# 1 INTRODUCTION

Advances in computational design allow designers to specify high-level constraints and automatically generate a large quantity of viable design options in a top-down approach. Generative models allow the creation of 3D models of general shapes specified using descriptions (e.g., "an old vintage car") or optimized 3D designs from desired loading conditions (e.g., a shelf bracket that can support 5 lbs.). How should human designers navigate through these outputs, either to find a final design or as an inspiring starting point for iterative refinement? This is particularly difficult under uncertainty, as designers face the challenge of accurately communicating their intent to explore the expansive design space. Additionally, many interactions with generative systems take place on computers, typical for design tools such as computer-aided design (CAD) software. However, given a new role of specifying desired outputs and then evaluating them, designers can utilize different interface types, such as virtual reality (VR), which we address in this work. VR interfaces have been promising for design because of their ability to facilitate spatial interaction with 3D objects and simulate environments in which designs might operate (Wang et al., 2020). Using these considerations, Jennings et al. (2022) created prototypes of interaction techniques, allowing users to narrow down candidate designs to their preferred style and function by interactively setting constraints. These techniques can be leveraged in immersive and non-immersive interfaces, which may afford different considerations for exploration.

This research builds upon those spatial interaction types to investigate how people explore a design space through constraints. We consider two interface modalities, computer-based ("2D") and VR, and how designers use these interfaces for design space exploration using the following research questions:

1. What exploration *strategies* emerge for each interaction type (constraints on design variables or function, visual search, and user embodiment) within an interface?
2. Does the *utility* of an interface type (2D or VR) for enabling breadth or depth of exploration differ?

To address these questions, a user study was conducted where participants selected designs from among thousands of options, using a 2D and VR interface. Participants' decision considerations and behavior during the design space navigation provide insights into how each *interaction* and *interface* type may contribute to *strategies for exploration*.

# 2 BACKGROUND

## 2.1 Considerations and Approaches for Exploring Large Design Spaces

The design process can be framed as searching for a solution among a vast space of (possibly unknown) options. Bang and Selva (2020) measure “learning" about a design space through design performance. However, sometimes design evaluation requires users to interact with the various options or requires consideration of subjective preference. In these cases, empathy, often understood as the ability to stand in another's shoes, becomes an important consideration. Prior work has indicated that designers should consider embodiment when trying to gain empathy (Heylighen and Dong, 2019). Thus, we incorporate consideration of embodiment into our study due to its potential to impact design space exploration.

Approaches for exploring large design spaces also involve directly interacting with design variables of interest to modify form and function (Mohiuddin and Woodbury, 2020; Schulz et al., 2018). For instance, Dream Lens allows the use of tools like a “chisel" to find preferred geometries of 3D models (Matejka et al., 2018), while Fab Forms allows tuning of design parameters and automatically checking functionality, preventing exploration of invalid design space regions (Shugrina et al., 2015). Relationships between parameters and the final output, both in terms of function and form, are important considerations for design space exploration. Therefore, we explicitly consider form and function when implementing the interactions in this study. Even a solution space that has been narrowed down from all possible options to a more constrained set can result in many designs that must be considered simultaneously. Prior work has extensively investigated visualization of large design spaces, adopting galleries and clustering to increase the ease of navigating through different design options (Marks et al., 1997; Erhan et al., 2015; Matejka et al., 2018). To this extent, attempts have been made to adapt gallery-based visualizations to VR interfaces, assisting the navigation of large solution spaces in VR (Keshavarzi et al., 2020). Leveraging the findings from these works, we utilize a gallery-based design visualization in our study to supplement constraint-based approaches for exploring the design space.

## 2.2 Design and Design Exploration in Immersive Environments

The aspects of design exploration discussed above are possible to achieve in immersive and non-immersive environments, yet differences may arise in the usefulness of interfaces to support these considerations. Most interfaces for interacting with generative systems are currently in desktop environments, often through CAD software (Matejka et al., 2018; Chen et al., 2018). However, immersive environments have also been investigated for their potential to support design activities. Work by Lee et al. (2018) shows that people can get a sense of scale in VR that helps when designing for themselves. Kim and Hyun (2022) find similar qualitative results regarding scale. Additionally, they discover, when comparing desktop and virtual environments for design creation, that people spend more time designing in VR but their satisfaction in the designs is higher. These studies focus on the designer as a creator, but in the scenario we consider, the designer must explore the design space through specifications rather than through creation (and the creation is left to a generative system).

A key interaction type available in immersive environments is gesture. For example, gesture can be used to carry out "situated modeling" using primitive 3D shapes in mixed reality (Lau et al., 2012). We utilize these principles by allowing users to create 3D shapes that interact functionally with the designs being considered. Closely related work is Calliope, which leverages gestural capability to allow users to manipulate meshes in collaboration with a generative adversarial network for design space exploration in VR (Urban Davis et al., 2021). A relevant guideline coming from this work is "Guided Sampling of Infinity," which suggests that interfaces should enable users to iteratively constrain the space as they explore to mitigate the overwhelming solution space from generative systems. We take such an approach here by allowing exploration in a top-down fashion through constraints, additionally focusing on factors that designers may consider alongside geometry, like function, users, and context of use.

# 3 METHODS

To investigate design space exploration across immersive and non-immersive interfaces, we expanded on an interactive system developed by our team (Jennings et al., 2022) for use on a desktop computer (2D) and VR. We then utilized a human subject study to collect participants' actions and self-reported measures during tasks in the two interfaces. The overall study examined two related aspects: the use of different interactions types and different modes (2D and VR) to navigate a large design space.

## 3.1 Experimental Design

### 3.1.1 *Participants*

Participants consisted of 28 students (20 men, 8 women). Programs represented were MEng (12) and PhD (7) in Mechanical Engineering, Master of Design (4), and BS/BA degrees unrelated to design (5). Participants' varied in design experience according to self-reported values on a 7-point Likert scale ranging from (1) no experience to (7) very experienced ($Med. = 5, Min. = 1, Max. = 6$). VR experience was not required and varied across participants in self-reported level ($Med. = 2, Min. = 1, Max. = 5$).

### 3.1.2 *Study Procedure*

Each participant completed a design task in each interface (half in VR first and half in 2D first). The interface order was assigned by alternating over the study occurrence timeline. Participants were required to select one (or more) designs that they determined to best satisfy the task, via saving designs in the interface. The tasks, summarized below, were presented in the same order to all participants.

1. Project display: Select an aesthetically pleasing display that sits at the front entrance and can allow visitors to view student projects. Consider that projects to display can be objects that people want to pick up and hold, such as 3D printed figures, or larger objects that will only be viewed.
2. Library display: Select an aesthetically pleasing display that sits beside the entrance and can allow visitors to select books from a small design library. Consider that the books may have varying sizes and that people may remove books and return them to different locations.

The study procedure is shown in Figure 1. Participants first filled out a pre-survey and then the facilitator demonstrated how to use the first interface. Participants then completed a walkthrough of the features and a "mini-task" in the demo scene, with assistance allowed. Finally, the scene for Task 1 was opened and the facilitator re-read the task instructions out loud. Participants were asked to select one or more designs that they thought best achieved the given task. There was no strict time limit for each section, though participants knew that the study would take approximately one hour. Participants then completed survey questions about the first interface. The procedure was repeated for the second interface. After completing questions about the second interface, participants completed post-task questions. The approximate task completion times were 6.57 minutes ($S.D. = 3.00, Range = 1.76 - 15.69$) in 2D and 7.70 minutes ($S.D. = 4.01, Range = 2.61 - 19.12$) in VR.

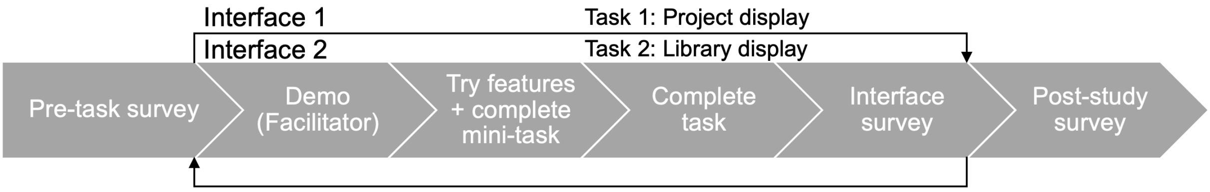


*Figure 1. Study procedure*

To feasibly study exploration, the design space was restricted to a set of 3600 designs. The set was a parametric combination of shelves differing in width, row number, row height, offset, column number, and depth, rather than outputs of a true generative system. The designs were diverse in visual and functional aspects relevant to the tasks and participants were not provided information about the parameterization.

## 3.2 System Interactions and Features

Figure 2 shows the interactions and features developed for each interface and available during the study.

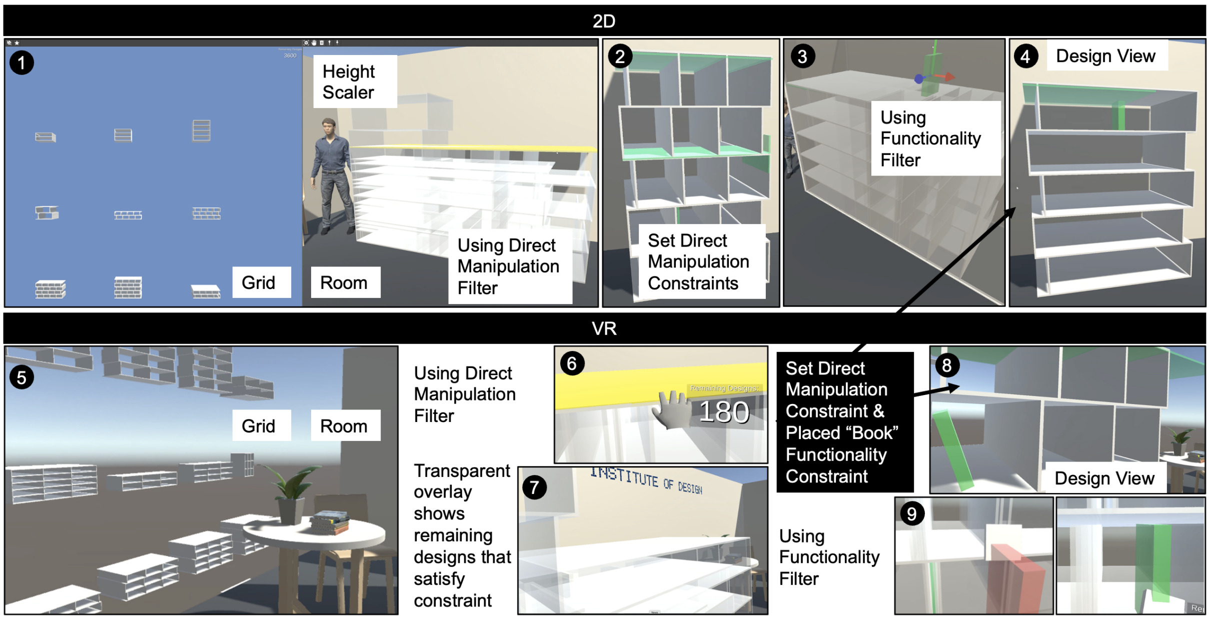


*Figure 2. Features of each interface (top: 2D, bottom: VR). First, the general interface view with a design gallery (1: 2D, 5: VR) is shown, followed by example use of the spatial interactions. The direct manipulation filter is set to a specific height by selecting (1-2: 2D) or grabbing (6-7: VR) and a book is created to place on the shelf using the functionality filter (3-4: 2D, 8-9: VR).*

### 3.2.1 *Direct Manipulation Filter: Constraints on Design Variables*

The direct manipulation filter allows participants to set constraints on parts of the design by clicking with a mouse or grabbing/dragging with the VR controller. For example, participants can grab the top of a shelf and set a desired height. Similarly, they can set the width or a location for a vertical support (Figure 2: 1, 2, 6). Participants can see how many designs in the grid remain (that fit the constraints they set) through an overlay of transparent shelves and a number (Figure 2: 1, 7).

### 3.2.2 Functionality Filter: Constraints on Design Function

The functionality filter allows participants to create and place items in preferred locations on the shelves. When placing the item, participants can see how many options will allow the desired function to be fulfilled through a transparent overlay (Figure 2: 3, 9) and a number. Here, a shelf fulfills the desired function if it can support the placed item with a shelf underneath with no intersections. In the VR interface, participants draw a bounding box to create the item and grab to place it (Figure 2: 9). In the 2D interface, instead of drawing, they add an item to the workspace, modify it (e.g., scale, rotate, move) and move the item in any XYZ direction (Figure 2: 3). Here, they can additionally duplicate the item. In VR, participants must duplicate an item by drawing another one, but the item itself is easier to create/move.

### 3.2.3 Grid and Design View: Allowing Visual Search

The grid view refers to the grid-like gallery allowing participants to view all the designs, while the design view refers to the ability to view one of the designs more closely. In the VR interface, a wall is removed from the room to display the grid and the design view is accessed by simply navigating to the design of interest, causing it to appear inside the room (Figure 2: 5, 8). The 2D interface is slightly different in that the grid view is kept separate from the design view. Here, participants select a design and it appears in the room on the other half of the screen (Figure 2: 1, 4).

### 3.2.4 Embodiment and Environment: Considering Users and Context

In the VR interface, participants can use a height scaler to incrementally increase or decrease their own height up to one foot from a first-person perspective, as well as reset to their original height. In 2D, participants can use the height scaler to increase or decrease the height of a person from a third-person perspective (Figure 2: 1). They are not provided with limits or ability to reset, as the height of the person is set in reference to the room walls. The tasks are set in a room (Figure 2: 1, 5) that resembles an entrance to a building, with slight changes based on the task. In the first task, the designs are to be placed at the front of the room next to a round table. In the second task, the designs are instead to be placed on the side wall adjacent to the front of the room. Here, the wall is empty, but adjacent to a wall with a round table. The modified environment is intended to convey a subtle difference in decision considerations allowed (e.g., more or less space) while remaining in the same design domain.

## 4 RESULTS AND DISCUSSION

The results were examined through logged data of the actions taken during each task and responses from the survey. This data was analyzed at the feature level, to understand the approaches participants took to explore the design space given the different interaction techniques, and at the interface level, to understand if non-immersive and immersive interfaces might play a role in this behavior.

### 4.1 Strategies for exploration by interaction type

As participants could use the different features as they deemed useful in a free-form manner, their behavior when using these features in the actual task was examined. One participant was removed from analysis of action (but not survey) data due to a delay which impacts timing-related analysis. *The outcomes reveal that participants spent large proportions of the task time visually assessing designs but did not prefer either "form" over "function" or vice versa.* First, the proportion of time spent on actions related to viewing designs vs. specifying constraints on designs was calculated for 2D (Viewing: $\mu = 0.28, \sigma = 0.12$, Direct Manipulation: $\mu = 0.19, \sigma = 0.12$, Functionality: $\mu = 0.18, \sigma = 0.13$) and VR (Viewing: $\mu = 0.35, \sigma = 0.13$, Direct Manipulation: $\mu = 0.19, \sigma = 0.090$, Functionality: $\mu = 0.16, \sigma = 0.096$). Viewing-related events indicate searching through the grid to find a desired design without specification. The direct manipulation events indicate articulating a particular look for the design (or a "fit" within the environment, although all designs could technically fit in the given space). The functionality events indicate expressing how the design will function, in this case to hold objects.

A repeated measures ANOVA reveals a difference in time proportions across action types in both the 2D ($F(2,52) = 3.49, p = 0.038$) and VR ($F(2,52) = 16.62, p < 0.001$) interfaces. A post-hoc Tukey test shows that this difference is driven by participants' tendency to spend more time on viewing-related actions compared to the direct manipulation and functionality filters in both 2D ($p = 0.027, p = 0.023$) and in VR ($p < 0.001$ for both). View-related events can be important in at least two differing cases, explaining this result. *Participants may spend much of their time viewing if they are unable to properly specify constraints and prefer to visually assess the designs to begin with. On the other hand, participants who do specify constraints might spend a large amount of time viewing to inspect the remaining designs that satisfy their constraints.* These two cases cannot be distinguished using overall time proportions, but future work can consider this distinction by analyzing the timing of the view events. No significant difference is found between the proportion of time in the task spent using the functionality filter vs. the direct manipulation filter across participants. *Therefore, no definite trend can be extracted regarding overarching behavior across all participants such as preference for "form" or "function"-related specification, implying more individual variation in behavior by participant.*

*More granular analysis of participants' actions throughout the task reveals that participants had different approaches to choosing the type and timing of constraint specification.* These actions were examined by dividing each session into thirds. The proportion of events related to the action type was calculated for each third, examples of which are shown in Figure 3 (left). Based on proportions during the task's

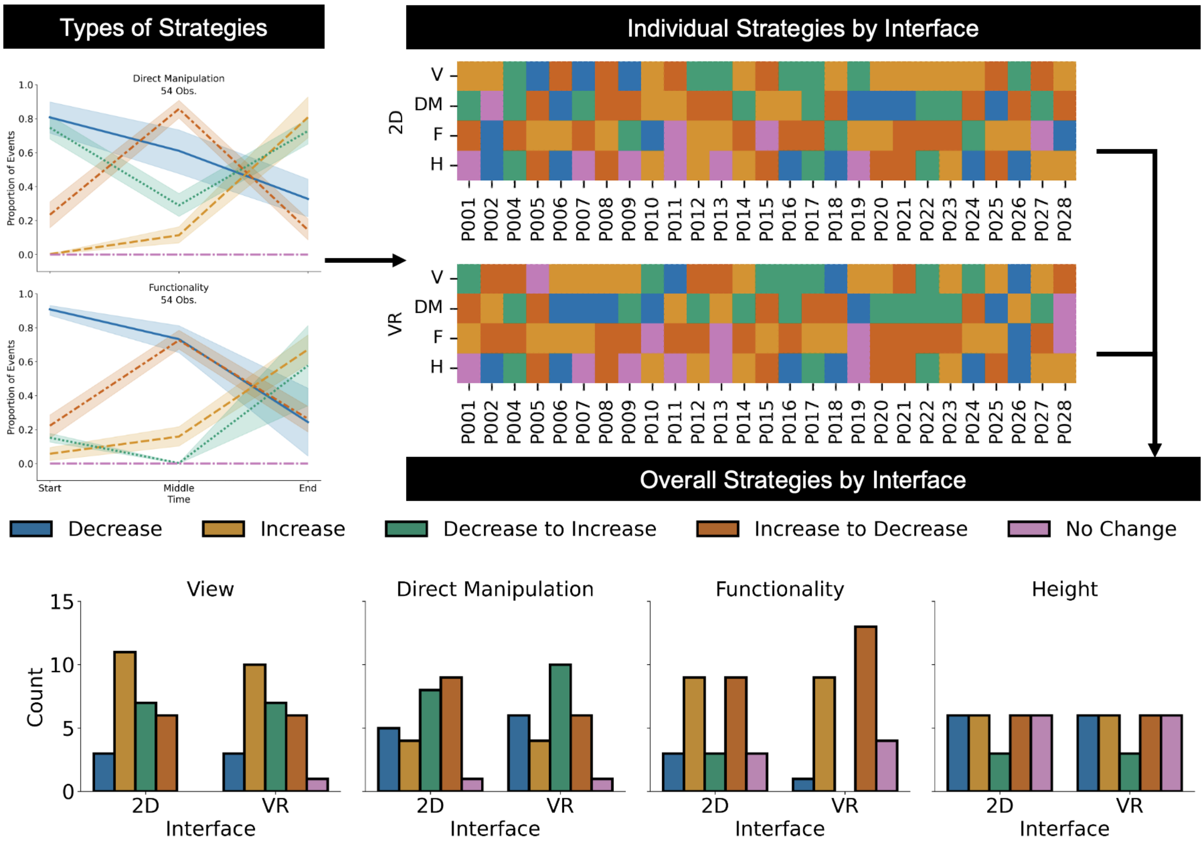


*Figure 3. Strategies based on feature use over time. Examples of the strategy types are shown for the direct manipulation and functionality interactions (left). The resulting strategies for each user, action type, and interface show differences across interfaces for individual participants (right), but aggregation results in similar distributions by interface (bottom).*

start, middle, and end, five "strategies" were qualitatively compared to disentangle how exploration was conducted using each feature type. These strategies are labeled as decrease (decreasing use of the feature from start to end), increase (increasing use of the feature from start to end), decrease to increase (reducing use of the feature in the middle then increasing use at the end), increase to decrease (increasing use of the feature in the middle then reducing use at the end), and no change (no change in feature use over time or no feature use at all). Figure 3 shows that participants use a variety of strategies across features, with none dominating overall. *These strategies sometimes differ across interfaces for the participant*

*(e.g., the functionality filter's use by P026 is an increase in 2D, but a decrease in VR). However, when combined across participants, strategies appear to be distributed similarly across interfaces.*
For example, strategies for the height scaler are evenly distributed in both interfaces, with some users explicitly modifying height early on or at the end, some considering height throughout, and others not utilizing this consideration at all. The most common strategies for the functionality filter are increase to decrease or increase. Increase implies that, instead of using the functionality filter to initially specify a constraint, the participants narrow the design space down and then check whether the desired object will fit or how it would look on the shelf. On the other hand, an increase to decrease implies that the participants took other actions, such as viewing or specifying direct manipulation constraints, before specifying functionality, but did not wait until the end to do so. All strategies except for an increase were common for the direct manipulation filter. In this case, a decrease strategy, for instance, implies a consistent narrowing of the design space through the parameter specifications. A uniquely frequent strategy for direct manipulation is decrease to increase, particularly in VR. This type of strategy might indicate initial specifications that are eventually re-specified to visit another part of the design space. Thus, additional work is needed to investigate how participants iteratively constrain and unconstrain the design space. This behavior also shows how the interaction techniques align with the guidelines raised by Urban Davis et al. (2021) that emphasize enabling "iterative constraint and need-finding."

## 4.2 Perceptions of interactions and exploration by interface type

Through the post-task survey, participants reported their perceptions of the features in each interface and exploration overall. Figure 4 shows participants' responses for the usefulness of each feature. The grid and design views as well as the direct manipulation filter are deemed useful regardless of the interface. This is expected since these features allow people to explore the designs in ways that are easier to understand or more familiar, like visually searching or specifying geometry. The features that demonstrate the most variation across participants (negative vs. positive ratings) are the functionality filter, height scaler, and room environment, which is notable as these are the features that are particularly suited to leverage the benefits of virtual reality. The distribution of the ratings, particularly for the latter three features, indicates how participants have different approaches when using the tools to navigate within the design space. While some features, such as the functionality filter, appear to show some differences in rating by interface, these differences are not statistically significant based on a Wilcoxon signed-rank

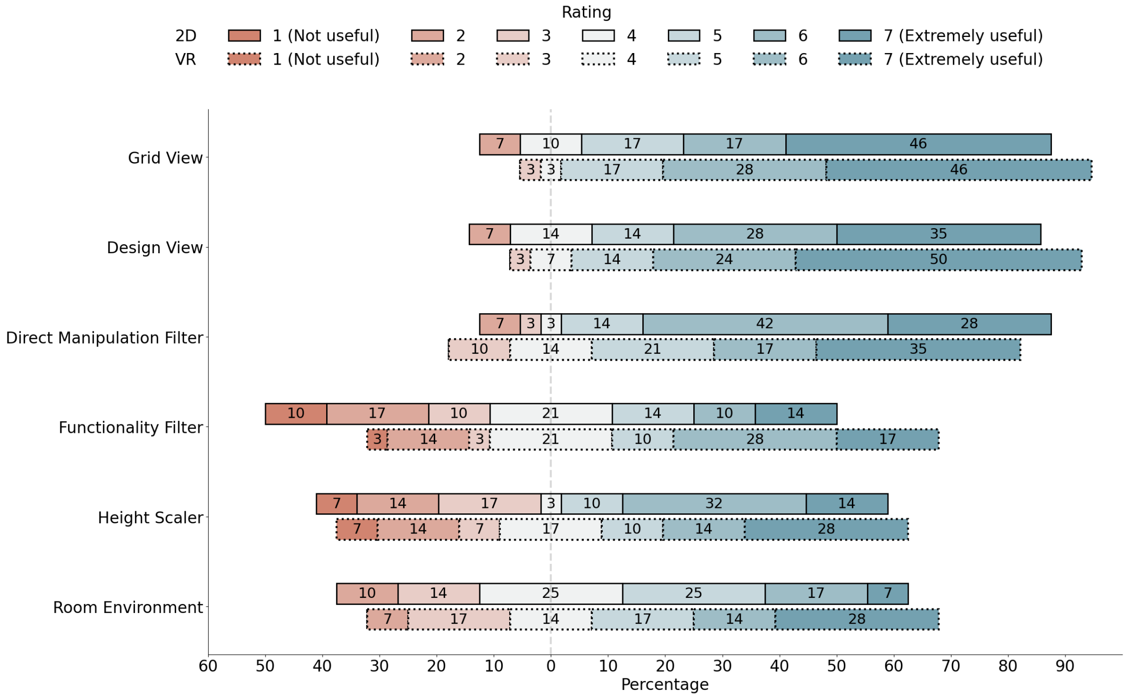
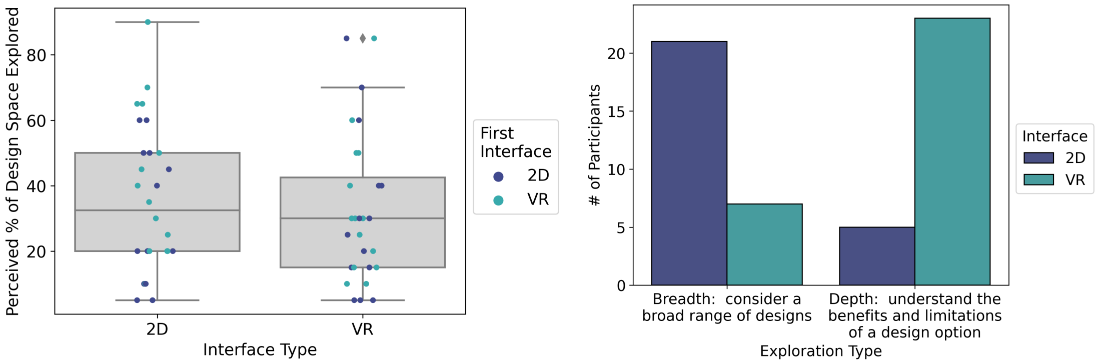


*Figure 4. 7-point Likert scale reported values of features usefulness (2D vs. VR). Differences are not significant between interfaces, though some features are found more useful across interfaces.*



(a) (b)

*Figure 5. (a) Perceived % of design space explored by interface* ($t(27) = 0.71, p = 0.486$) *(b) Exploration type better enabled by different interfaces* ($p = 3.74 \times 10^{-}5$)

test (Grid View: $W = 62.5, p = 0.50$, Design View: $W = 27.5, p = 0.029$, Direct Manipulation Filter: $W = 87.0, p = 0.49$, Functionality Filter: $W = 84.0, p = 0.097$, Height Scaler: $W = 166.0, p = 0.81$, Room Environment: $W = 76.5, p = 0.17$). *Overall, considerations and strategies differ from person to person but do not significantly differ across interfaces in this study. Yet some differences arise from participants' answers to questions regarding exploration in each interface.*

Figure 5a displays answers to the amount of design space the participants perceived they had explored (after each task/interface), showing no significant difference using a paired t-test ($t(27) = 0.71, p = 0.49$). Further work is needed to quantify how much of the design space participants actually explored. Figure 5b then shows participants' answers to which interface better enabled different aspects of exploration: consideration of a broad range of different designs, referred to as "breadth," or understanding of the benefits and limitations of individual design options, referred to as "depth." *Despite not expressing significantly different amounts of perceived design space exploration or usefulness of features across the two interfaces, participants report holistically that the 2D interface enabled them to better explore in terms of breadth, while the VR interface better enabled them to explore in terms of depth* when comparing them to each other ($p = 3.74 \times 10^{-}5$) based on Fisher's exact test. Responses to an open-ended survey question following the answers in Figure 5 provide further insights into why participants selected each interface. The responses were manually categorized based on references to available features, ways of using an interface (e.g., scrolling, clicking, physical movement, pressing buttons), or feelings/perceptions invoked by an interface (e.g., constrained, scale, in-person). Examples of categorization are shown in Table 1. Category frequencies are shown in Table 2. Each participant's comments (one excluded for vagueness) were included in one or more categories. Reasons for either interface better enabling breadth reference ease of navigation due to interface affordances. The majority (2D) also cite the grid feature, while the minority (VR) cite perceptions invoked by the interface. Those who selected the VR interface as better for depth primarily reference perceptions afforded by the interface and secondarily the functionality filter or height scaler. *The responses imply that the anticipated benefits of VR considered during system development and their translation into interactions appear to impact participants' impressions during the task.*

### 4.3 Limitations and Future Work

Participants may have had difficulty using a new interface type or engaging in "design as search" more broadly due to familiarity with typical design tools, partially explaining the observed behaviors. Notably, users sometimes defaulted to visual search, which may be undesirable when interacting with real generative systems, where the design space is larger and more diverse or not pre-specified. Additionally, participants had little VR experience. The use of the interactions in the VR interface may change as participants build a better mental model of them. However, survey responses regarding advantages and disadvantages of each interface type and associated interactions for design space exploration indicate the potential for varying approaches depending on the desired outcome. Future work includes better quantifying design space coverage and considering task outcomes. Additionally, many participants

Table 1. Example reasoning for selecting an interface as better for an exploration type

| Answer | | Reasoning |
|---|---|---|
| Breadth | 2D | *"By being able to physically, or in this case, virtually, experience the designs in person gave it a greater sense of how a user would be interacting with the design constrained heavily the ranges of designs I could consider. With 2D, I didn't feel like I was in the space and constrained, which allowed me to look at more designs in the context of the design problem."* **Perception** |
| | 2D | *"I think it was slightly easier in 2D to skim through the grid view. I also had a better field of vision in 2D when looking at all the stacked designs when doing Direct Manipulation."* **Grid, Direct Manipulation** |
| | VR | *"While the fly-in grid arrangement was a little bit jarring to navigate at first, it ultimately enabled me to pull in a significant variety of options and consider them in a split second, without having to scroll and click and scroll and click through options. The additional depth visible in the grid view also enabled me to navigate at a faster rate from a distance, scrolling through dozens of options very quickly to grab the ones I wanted just based on the dimensions of the thumbnail."* **Grid, Interface** |
| Depth | 2D | *"Seeing the person on the left made it clear what height was being limited to using each design."* **Height** |
| | VR | *"Clearly, when I used VR, I could create several objects that were the size of a book, and place them exactly as they would be put in real life, seeing how they would fit in my chosen design and decide better if that is the thing that I wanted or not."* **Functionality** |
| | VR | *"Although it took a while to get used to the control, I was able to better imagine myself using the design and get a better sense of scale. There were times where I couldn't reach the top of the shelve[s], and that helped me choose what height shelves I should use."* **Interface, Perception** |

Table 2. Frequency of categories (feature or interface-level) mentioned in open-ended answer

| Answer | | Grid | Direct Manip. | Functionality | Height | Room | Interface | Perception |
|---|---|---|---|---|---|---|---|---|
| Breadth | 2D | 6 | 1 | 0 | 0 | 2 | 14 | 3 |
| | VR | 1 | 0 | 1 | 0 | 0 | 3 | 3 |
| Depth | 2D | 0 | 0 | 0 | 1 | 0 | 3 | 0 |
| | VR | 0 | 1 | 6 | 6 | 3 | 5 | 16 |

successfully used the interaction techniques, motivating directions for further investigation into these. Implemented for the specific domain here, these techniques can be readily extended to other cases. For example, functionality can be specified as a light frustrum for a lamp, or the reach area for a robotic arm instead of holding items on the shelf. The height scaler and room are implemented passively, yet these could also be used to constrain and explore the design space (e.g., specify/filter by designs reachable to certain heights or fit in part of a room).

## 5 CONCLUSION

We developed several spatial, constraint-based interaction techniques for both a non-immersive and immersive interface, employing them in a study ($N = 28$) to determine if the technique and the interface's modality impacts design space exploration. Various exploration strategies were observed, with participants considering form, function, and users at different times. For example, some appeared to narrow the space down by geometry and check for function at the end, while others seemed to iteratively narrow and expand their search using the interactions. Significant differences were not observed between interfaces by the use of interactions, yet perceptions of each interface's affordances differed. People felt better enabled to explore a large range of designs in 2D, and to understand the limitations and benefits of design options in VR despite both interfaces being equipped with similar features. More work into investigating how these perception differences might manifest in behavior will be necessary to develop future interfaces that better support design space exploration and enhance design creativity.

## ACKNOWLEDGMENTS

This work was supported by NSF (2145432-CAREER) and a gift from Accenture Labs.

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