs (45%) used the horizontal dimension, and 4 GAs (14%) used the vertical dimension. The remaining 12 GAs used both dimensions.

ENUMERATION (4 GAS, 7.4%): Enumerations such as roman numerals (i, ii, iii), letters (a, b, c) or others can reinforce the reading order in spatial mappings where it is otherwise ambiguous.

ARROWS (39 GAS, 72.2%): More common than enumerations are arrows, a widely used symbol to indicate the intended direction in which visual elements should be examined. We observed GAs using arrows in two ways: 1) to indicate sequence between pictures in a spatial mapping (e.g., *SM#7*), and 2) to indicate direction of movement or action in a depiction of a dynamic process (*SM#3*).

SYMBOLIC (5 GAS, 9.3%): Other forms of symbolic representations for depicting time are relatively rare in GAs. For example, change can be depicted through blur atop a changing object (e.g., *SM#29*) .

5.3 Text Usage

Many GAs combined visual representations with text. Research indicates that combining visual and text modalities promotes better understanding of complex phenomena, presumably because of the benefits of the cognitive work required to integrate information across modalities [19]. In particular, prior work has shown that to clearly convey a process often necessitates both text and diagrams [8].

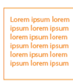
We observed a range of uses of text in GAs. Text served multiple functions across GAs in our sample, ranging from concise use of text to *denote* objects or processes that were not otherwise represented, to longer descriptions used to *narrate* or reason about a depicted phenomena (similar to those studied in prior work on diagrams). Text usage also varied in how "anchored" the text was to the visual element. For example, labels were clearly anchored to their referents, while the intended referent of a commentary was generally ambiguous.

INDEX (8 GAS, 14.8%) : Some GAs substituted text for visual representations of an entity. In these examples, text is used as an index, either for an organism or substance (e.g., Figure 1(b)) or process (e.g., Figure 1(a)).

LABEL (43 GAS, 79.6%) : The most common use of text in the GAs in our sample is to label a visually-represented object, process, or state in a process (e.g., Figure 3(a)). When used as labels, the primary function of the text is to name. Labels can describe simple atomic pictures (e.g., *SM#7*, *SM#20*) or more complex composites comprised of multiple pictures (e.g., Figure 1(a) ‘stable complexes’). Some GAs labels color coded labels so that they perform the additional function of associating objects, process states or labels with one another (e.g., Figure 4).

Legends (11 GAs, 20.4%) : Legends provide global explanations, explaining symbols in visual notation (e.g., *SM#9*) or visual encodings in data visualizations (e.g., Figure 3b).

Caption (37 GAs, 68.5%) : Some GAs used text to describe a set of visually-represented entities, as opposed to simply naming individual elements. These captions varied from providing concise descriptive information such as measurements (e.g., Figure 1(a) ‘3,990 runs’) to complete sentences describing processes or states (e.g., Figure 1(a) text in center and bottom panels). Captions varied in how explicitly they were related to the representations they described. For example, some GAs used multiple parallel frames, each had a similarly-styled caption in the same location from the frame (e.g., *SM#23*, *SM#50*). In other cases, captions are more implicitly associated with sets of representations through proximity (e.g., Figure 1(a) center left).



Commentary (3 GAs, 5.6%) : While captions were used to describe distinguishable subsets of a GA, text could also be used to describe without clearly referencing parts of the GA. Instead, text as commentary added explanation or context for the GA without any apparent anchor (e.g., *SM#23* center).

Only 3 of the GAs in our sample used no text.

5.4 Representational Genre

Most GAs combine two or more types of representations, each conveying a particular type of information. Examples include photographs, hand-drawn illustrations, computer generated visualizations, or schematic representations. Each representational genre may be associated with a plethora of subtypes, e.g., different types of data visualizations or different types of schemata. For our purposes of describing the design space of GAs, we are primarily interested in the broader distinctions between the genres used, including what types of information each conveys.

We differentiate representational genres according to their Iconicity, the degree to which they show real world elements or conceptual and abstract ideas. Structuralists differentiated between *icons* as precise representation of real objects, and *symbols* being abstract visual constructs (e.g. cross, circle) but referring to general ideas (e.g., Christianity, women’s bathroom) [20]. A high iconicity representation focuses on a specific real world entity such as a specific cell (*SM#3*) or crystalline formation (*SM#19*). Representations with high iconicity depict real world objects that are potentially visible to the human eye and captured through cameras or microscopes. These representations can be used to imply the individuality or detail of the entity pictured. On the other side

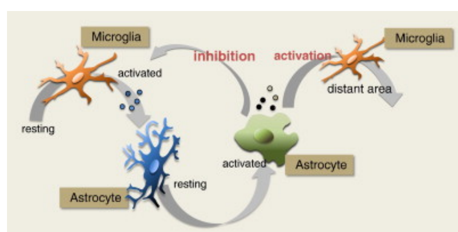


Fig. 4. A GA using a schema to show activation patterns in the nervous system.

of the spectrum are pictures with a low iconicity: schemas depicting abstract or general constructs such as center periphery (e.g., *SM#22*) or flow diagrams (e.g., Figure 4).

The representational genre—such as photo, scientific visualization, illustration, data visualization, symbolic notation, and schema—is in many cases influenced by the information to be shown. However, the level of iconicity can imply information and meaning beyond what is shown. For example, a visualization of an fMRI scan can refer to a single patient, implying an exemplary or abnormal case. A hand-draw illustration of the same "data" can imply a class of cases.

GAs in our sample employed a spectrum of representations that lay between photos and schemas in iconicity. We describe these in order of decreasing iconicity.

PHOTOGRAPHS (7 GAS, 13%): Photographs include photographs taken with an ordinary camera (e.g. or a study setup), or through a microscope (e.g., Figure 3(b) left).

SCIENTIFIC VISUALIZATIONS (7 GAS, 13%): Scientific visualization is concerned with the representation, rendering, and exploration of intrinsically "spatial" three-dimensional data: anatomical body scans, particle flows, architecture, or machinery. The visualizations are intended to faithfully represent these objects to allow exploration and analysis of their structures; for example, brain tumors or functional MRI data. Scientific visualizations have become a standard method in many scientific domains.Their iconicity is high; however, as the data may be incomplete (sampling rate, sampling errors), it is possible that detail about the real world object may have been lost. In GAs, scientific visualizations have been used to show MRI (e.g., *SM#14*) and other anatomical data (e.g., *SM#15*, *SM#16*), as well as 3D protein structures (e.g., *SM#19*) and tectonic structures (e.g., *SM#35*).

ILLUSTRATIONS (37 GAS, 68.5%): Illustrations are hand-drawings (using tools such as, e.g., Adobe Illustrator) showing objects in somewhat higher abstraction and less detail. Examples include animals (e.g., Figure 1(b)), cells (e.g., Figure 3(a)), and tools (e.g., Figure 3(c), top). Illustrations are not meant to replicate specific real-world elements, but to represent a class of these objects, or the general idea: e.g., "hormone injected in mouse". Illustrations appearing in our GA sample were often used to show processes such as the interaction between biological entities (e.g., *SM#1*, *SM#3*) or to illustrate a specific research methodology (e.g., Figure 1(b)).

DATA VISUALIZATIONS (11 GAS, 20.4%): Data visualizations are representations of abstract data, i.e., data that is not associated with an inherent three-dimensional representation. Abstract data involves numeric values such as scientific measures and statistics, but can also refer to more complex data structures such as trees (e.g. taxonomies), networks, and temporal data. GAs in our sample used data visualizations in the context of measurement presentation (charts in Figure 1(a); Figure 3(b) right) and gene expression levels (*SM#24*), among others. Data visualizations can be snapshotted directly from a visualization program (e.g. python), or further abstracted by recreating using, e.g., Adobe Illustrator.

SYMBOLIC NOTATION (13 GAS, 24.1%): Symbolic notation refers to graphical codes that use mostly domain specific symbols and compositions. Symbolic notation is used, e.g., to depict chemical molecules (e.g., *SM#32*) or convey information about genes (e..g, symbols on the bottom line of the green charts in

SM#24). Symbolic notation is similar to data visualization but rather than showing a particular real-world instance (that the data is describing), these symbols often express non-existing concepts (e.g., *SM#17*) and even processes (e.g., *SM#24*).

SCHEMAS (29 GAS, 53.7%): Schemas are the most abstract representational genre used in GAs. Schemas employ various common symbols and spatial mappings to express ideas, concepts, and processes. Schematic elements can span an entire GA, effectively turning the entire GA into a schema (e.g., Figure 4). More than other genres, schemas employ layout devices that help convey the logic behind the depiction (e.g., linear to denote a process, parallel to denote alternatives, etc.).

6 Discussion

6.1 Scope and Results

Our analysis is based on 54 GAs. While many journals require GAs, identifying a diverse sample of GAs is challenging. We aimed to retrieve GAs from a variety of domains our sample remains dominated by GAs from biology and chemical sciences. However, we believe the design patterns that we identified are not specific to any domain. Moreover, we suspect that our design patterns could also be applied to other genres of scientific presentations such as posters, infographics, or data comics [3]. As GAs become a more common requirement, future work should seek more reliable ways of collecting graphical abstracts across disciplines.

The patterns and dimensions that our analysis identified (layout, depiction of time, text usage, and representational genre) were arrived at through considerable discussion. These patterns and dimensions represent those that both authors determined best discriminated between differences in GAs in the sample. Additional dimensions could include color or visual styling, though we found these dimensions where less related to the content and the message of the graphical abstract.

While various publishers [5,25,41] and online guides [37,6] provide high level design advice to GA authors (e.g., "Use subtle colors" [6,25], "use captions" [41], "designate a clear reading order" [25,5]), it may be unrealistic to expect scientists who have little prior experience or training in graphic design to implement these guidelines. Our patterns provide a much more concrete starting point to assess what makes for an efficient and effective GA. Our framework can facilitate the process of developing guidelines; e.g., the effectiveness of a particular pattern can be assessed for different intentions (e.g., unidirectional layout for demonstrating sequential steps) or critiqued from a perspective that assumes more general goals like designating a clear reading order and clearly conveying the contribution of the research.

6.2 Ambiguity in the Design of GAs

Many prior studies have focused on professionally created diagrams such as those appearing in textbooks [30,32]. Relative to Tversky's [32] study of charts in textbooks, the design of GAs is more diverse in its use of spatial layout than the textbook diagrams, which were presumably created by professional artists.

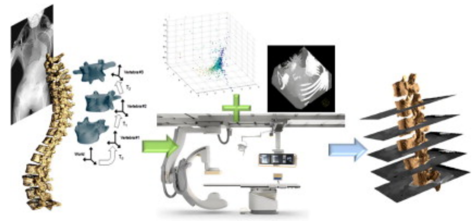


Fig. 5. A GA published with a paper on an inference method for articulated spine model [12], presented as an exemplar GA by Elsevier [5].

Only 27 out of the 54 GAs in our sample used a vertical organization, and only three of those GAs used a vertical organization alone. Instead, many of the layouts used in GAs in our sample that made use of both vertical and horizontal space (28/54 or 52%) lacked visual features that would prioritize one of the dimensions to guide reading. Figure 5 depicts one such GA. Similarly, of the GAs that used spatial layout to depict time, while horizontal time was more common (by roughly 3 to 1 odds) only 4 GAs used vertical alone, while the others used both dimensions, lending ambiguity in reading order in some cases.

In addition to unclear reading orders, we observed various other violations across multiple GAs in our sample. **Unclear relationships between pictures** make it ambiguous whether multiple pictures refer to a natural, temporal sequence, or a methodology based on human intervention, or whether they represented equal alternatives. **Missing annotations** make it hard to explain and interpret visual elements in illustrations or pictures, including data visualizations. **Inconsistent visual styles** for text and graphical elements raise questions about whether the differences are intended to convey information or are arbitrary.

6.3 Toward Mixed-Initiative GA Design Tools

We suspect that many GA authors currently use general visual design tools, like Adobe Illustrator, Adobe Photoshop, or even simpler tools such as MS Powerpoint and Keynote. Authors in certain disciplines are likely to use domain specific programs to create diagrams (e.g., molecular structures). However, the GAs that we observed that appeared to be created using specialized programs were more likely to lack clear labeling, reading order, and other visual cues to support reading, perhaps because the program used does not offer or emphasize such functions. To enable effective GA design among the many untrained graphic designers who are tasked with creating GAs may require a new breed of GA authoring tools that are customized to the communication intents of GAs.

Design templates that organize or style information according to different patterns or themes (e.g., [29,40]) are one possible solution for lowering the barrier for visual design of GAs. The design patterns we identify suggest a set of *design templates*, common configurations of pictorial and symbolic elements, that might be used to constrain the large space of possibilities available to authors. For instance, patterns that we observed which seem indicative of differences in the style of research include:

- **Process illustrations:** The majority of GAs depicted processes using (hand-crafted) illustrations on a linear or forking layout. Labels were used to name elements while arrows connected between the individual stages and pictures.
- **Result representations:** Many GAs incorporated data visualizations to depict research results in the form of line charts (e.g., Figure 3(c)), often in the context of a larger flow diagram or another spatial mapping used to depict a temporal process.

- **Parallel layouts:** Some GAs consisted of parallel pictures laid out horizontally on the GA plane (e.g., Figure 3(c)). These GAs were frequently associated with survey and review type articles, as well as research that contributed a comparison between alternative forms of a process or structure. In these examples, both pictures are intended to be of equal importance, with no indication of sequence between them.

We envision a system that presents a designer with an initial choice of templates like those above. Such a system could integrate examples (e.g, GAs plus text abstracts for context) to better allow an author to identify the right pattern for the type of contributions their work makes. Exposure to examples in the design process can help designers realize important structures and transfer these to other situations [7], and has been shown to improve design quality [16]. Given techniques for extracting and sufficiently annotating GAs with contextual information, authors could search a GA example library directly or receive automatic suggestions of relevant designs in the design process from GAs expressing similar research contributions or visual elements.

Mixed initiative tools are those in which a human creator is given access to system recommendations to help his or her work. Mixed initiative tools for visual design have included authoring tools for single page graphic designs like posters and flyers (e.g., [23]). As complex visual compositions that contain schematic elements, photographs, visualizations, and text, GA designers could likely benefit from system suggestions regarding different design aspects.

For example, a template and example-oriented approach can be combined with automated suggestions to improve features of a GA as an author creates it. Interactive layout suggestions, including changes in the position, scale, and alignment of elements, have been shown to help novices produce better quality designs, as rated by other novices [21]. Such suggestions can include refinements aimed at improving an author's current design, or larger proposed changes to the style of a design, including the layout [21]. A "design validator" tool could allow GA authors who are not confident in their graphic design skills to get suggestions and feedback on aspects of a design like font choices [22] or color choices.

Automatic tools that generate GAs by extracting content and structure from a scientific article are another possible direction. For example, the DocumentCards [28] creates a visual summary of a paper. However, DocumentCards rely on a simple "formula" designed to fit the structure of the average research paper, and cannot take into account differences between the research content or purposes of papers. The difficulty of extracting an expert's notion of which contributions of a work are critical or how they differ from other works suggest that a hybrid approach combining judgments from a human scientist with automatic features may be most effective for facilitating GA design.

7 Conclusion

Graphical Abstracts (GAs) are increasingly required by publishers to make scientific findings more accessible across and within disciplines. We contributed the first analysis of the pictorial and symbolic design space of GAs. By applying visual communication knowledge and qualitative coding, our analysis aims to pave the way for future empirical work and authoring systems focused on GA design. We identified four design aspects–*layout*, *depiction of time*, *text usage*, and *representational genre*–differentiating a range of design patterns associated with each. We describe how the design choices made in GAs point to common design templates and the design advice they imply. We outline directions for future study and development to facilitate GA design.

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