Design Patterns for Situated Visualization in Augmented Reality: Supplementary Material

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1 Introduction

This supplementary document provides further insights from our survey, which applied a codebook of 10 situated visualization design patterns to a corpus of 293 papers. Please refer to Sections 3.1 and 3.2 in the main manuscript for full details about the survey's scope and methodology.

It is important to reiterate that the survey primarily serves as the theoretical and literary basis for our 10 situated visualization design patterns. Thus, this supplementary document goes into further detail as to how each design pattern has been used in the literature, rather than identifying research gaps and opportunities. For more in-depth and comprehensive literature surveys, particularly for the identification of research gaps and opportunities, we refer to a recent 2022 survey by Bressa et al. [23] on situated visualization, and a very recent 2023 survey by Shin et al. [231] on situated analytics. Note that almost all in-text citations in this document are non-exhaustive.

2 Corpus Characteristics

The vast majority of papers in the corpus originate from the visualization and augmented reality (AR) research communities, including ISMAR, VR, TVCG, and CHI. It includes full papers as well as short papers, workshop papers, and posters, such as those from ISMAR-ADJUNCT and CHI EA.

Figure 1 shows the number of papers that were published in each year in our corpus. As to be expected, there is a noted increase in papers roughly around 2019, in part due to the inclusion of numerous immersive analytics papers. It is important to stress however that these counts should not be used as an indication of research interest in situated visualization, due to our convenience sampling of papers as described in the original manuscript. Nevertheless, the corpus contains a fair balance of papers throughout the past 2+ decades, which we believe provides a consistent view of how the AR and visualization fields have used situated visualization. The only notable outlier in our corpus in terms of publication year is the paper on cutaways and ghosting by Feiner and Seligmann [56], which was included due how well it demonstrates the so-called "X-ray lens" design.

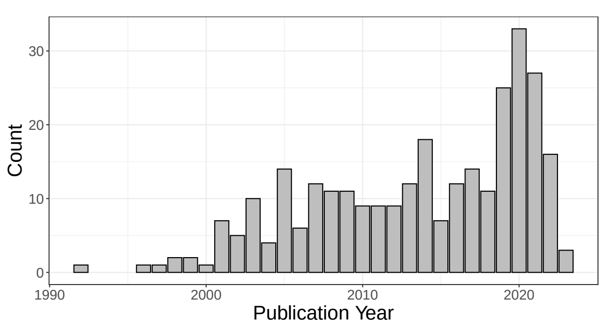

Fig. 1: Number of papers published per year in our corpus.

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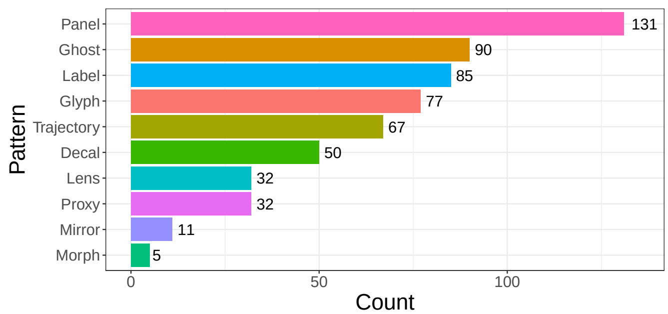


Fig. 2: Ranked frequency of each pattern in our survey. A paper may be assigned to more than one pattern.

3 Popularity and Usage of Patterns

Table 1 lists the 10 patterns and provides references to the papers which were assigned to each of them. Figure 2 provides a visual representation of the same data as the table, but sorted by frequency. In contrast to Section 3 of the original manuscript which sought to define the patterns, this section aims to provide further insight into the ways in which each pattern is used in our corpus (roughly sorted by frequency).

Panels are clearly the most used pattern in our corpus. This is not surprising, as it is a flexible, intuitive, and straightforward method of displaying information to the user. Panels are usually text-based (e.g., to show instructions/documents to the user [117, 186, 281], to show WIMP-style user interfaces [94, 130, 162]). With the growth of immersive analytics, it is now common to use panels to show abstract data visualizations (e.g., [58, 113, 184, 254]), as they are an obvious means to do so—particularly for 2D visualizations.

Labels are also a popular pattern as they are a simple and effective method of embedding information onto physical referents, with the majority of research using it as such. Labels can not only show static information (e.g., names of locations [13, 69]), but also show dynamically updating values based on the state of the referent and/or user's input (e.g., for measurement [195], for 3D manipulation [108]). As mentioned in the original manuscript, the placement of labels is a research challenge in and of itself, with myriad considerations such as clutter, label crossing, and overlap with other labels and salient areas [69].

Ghosts are a unique pattern in that they are virtual objects that appear to be part of the actual physical scene, and thus serve to complement it. Given the interlink between AR and 3D graphics, it is unsurprising that ghosts are frequently used. Ghosts can stand on their own without being fixed to any physical referent (e.g., as an autonomously moving virtual agent [7, 11], for factory planning [86], to visualize full-body movements at discrete steps [31]). Likewise, ghosts can also be affixed to a physical referent. A straightforward example are ghosts which indicate where on the referent a physical component should be attached in manual assembly (e.g., [92, 238, 295]). Another example is spatially superimposing the ghost onto the referent, such that the user believes they are instead holding the ghost (e.g., [89, 257]). From an information visualization perspective, ghosts have been used to facilitate unit visualizations, with each data point being represented as a 3D object (e.g., [4, 37]). Ghosts can also provide further context to aid in the posthoc analysis of spatio-temporal data (e.g., an avatar representation of the user at a given point in time [149], virtual representations of pre-existing objects [24]).

Glyphs are another common pattern. While glyphs can be used to encode some data directly on the physical referent (e.g., for immersive analytics [26, 37, 213]), they are most popularly used to either highlight some part of the referent (e.g., using a floating marker [20, 109, 130]) and/or to indicate where some action should be performed (e.g., where to push [117, 233], where to drill/insert [45, 80, 92, 110]). Glyphs can also be combined with the trajectory pattern as an arrow to denote a particular direction or path the action needs to be taken (e.g., rotate an object clockwise or counter-clockwise [30, 245, 281], look or move in the specified direction [171, 185]). Note that these glyphs and trajectories may also be freely drawn by a user (e.g., during remote assistance as annotations [43, 63, 162, 176], for sketching [62, 134, 209]).

Trajectories, as mentioned earlier, are typically used with glyphs to show directions, whether they be provided by the system or drawn by a user. They may indicate a path which an object (or the user) should directly follow (e.g., for drones [296], for navigation [139, 201, 229]). Trajectories are also obvious candidates for posthoc analysis of spatio-temporal data, particularly that of physical movements (e.g., [24, 94, 149]). Trajectories can also simply be used as regular trajectories and visual links as per information visualizations (e.g., [127, 194, 213]). They may also be used to connect and draw links between multiple referents (e.g., in networks [26, 52, 84, 228], along different points of space [174, 201, 289]), or between a referent and another visualization pattern (e.g., panels [276, 294], labels [69, 203, 252]).

Decals are comparatively less common than other patterns. This may be for a number of reasons, from the need to accurately detect and track the referent's surface, to the possibility of the decal occluding the underlying referent. Nevertheless, decals have been used in a wide range of physical scales: large scale (e.g., in agriculture [114, 289], building acceptance [210, 227, 297], environmental monitoring [259, 260]); medium scale (e.g., in rooms [149]); and small scale (e.g., on tabletops [2], on human faces [205]). Decals can show continuous field data (e.g., of physical movements [149], of crop yields [114]), can be used similarly to panels embedded on the referent (e.g., affinity diagramming with post-it notes [240]), and can provide more visual guidance to facilitate a given task (e.g., a virtual grid on a table [2, 35], a virtual target [80], overlaid textures to indicate selection [108]).

Proxies are similar to ghosts in that they appear as virtual 3D objects, but dissimilar in that they are replications of the referent itself (i.e., digital twin). As such, proxies are used comparatively little as the user can oftentimes already see the referent itself. As stated in the original manuscript, proxies are generally used to visualize referents that are too large in scale or are difficult to acquire (e.g., buildings [70, 251], human organs [104, 222]). Because proxies are inherently virtual, they can be freely manipulated by the user without physical constraints for myriad purposes (e.g., to explore intricate parts of the referent [79, 248, 249], for zooming [91], for scaling [128], for shopping and try-on [42, 99]). A proxy can also be used to indicate the desired state that the referent should be in (e.g., after product assembly [92, 143, 283]). Of course, proxies are perhaps most commonly used for navigation (e.g., as 3D worlds-in-miniature [107, 129, 170, 174, 184, 200, 267], as 2D top-down maps [237, 289]).

Magic Lenses fulfill a niche in that they are mainly used to reveal the internal structure of referents. As with proxies (and to some extent morphs and mirrors), this typically requires a digital twin of the referent in order to accurately visualize and position the contents revealed by the lens. Lenses can be used when it is important to look inside of a referent (e.g., to understand structures without occlusion [56, 102, 156], for surgery [45, 75], for maintenance [160, 215]). It can also be used to look directly through referents as though they were transparent (e.g., while driving [190], for occluded interaction [55, 140, 158]). Lenses may either reveal a portion of the referent when viewed through a specified region of space (e.g., [102, 120, 144, 156]), or be always visible to the user (e.g., [101, 216]). A compelling form of lens is to utilize a flashlight metaphor for shining AR visuals onto referents (e.g., on cultural artifacts in museums [204], on human bodies [34]). Another compelling use of lens is to leverage a physical handheld lens to enable tangible interaction of AR objects [120].

Mirrors are one of the two underutilized patterns. A likely reason is that mirrors require the user to look at a 2D plane that is separate from the original referent, increasing the level of spatial indirection which makes it harder to perform some physical task. That said, mirrors are perfectly suited in applications where the user needs to see their own face or body (e.g., [3, 22, 161, 205, 286]), just like an actual mirror. Mirrors can also be used in place of head-mounted AR displays (e.g., using projectors [14, 17], using a monitor [198, 233, 283]), which may be beneficial if wearing a head-mounted display is impractical.

Morphs are the rarest pattern found in the literature. While manipulating the appearance of a referent can resolve issues like occlusion (e.g., explosion diagrams [105], diminished reality [165]), it may be problematic when the user still requires awareness of the physical structure of the referent—particularly when they need to touch and manipulate it. Therefore, most works that modify the appearance of a referent would keep to salient augmentations like ghosts, or preserve the outer structure of the referent while revealing the internal structure using a magic lens.

4 Pattern Usage Over Time

Figure 3 shows the frequency that each individual pattern appeared in our corpus per year. Glyph, ghost, trajectory, label, and panel all clearly see a spike in usage in 2019 and beyond. Of course, this is in part due to the increase in the total number of papers included in the corpus from those years. That said it is interesting to see that the other five patterns did not see similar increases. As mentioned in Section 2, this may simply be the result of the manner in which the corpus was generated. Nevertheless, this does point towards some patterns being more relevant to so-called modern-day situated visualization than others. Panels are more likely to be used to display 2D visualizations and user interfaces (e.g., [58, 184, 213, 276]), ghosts benefit from 3D models being easier to create and more readily accessible (e.g., [4, 37]), and trajectories being used more in analytical contexts of spatio-temporal data (e.g., [24, 94, 149]).

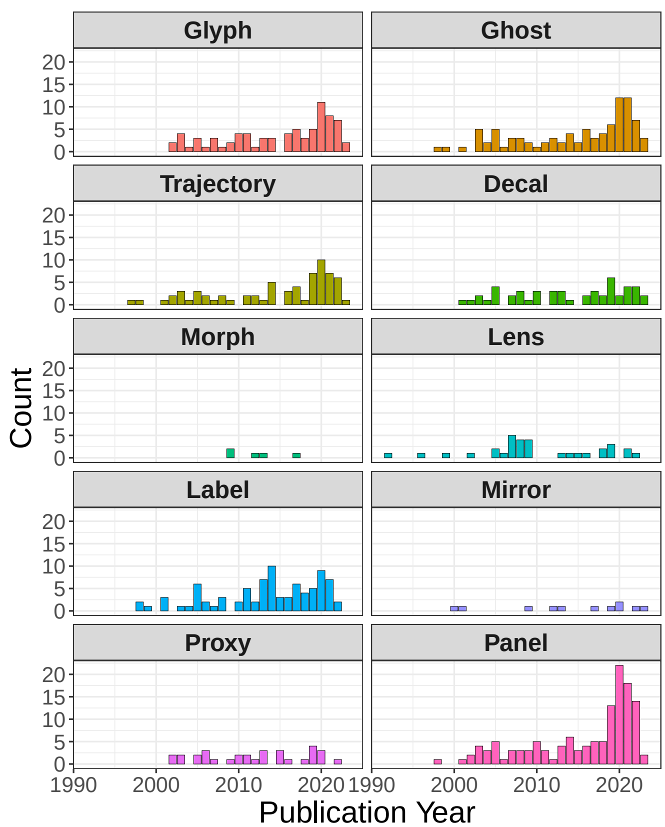


Fig. 3: Number of papers per year in our corpus, faceted by pattern.

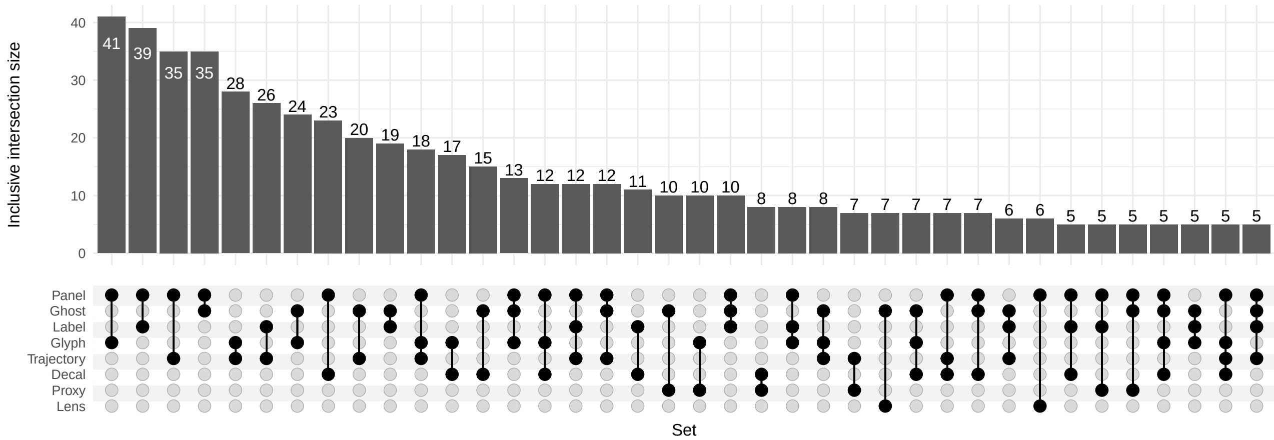


Fig. 4: An UpSet plot [40, 137] showing the frequency of set combinations between the 10 patterns with the intersect mode (i.e., a set can overlap with other sets). Only sets with a degree of two or higher, and with five or more members are shown.

5 Common pattern combinations

Figure 4 shows an UpSet plot [40, 137] of the frequency of different combinations of the 10 patterns used in our corpus. Note however that, as mentioned in the original manuscript, multiple patterns were assigned to a paper regardless of whether or not the patterns were used simultaneously. For instance, a paper that would demonstrate the use of panels in one prototype and glyphs in another prototype was coded identically to one that used both together.

The 1st to 4th most popular sets are all a combination of panel with another pattern (glyph, label, trajectory, ghost), with panel + decal coming at 8th. This is unsurprising given that these are the most popular patterns (Figure 2). Even so, this demonstrates the raw versatility that the panel pattern has—even if boring from a novelty perspective. Whenever some information needs to be displayed, be it text, a data visualization, or even a user interface, a panel can be used.

The most popular set which does not include a panel is glyph + trajectory. As mentioned, the two typically go hand. An arrow may point the user to move or look in a specific direction, or be used to highlight some part of the referent which the user should perform some task on. Trajectories can also easily connect multiple glyphs together, akin to a network (e.g., [26, 52]) or a chain of waypoints to follow (e.g., [201, 289, 296]).

Trajectory + label is the next most popular non-panel set. This is mainly the use of labels combined with leader lines (e.g., [69, 77, 139, 151, 163, 188, 203, 252]), which count as trajectories connecting the label to the referent. Otherwise, the use of this set is merely coincidental, with the system offering trajectory and label views separately from each other (e.g., [58, 77, 127]).

The first set utilizing three patterns is panel + glyph + trajectory. This is effectively a combination of the previous two sets (glyph + trajectory, trajectory + label). A clear use of this set is for navigation, whereby glyphs are used to represent key points of interest, labels provide further information about these points, and trajectories show a guide path between each point (e.g., [139, 201]).

None of the sets in Figure 4 include the mirror nor morph patterns. This is to be expected given their already low total occurrences in the corpus. The only noteworthy combinations here involve mirror, which has been combined with glyph, ghost, and panel (i.e., [3, 161, 205, 233, 283, 286]). In these instances, the mirror mostly acts to facilitate the AR experience without the use of head-mounted display, and thus can theoretically be combined with any other pattern.

6 Survey conclusions and limitations

This survey provides further insight as to how the patterns have been used by the papers contained within our corpus. It is not indicative of the entire fields of AR and (situated) visualization, and thus we do not discuss nor provide recommendations for research directions. What we can conclude is that our patterns are expressive enough to cover a wide range of different applications, designs, and use cases. We hope this survey would serve as a starting point for both researchers and situated visualization designers to classify existing work and express new ideas.

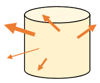
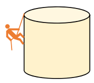
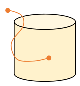
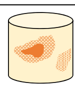
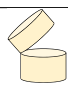
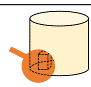
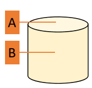
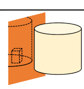
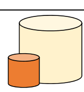
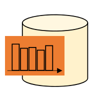
Pattern	Image	References	Count
Glyph		[20, 24, 26, 30, 31, 37, 39, 42, 43, 45, 47, 51–53, 78, 79, 85, 87, 90, 92, 94, 107, 109, 110, 113, 116, 117, 119, 123, 125, 127, 130, 142, 147, 149, 154, 161, 162, 169–173, 176, 185, 186, 189, 194, 195, 199–201, 205, 207–209, 213, 222, 224, 225, 232, 233, 238, 245, 247, 255, 262, 272, 278, 280, 281, 286, 288, 289, 293, 294, 296]	77
Ghost		[1, 4, 7–11, 18, 20, 28, 30–32, 37, 38, 50, 51, 53, 58, 61, 64, 67, 68, 71, 73, 81, 86, 89, 92–94, 97, 101, 103, 106, 110, 119–121, 127, 128, 134, 138, 143, 149, 150, 152, 155, 160, 164, 180, 185, 188, 189, 192–194, 203, 205, 208, 215, 224, 225, 227, 230, 233–238, 241, 244, 246, 247, 253, 257, 266–268, 271, 272, 274, 276, 283, 284, 286, 291, 292, 295]	90
Trajectory		[24, 26, 30, 32, 33, 37, 47, 52, 58, 60, 62–64, 69, 73, 74, 76, 77, 84, 94, 95, 109, 112, 116, 120, 127, 133–135, 139, 149, 151, 162–164, 170, 174, 175, 186, 188, 194, 199, 201–203, 209, 213, 222, 224, 226, 228, 229, 242, 245, 252, 255, 256, 263, 267, 274, 276, 279, 281, 286, 289, 294, 296]	67
Decal		[1, 2, 9, 20, 21, 32, 35, 49, 51, 53, 57, 68, 70, 80, 90, 91, 95, 98, 100, 108, 114, 124, 125, 129, 141, 142, 149, 159, 172, 186, 189, 194, 200, 201, 205, 210, 218, 220, 227, 239–241, 253, 259, 260, 278, 280, 289, 295, 297]	50
Morph		[105, 165, 207, 251, 260]	5
Magic Lens		[22, 34, 45, 47, 55, 56, 75, 101–103, 106, 120, 140, 144, 156–158, 160, 190, 194, 204, 206, 214–219, 222, 223, 242, 264]	32
Label		[6, 9, 12, 13, 15, 28, 29, 33, 35, 36, 38, 51, 58, 63, 69, 70, 72, 74, 77, 79, 81–84, 86, 88, 96, 108–110, 112, 113, 115, 118, 124, 126, 127, 131, 136, 139, 145, 151, 163, 167, 168, 174, 175, 177–179, 181, 182, 184, 185, 188, 195, 201–203, 221, 226, 228, 236, 237, 240–243, 246, 250–252, 258, 259, 263, 265, 269, 272, 274, 276, 278, 282, 285, 290, 293]	85
Mirror		[3, 14, 16, 17, 22, 161, 198, 205, 233, 283, 286]	11
Proxy		[9, 42, 70, 79, 91, 92, 99, 104, 107, 128, 129, 143, 145, 153, 170, 174, 184, 192, 193, 200, 213, 222, 237, 248, 249, 251, 253, 260, 267, 272, 279, 289]	32
Panel		[3, 5, 8, 15, 19, 24, 25, 27, 32, 38, 39, 41, 43, 44, 46–48, 51, 53, 54, 58, 59, 65, 66, 72, 73, 77, 78, 81, 82, 84, 91–96, 98, 100, 111, 113, 114, 117, 119, 120, 122, 124, 125, 127, 130–132, 134, 135, 145, 146, 148, 149, 152, 155, 162, 166, 170, 172, 174, 179–184, 186–188, 191–197, 199, 201, 202, 205, 209, 211–213, 216, 217, 220–222, 225, 228, 229, 233, 237, 238, 240, 243, 245, 254, 260–263, 265, 266, 269, 270, 272–278, 280–283, 287–290, 292–295]	131

Table 1: Table of results from our survey (N = 293). A paper may be assigned to more than one pattern.

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