

DreamRooms: Prototyping Rooms in Collaboration with a Generative Process

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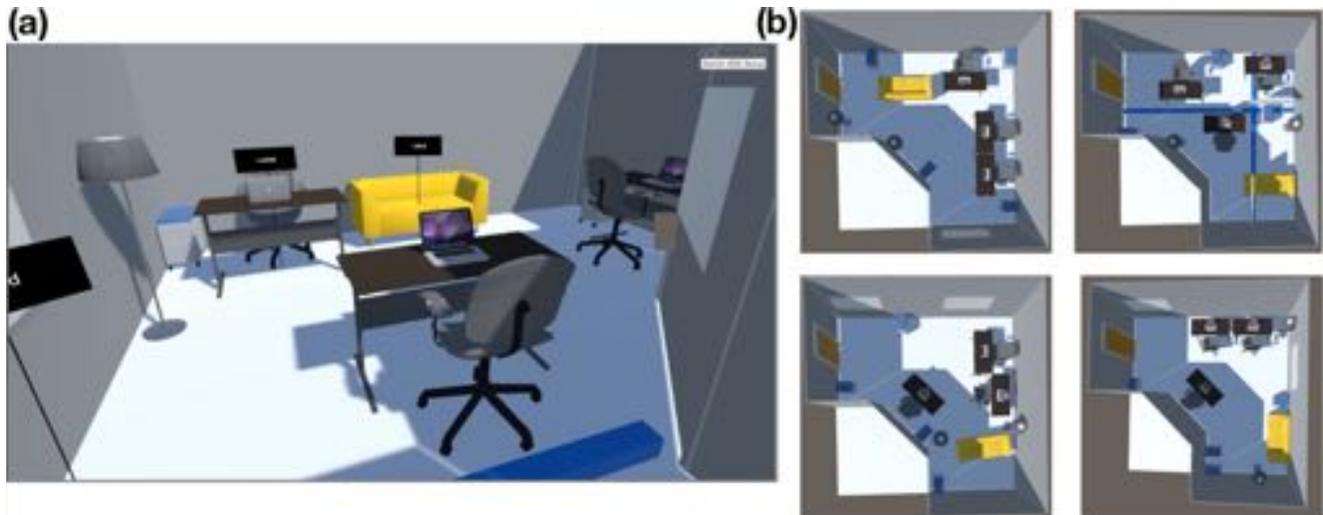


Figure 1: Screenshot of the DreamRooms system. (a) a room prototype in progress, (b) different room layouts prototyped in a session.

ABSTRACT

Generative design techniques use algorithmic encodings of domain knowledge to automate parts of the design process. This approach has worked well when success can be written as an optimization problem, but useful evaluation criteria are often discovered during the design process. To study how these criteria are developed we built *DreamRooms*, a room layout prototyping tool with a tight interaction loop between the designer and a generative process that does not encode *a priori* objective measures of quality. *DreamRooms* consists of a VR environment wherein the user can set constraints and gradually lower the entropy of a generative process that produces alternative layouts for the user to consider and iterate on. In addition to the *DreamRooms* system, we present the results of an observational study which revealed benefits to rapid collaboration between a designer and the generative process in an embodied environment and points towards mechanisms for communicating design intent to the generative process.

Keywords: Generative design, parallel prototyping, mixed-initiative interfaces.

Index Terms: H.5.m Information Interfaces and Presentation (e.g., HCI); Miscellaneous.

1 INTRODUCTION

Design used to be a process that was conducted on top of single-artifact authoring tools like Photoshop or AutoCAD, but increasingly design software has added support for design activities like parallel prototyping [1]. Automation is also increasingly

becoming a part of design tools, powered by advances in areas such as simulation, parametric design, artificial intelligence, and optimization techniques. A new class of “generative design” tools automate the design of artifacts based on high-level design goals (e.g., the forces a chair must be able to withstand), with the system working out the details of how to meet those goals (e.g. generating the geometry of a chair that will meet those requirements) [2].

Generative design approaches have been effective in scenarios where the design goals are encoded in an optimizable function [3], [4], but objective measures of quality are often not available early in the design process when designers are still searching for the “right design” instead of getting the “design right” [5]. Design at this stage is often a process of “enlightened trial and error” [1], where the designer iteratively investigates a space, “nam[ing] the things to which we will attend and fram[ing] the context in which we will attend to them” [6] to both gain an understanding of the problem setting, and explore potential solutions. In contrast to problem *solving*, in this problem *setting* process the criteria by which designs should be evaluated is subjective, and still being developed.

Motivated by the above, we are interested in how *generative prototyping* techniques could be developed, which apply the generative design approach to the early prototyping stages of the design process. We believe this approach could be particularly impactful for prototyping human-scale products, where emerging technologies such as augmented and virtual reality will enable designers to get an embodied experience of the outputs of the generative process.

This paper introduces an approach to generative prototyping and provides a reference implementation in *DreamRooms* (Figure 1), a generative, virtual reality (VR) room layout prototyping tool. *DreamRooms* is a prototyping environment in which the user works in a tight feedback loop with the system, which is powered by a procedural generative process. Initially, the layout procedure follows only two constraints: furniture should be placed inside the room, and not inside other furniture. From this high-entropy state, the user uses tools to constrain the degrees of freedom and provide

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design cues to direct the generative process in a divergent and convergent exploration of the design space.

In addition to presenting the design of DreamRooms, we present a qualitative observational study where participants were asked to come up with as many unique layouts as they could for two rooms. Participants enjoyed a rapid back forth with the generative process when they needed inspiration or an idea “filled in”. The flexible problem representation of the system enabled users to break the space into sections, corresponding to higher-level design intents for the space. Participants also interpreted generated designs through social interactions that could be enabled through particular configurations of furniture. Finally, participants used the virtual reality environment to understand how walking through a space felt and to evaluate the spaces from specific points of view. User-directed generative prototyping was immediately useful to participants in creating divergent designs. Some challenges they encountered provide insight into interaction techniques that new generative prototyping systems can explore.

Our work makes the following contributions to the existing HCI literature: (1) a prototype system demonstrating a new interactive model for human-scale generative prototyping in a VR environment; and (2) the results of a qualitative study, which provide insights into the effectiveness of this approach, and point the way to refinements for future interactive generative prototyping systems.

2 RELATED WORK

There are two main areas of past work that are closely related to our work on DreamRooms: interfaces for generative design systems, and space design tools, including virtual-reality systems.

2.1 Generative Design

Generative design tools automate parts of the design process, based on algorithms that are able to generate artifacts based on higher-level specifications of design intent. Powered by advances in parametric design, simulation, artificial intelligence, and optimization techniques, these tools enable the designer to specify high-level goals and constraints to the system, which are translated into candidate solutions [4]. This approach has been applied to a range of domains, including creating lightweight partitions for use in airplanes [7], designing furniture [2], and optimizing the layout of office buildings [8].

While powerful, these systems create their own set of interaction challenges. First, the techniques are typically limited to design problems where success has already been encoded as an optimization problem, which is not always possible or appropriate. Second, by making variations to the goals, constraints, or algorithms, these systems can generate a huge number of design alternatives that the user then needs to sort through. Finally, the optimization algorithms used in these systems are typically high-latency, which limits their interactivity.

To address some of these challenges, recent work has explored generative design systems where sketches are interpreted by the system and converted into problem representations [9], [10], and interfaces have been developed for exploring and visualizing the large data sets of design solutions generated by these systems [11].

In contrast to the work reviewed above, we are interested in investigating interactions with a generative process for prototyping *without* an initial objective function against which to optimize. Specifically, the DreamRooms system enables the designer to interact with the generative process in a tight interactive loop, evaluating artifacts generated by the system and simultaneously refining their subjective criteria for success. In addition, we are interested in the specific task of human-scale designs (room layout) and present the first investigation, that we are aware of, into how

VR can be used to interactively explore generatively designed alternatives.

2.2 Room Design Tools

Several projects have looked at how to support room design tasks. Commercial software tools for creating floor plans typically provide a top-down 2D view of a space where users can add individual furniture elements and interact with them using a drag and drop paradigm [12], [13]. Some tools offer the capability to produce 3D renderings of a space [14], or to view it in VR [15]–[17], though this is typically for the purpose of evaluating the produced design, rather than using the 3D method actively in the design process. A notable example is the IKEA VR experience [18], which allows the user to explore variations in material finishes on the furniture in a space (e.g., trying out different paint colors, or backsplashes in a kitchen), and to explore the space as different types of users (e.g., from a child’s size and point of view). However, the IKEA VR experience does not support the exploration of variations in how the furniture in a space is placed and arranged, which is our focus in this paper.

Closer to our generative approach, Merrell et al. developed a system for interactive furniture layout that interactively suggests arrangements based on interior design guidelines, and demonstrated that this approach can increase the quality of arrangements produced by users without prior training in interior design [19]. Room designs are generated and evaluated according to functional and aesthetic criteria, measured through mathematical operationalizations of interior design guidelines such as clearance around objects and alignment of furniture with the focal points in a room. We take inspiration from this prior work, and investigate how such an approach can be adapted to (1) the generative prototyping scenario, in which embedded optimization functions for generated designs are not baked into the system, and (2) an embodied VR experience, which allows users to get a subjective sense of what it is like to be in the rooms as they are generated.

In addition to the above projects, there has been some work on tools that automate parts of the office design process. WeWork, a company that offers co-working office spaces, uses procedural algorithms to help their architects place desks in the office spaces they acquire [20].

In contrast to the commercial tools discussed above, which facilitate the creation and evaluation of point designs, we investigate how an interactive generative design tool can facilitate divergent exploration in the early stages of the design process. Exploring many designs grounds subjective preferences in lived experience, which is further supported by the VR presentation. In the above way, we see this work as complementary to these existing approaches, which would be more appropriate later in the design process, once the designer had converged on a particular design and is working on refining that design or adding finishing details.

3 DESIGN GOALS FOR GENERATIVE PROTOTYPING

Our design goals for generative prototyping are informed by the literature on rapid prototyping systems, and have been adapted for generative design tools based on our review of related work and consideration of existing generative design systems.

D1. Favor Divergence over Refinement. The artifacts produced by generative design systems often require manual refinement to achieve desired results [2]. Instead of aiming for fully-automated design, generative prototyping systems should act as a brainstorming tool that produce creative prompts – rough designs that can be refined in existing human design workflows. The utility of this idea generation role is supported by past work showing that creating multiple prototypes to receive feedback in parallel leads to better design results [21]; iterating continuously on a single artifact

may cause fixation and systematic bias in success artifacts [22]; and creating distinct alternatives provides the designer with a more complete understanding of the design space [23]. Discussing multiple prototypes also has been shown to help stakeholders to better communicate their requirements [24].

D2. Provide a malleable problem definition. Early prototyping tools should provide a more malleable problem definition to enable “a process in which, interactively, we name the things to which we will attend and frame the context in which we will attend to them”, as well as creating potential solutions [6]. Most existing generative design tools assume a fixed problem representation (e.g., forces acting on a part) and employ an optimization algorithm (e.g. topological optimization [10], [11]) to produce solutions against this fixed model. By instead ceding quality measures to the user, generative prototyping tools can explore unorthodox ideas that do not conform to expert opinions of correctness.

D3. Enable a tight interaction loop between the generative process and the user. Iteration is a central component of the design process, and should be a core concern for digital design tools [21], [25]. To support this, the interaction between the user and the generative process should explicitly support *working through* the problem rather than sitting back and *thinking through* a set of presented options [6]. Supporting this in generative prototyping tools requires both low latency generation of alternatives as well as techniques for helping users understand the changes between iterations.

D4. Embodied engagement with prototypes. Generative design tools can produce many alternatives. Differences between them may not be entirely intrinsic but come from an interaction with their environment. Existing generative design tools afford a “pictures under glass” [26] interaction with generated artifacts. A design process for objects for human use should support embodied engagement with prototypes [27]. Thus, for room-scale designs, it would be beneficial for generative prototyping systems to provide in-situ design tools for the user to get an embodied sense of the generated prototypes. because it can be difficult to understand the potential uses and “feel” of a space until you are physically present within the space.

4 DREAMROOMS

Guided by these design goals, we developed *DreamRooms*, a virtual-reality generative prototyping system for room layouts. In terms of a target audience, DreamRooms is aimed at end users (i.e., not interior design professionals) who might use the system to create preliminary designs that could then be shared with an interior designer who would continue the design process.

At a conceptual level, DreamRooms supports a process of iteratively exploring the space of potential designs. From a random starting point in the space of potential layouts (Figure 2 (1)), the system enables the user to conduct a series of local optimizations (Figure 2 (2-4)). After the user has reached a “local maxima”, they can save the design and restart the process from a new random design configuration (e.g., Figure 2 (5)).

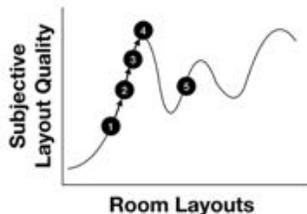


Figure 2: Conceptual representation of the DreamRooms design process. Users start with a random layout and iterate until it captures an interesting idea (1-4), then jump to a new random point in the design space (5) and repeat the process.

4.1 System Overview

DreamRooms requires as input the geometry of the room to be prototyped, and a list of the furniture items to be placed in the room. In our example system, these elements are hardcoded, but it would be straightforward to import these from a traditional 2D or 3D design tool.

The user starts in a virtual reality rendering of the room, with the furniture in a random placement produced by a custom-designed generative process. The user can then interact with the generative process in two main ways. First, they can set constraints and provide cues to the generative process through interactions with the furniture, walls, and floor (Figure 3). Second, they can request a new iteration of the room layout, which will be generated respecting the constraints and cues that they have previously set. This cycle of applying constraints and generating new iterations continues until the user is satisfied with a layout, at which point they can save it for later consideration, or as a starting point for further exploration. The user can also choose to start fresh, removing all current constraints and starting from the initial high-entropy state.

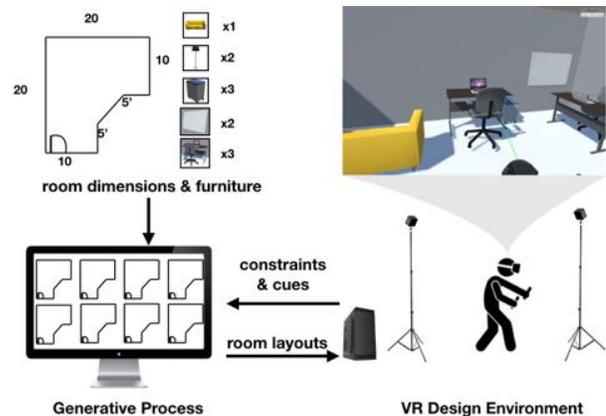


Figure 3: The Dream Rooms System Architecture

In keeping with D1, we intentionally did not implement tools for manually placing or moving furniture in the space, to maintain the focus on the collaboration between the designer and the generative process. Instead, we imagine that this system would be used to create a range of initial prototypes for a space, which are the refined using traditional design tools with fine-grained positioning capabilities.

In the next section, we describe the furniture layout procedure used by the generative process, and then the specific interaction techniques between the user and generative process.

4.2 The Generative Furniture Layout Process

We developed a custom constraint-based algorithm to place furniture in the room, allowing new designs to be generated at interactive speeds. The algorithm itself is not the focus of our contributions and could be substituted with more advanced generative algorithms [8], [19] in future implementations.

The algorithm randomly places furniture subject to three rules: (1) furniture is placed up against the walls of a room or other artificial landmarks (described later); (2) furniture is placed so it does not overlap other furniture and the clearance settings for the furniture (described later) are respected; and (3) the current set of constraints specified by the user is respected.

The input to the algorithm consists of the walls of the room and the furniture being placed in it. The placement of furniture is considered on a 2D cartesian plane. Each piece of furniture is represented by a bounding box. For each piece of furniture, a wall or user-designated landmark is chosen at random and then the piece

is placed parallel to it at a randomly selected position. Pieces are placed in descending order of size.

Next, we describe the interaction techniques available to the user for interacting with the generative process, and the specific constraints and cues they can set for the process.

4.3 System Interface

The system follows a number of standard VR conventions in terms of how users navigate and interact with the environment. The user has two handheld HTC Vive controllers, tracked by the VR system. One controller is primarily used for navigation, supported through a teleporting paradigm (i.e., point to a location in the space and click a button to move there). The user's position is tracked so they can also navigate in a 2x3 meter space by walking. This controller's trigger requests a new design from the generative process.

The second controller uses a laser pointer paradigm to enable selection and interaction with objects in the space (furniture, walls, floors, and other objects created by the system). Objects are interacted with by pointing a virtual laser pointer at them and clicking a button to bring up a contextual menu containing all the potential actions that could be performed on that object (Figure 4).

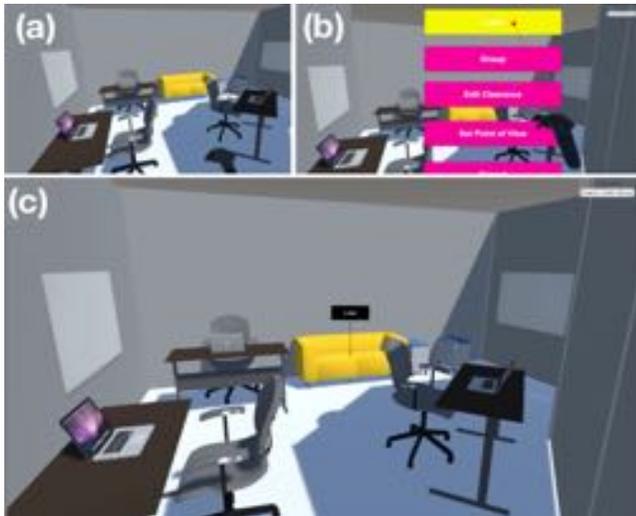


Figure 4: To interact with an object, (a) the user selects it with a laser pointer, (b) chooses an action from the pop-up menu, and (c) the change is applied.

4.4 Collaborating with the Generative Process

In this section we describe the interaction techniques through which the designer collaborates with the generative process by setting constraints, guiding the generation of alternative designs, and reviewing and comparing generated designs. The interactions are built using standard VR user interface patterns and directly manipulate items in the space. All of the interactions are lightweight and rapid to perform, which helps create a tight interaction loop between the system and the user (D3).

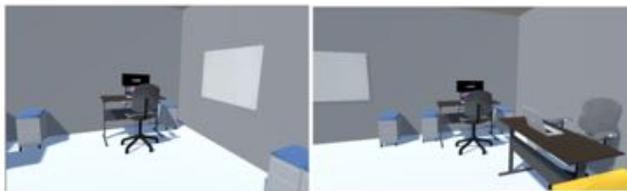


Figure 5: The locked desk remains in the same position as other objects are assigned to new positions.

4.4.1 Locking

When the user sees a partial configuration of furniture that they like, they can lock the associated individual items into place by opening the context menu on the item and selecting 'Lock'. This forces the layout algorithm to place the locked piece of furniture in the same position in the room before computing new positions for the remaining unlocked pieces (Figure 5).



Figure 6: Two couches in an L configuration are grouped. In the next iteration of the system, the two couches form a seating area in the corner of the room.

4.4.2 Grouping

Alternatively, when the user sees a relative positioning of two pieces of furniture that they like, they can group them together into a single object, by selecting 'Group' from the context menu for one object, and then selecting a second object. For this compound object, the generative process will compute a new bounding box that surrounds both pieces of furniture and place them as if they were a single piece of furniture (Figure 6). The interaction is similar to creating groups in vector graphics tools; however, in DreamRooms, it also re-defines the list of furniture for the space and thus the problem formulation being prototyped against. The goal is that by grouping pairs of furniture, the user can "teach" the generative process higher level "chunks" with which the space can be designed.



Figure 7: Guide walls (blue) being used to create a private working area in the foreground and a pair of desks surrounded by whiteboards in the background.

4.4.3 Guide Walls

As the user envisions subdivisions of the room, they can place guide walls – artificial landmarks that the algorithm will use as additional anchor points for furniture in the space. This is achieved by pointing to a wall or floor, opening the context menu, and selecting "Create Guide Wall". Guide walls are defined by selecting a start point and an end point on either the walls or floor. They are represented as low blue bars in the space (Figure 7).

4.4.4 Editing Furniture Clearance

Furniture typically requires some space for a human to walk up and use it. For example, a desk requires some amount of space behind

in order to pull out the chair and sit comfortably. This space is referred to as “clearance” in the DreamRooms system. Every object comes with a default amount of clearance and this can be adjusted by the user in order to suit their preference. Clearance is available in the direction in which a human would approach the piece of furniture to use it. The clearance setting is specified by selecting the ‘Edit Clearance’ option for an object, and then using the handheld VR controller to “grab” the clearance handle and drag it out from the object (Figure 8). Clearance is a form of “negative volume” that can be manipulated around objects, as defined by Smith et al. [28].

Collectively, the constraints specified by locking, grouping, setting guide walls, and editing furniture clearance define the problem definition that each new design iteration is generated against. In this way, these features enable a malleable problem definition for the generative process (D2).

4.4.5 Saving and Reviewing Designs

The ability for the user to rapidly generate new designs while standing in the space itself enables the user to get an immediate, embodied sense of each prototype design (D4). To enable the user to collect candidate designs for further consideration, the user can save a design at any time with a dedicated button on one of the handheld controllers. Once the user has saved several designs and wishes to review them, they can cycle through their saved designs using a separate dedicated button on one of the controllers.

Users have two options for how they browse through their saved designs: an absolute point of view or a relative point of view. In the absolute point of view, the room changes around the user and they remain in the same spot relative to the geometry of the room. This is useful for understanding how a room will feel from a fixed vantage point, for example when walking through the door.

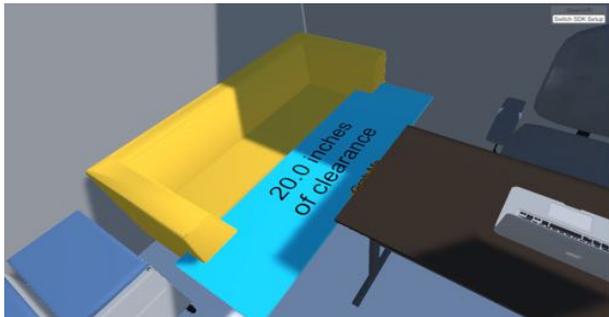


Figure 8: Editing clearance around an object – the user drags out a blue bar to indicate the required clearance.

In the relative point of view, the user can choose a piece of furniture from which they want to view the succession of saved designs (selected by opening the context menu on the object and selecting ‘Set Point of View’). This is useful for understanding how each room feels in action, such as working at one’s desk (Figure 9) without requiring the user to move to the desk in each design (further contributing to design goal D4).

4.5 Implementation

DreamRooms is implemented in two main components: the room layout generative process, and the virtual reality design environment. The virtual reality environment is built with the Unity Game Engine using the open source virtual reality interaction library VRTK (Virtual Reality Toolkit) [29]. 3D models were drawn from the Shapenet 3D Model Repository [30]. DreamRooms is designed to work with the HTC Vive VR system in its room-sized tracking configuration.

The generative process and room layout algorithms were implemented in JavaScript and Node.js. Communication between

the design environment and the generative process was implemented through WebSockets using Socket.io.



Figure 9: Point of view for “sitting” at a desk.

5 EVALUATION

We conducted a preliminary observational study of DreamRooms with two main goals. First, we wanted to observe individuals collaborating with a generative process and elicit their feedback on the experience. Second, we wanted to uncover where the interaction techniques offered by DreamRooms were not sufficient for participants to express their subjective preferences for a space.

5.1 Procedure

The experimental procedure had three parts: a pre-study questionnaire, using the DreamRooms system for two sample tasks, and a semi-structured exit interview.

The study began with a pre-study questionnaire, asking participants about their previous experience with VR systems and room design software.

Next, participants were given an opportunity to use the DreamRooms system. This part of the study began by giving the participants a walkthrough of how to move in the VR environment and then how to use the various features of the DreamRooms system. Once the participants were comfortable with the controls, participants were asked to complete a specific design task: they were put in the role of a design consultant whose firm had been hired to design a couple of office spaces for an incoming group of interns. Participants were asked to come up with as many unique designs as they could with a focus on fostering collaboration and conversation between the interns.

This part of the study lasted approximately 35 minutes. Participants were asked to spend approximately 30 minutes on creating as many alternatives as they could come up with and then 5 minutes reviewing and explaining their saved designs. This procedure was repeated for two rooms, a small room (Figure 10a) and a larger room (Figure 10b).

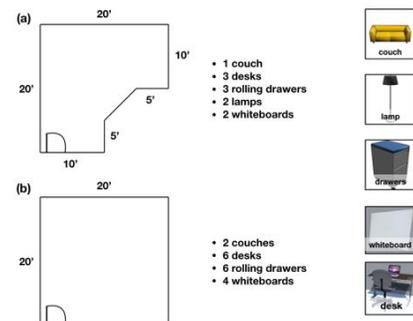


Figure 10: The geometry and furniture lists for the (a) small room, and (b) large room used in the study.

Finally, after completing the design tasks, a semi-structured exit interview was conducted with the participants, to gather feedback on their experience with the system.

5.2 Participants

We recruited 7 participants (4 male, 3 female, ages 25-38 (mean 32)) through an email to employees of a large software company. All of the participants had tried some VR demos, but none had regularly used a VR system for entertainment or development. No one reported prior experience using software for room design. Participants were given a \$25 gift card for participating in the study.

6 RESULTS

Overall, participants enjoyed using the system. All users were able to successfully create a set of design alternatives for the given design task. In the 30 minutes they had for each room, participants created an average of 10.3 designs for the small room (SD 5.7), and an average of 10.0 designs for the large room (SD 4.0). In terms of the time spent using the system per saved design, for the small room participants spent an average of 110 seconds per design (SD 128 seconds), and for the large room spent an average of 127 seconds per design (SD 157 seconds).

Participants expressed appreciation for how little effort it took to receive a complete design, compared to traditional drag and drop floor planning:

It made it easy to immediately have an idea. You didn't have to focus on the minutiae of this should go here or that there. You could quickly scroll through the ideas - P1

In the remainder of this section, we present six themes that we observed regarding how participants used DreamRooms and interacted with its generative process.

6.1 Support for Rapid Ideation

A common theme we observed was that participants enjoyed a rapid back forth with the generative process when they needed inspiration or an idea for how to proceed with a design. In some cases, we observed the system providing serendipitous input to the prototyping process, as in the following quote:

Oh that's an interesting layout, not what I was going for, but I will save this one too. - P5

Some participants would come up with a rough goal for a space and then iterate through alternatives until they found a design that matched their expectations, offloading the task of generating ideas for how to achieve that goal to the system:

When you think about it, it's a fuzzy idea in your head, but then you see it. it's like playing a lottery and you won, and you got the design that you were looking for - P1

Participants also enjoyed the rapidity with which the system could generate new designs, creating an experience in which they rapidly generated and evaluated the design outputs of the system:

I loved how fast it was. It was intuitive to play with. Iterating is very fast, so it's easy to become really trigger happy. - P3

We also observed that many people would simply not bother to adjust finer details of their designs, which may suggest a recognition and acceptance that the system is meant for rough prototyping in the early design phase:

I want to move these guys [rolling drawers]. Ah, whatever, they're fine there. - P4

This feedback also suggests the importance of integrating capabilities from later stage design tools into DreamRooms, to provide more fine-grained manual editing capabilities.

Finally, we observed that participants sometimes saved designs to capture an idea for the placement of a single type of furniture, with little concern if other furniture types were misplaced:

Other than the couch blocking the door (I didn't care to move it) everyone can walk into the space and work together. - P4

Revisiting our design goals, this feedback provides support for the system enabling a tight interaction loop between the generative process and user (D3), and its ability to favor divergence over refinement (D1).

6.2 Focusing the Generative Process on Subproblems

A second theme that we observed was that participants would often subdivide the space into smaller areas, using the guide walls feature. This enabled them to address the problem of designing for the entire space as a set of smaller subproblems.

I want to create like a "town square" (in the center) - P1

Guide walls would often be drawn parallel to existing walls or used to connect corners and wall-midpoints in the room. Despite this predictable usage, some participants felt like they were taking a radical step:

I'm going to try something crazy. I'll put a couple x's across [the space] - P6

An inconvenience that users ran into after using guide walls is that they could not explicitly pin furniture to generate only in their newly envisioned space:

It would be nice to create zones, like a relaxation zone, like the couches are positioned in a certain place. - P5

This suggests that a divide and conquer approach to furniture placement in VR would complement the anchor points by restricting certain pieces of furniture to the sub-area of the room being designed.

Another challenge is that design inspiration would come as a relation between furniture. For example, one participant used guide walls to place desks facing outward from the center of the room, and then wanted to create whiteboards around the room at the focal points for the desks:

I was trying to make the focal points all around. get the whiteboards around the walls. - P1

In DreamRooms, the user can preserve a relation between objects through grouping but cannot propagate this relation to other objects of the same types.

The above examples highlight areas where the interaction with the generative process could be improved, and further highlight the importance of generative prototyping systems providing a malleable problem definition (D2). What's interesting is that the malleability of the problem definition may require the system to have a deeper appreciation of the meaning of the objects being arranged (such as the focal points created by users sitting in desks).

6.3 Human-Centered Interpretation of Designs

In our task, we specifically asked participants to design with the intention of fostering conversation and collaboration. We observed a few different ways in which participants interpreted designs through the social interactions that they could enable or formed social goals for the spaces.

For one participant, the anticipated level of human activity was used to assign different roles to partitions of the space:

This is your breakout room essentially... this one was grouping all the seats together to separate out a quiet area from a working together collaboration area. – P3

I liked that these two whiteboards are here [on a corner] where people can chat or have a scrum. – P5

The relative positioning of furniture relative to desks also indicated a sense of ownership:

I thought the couch was in a neutral spot, it doesn't "belong" to any one person. – P4

Though it is difficult to tell without a more controlled study, these manners of describing spaces through a social and human lens may suggest a benefit to the embodied VR engagement with the generated prototypes (D4), enabling the designer to more easily envision uses of the space. It may also suggest the promise of collaborative VR experience for the system, to allow more than one person to try out the generated spaces, and role play with generated designs. These experiences also support the importance of our goal of a malleable problem definition (D2), to allow the designer to communicate human-centered design goals and constraints to the system.

Related to the theme of human-centered interpretations and goals for designs, participants used the embodied experience provided by the VR environment to get a sense for how walking through the space would feel, and to evaluate it from particular points of view, such as from the door:

First thing I had in mind – when I'm entering the room, what's the first thing I see? So, I'd go straight to the entrance point. – P7

Using their bodies to view the space, some participants discovered ergonomic issues while discussing how people would use the space:

This design felt more cramped, but... everyone is very close to each other – no loud speaking, they can talk easily. Everyone has access to see that board very easily – no neck craning. – P7

This suggests our system satisfied our design goal of enabling embodied engagement with the generated prototypes (D4), and also highlights a particular opportunity for generative prototyping systems – because the generative process takes an active role in creating particular designs, the user is freed of the need to use a large number of tools to do so, which allows the user to focus more on trying out and getting a feel for the generated prototypes.

While the use of a VR environment had advantages in understanding specific parts of the space, some participants had difficulty understanding the generated designs as a whole:

The larger the space, it's harder to figure out where everything is. It'd be nice to get a bird's eye view of everything. – P6

This could potentially be addressed through mechanisms for promoting more rapid awareness of the entire space, and changes between iterations (e.g. by animating the movement of furniture positions between iterations), or by leveraging existing VR techniques for getting overviews of a scene, such as world-in-miniature [31].

6.4 Desire for More Control over Grouping Behavior

A final theme we observed was that participants wanted more fine-grained control over how hierarchical groups of objects were formed and indicated to the generative process. In our current implementation, grouping objects preserves the relative positioning of those objects (say, a desk and a cabinet), but does not affect other instances of those objects in the space (e.g., other desks and cabinets). In some cases, participants were interested in applying

this relative positioning constraint to all pairs of two types of objects, rather than a specific instance:

...ideally you'd have one set of drawers group with every desk. Again, you can't place it where you would want it to be. It would be cool if you could group all items of a certain type e.g. all desks and drawers should be grouped. – P4

And every participant had a moment of frustration where they could not adjust the fine positioning of elements within groups:

I would really like to have this desk facing this one. It got 98% of what I wanted, but I couldn't tweak it. – P7

This feedback is interesting, because it suggests that the overall idea of grouping could be broken up into a richer family of different grouping tools for expressing design intents to the generative process. This again highlights the importance of generative prototyping systems supporting a malleable problem definition (D2). Providing limited manual positioning capabilities for specifying how objects are grouped increases the user's influence over the generative process without allowing them to resort to manual placement. However, we believe there is a tradeoff here, where adding too many of these capabilities could lead users to become overly focused on smaller design details during the initial ideation process [5].

6.5 Reviewing Saved Designs

Finally, we observed several themes related to how participants reviewed the set of designs they had created with the system during the final phase of the study.

When asked to explain the rationale for the designs they had created, participants typically explained them through the constraints they had imposed on the generative process:

I wanted one cabinet next to each desk so I iterated a bunch. then locked those down, then I iterated through the lamps for a bit to get them spread out. – P5

Participants sometimes had difficulty remembering why they had saved a particular design. This may be a result of the rapidity with which the user can generate and save designs in the system. For example, during the design creation phase, P2 noticed an iteration he liked and saved it:

I'm gonna save this one too, I didn't even have to do anything. – P2

Later, when reviewing the designs, he did not recall that he had created this design:

This one just generated on its own, I think. I can't remember exactly. – P2

The above examples suggest that engaging in a tight interaction loop with the generative process (D3) may make designs more personally meaningful to participants. It also suggests that tools that allow the user to record their intent for saving a design, or particular elements of the design that they liked, could be a valuable addition to the system.

A final observation we made of the design review phase, is that participants continued to come up with new ideas for iterating on the designs as they reviewed them:

In retrospect, I could have gone back to this design and grouped these desks together. – P5

They also identified sub-elements of saved designs that they liked, even if they did not like the design as a whole:

I saved this as a starting off point, but I don't think it's really good or feasible. This couch is really nice in this corner over here. – P5

This suggests that interactions for explicitly supporting a practice of combining usable elements from multiple saved designs may be valuable. This could form another method of communicating intent to the generative process (D2).

7 DISCUSSION AND FUTURE WORK

Overall, our study findings indicate support for the overall idea of generative prototyping. The user-directed generative process enabled participants to rapidly create designs which suggests that this approach could be immediately beneficial to incorporate into existing commercial tools where manual placement of furniture is the main mode of interaction. Specifically, the tight interaction loop enabled participants to rapidly evaluate generated designs, make serendipitous discoveries, and create a diverse set of designs. Below we discuss some of the core insights, limitations, and areas of future work arising from our implementations and observations

7.1 Embodied Experiences with Generative Design

We believe the ability to rapidly guide and explore design alternatives was uniquely enabled by the embodied engagement with the prototypes that was afforded by the VR environment. Because the user was able to stand within the generated rooms themselves, they could leverage quick recognition to evaluate designs from a first-person perspective. This capability is not possible in desktop design applications, where each generated prototype would require added effort to imagine what it might be like for users of the space. Future work could look at the utility of leveraging embodied experiences to assess design in domains outside of room planning, and at scales larger and smaller than those which we have explored. One limitation that we noticed is that, in larger spaces, it could be difficult to notice and appreciate the changes between iterations. Visualizing the difference between iterations either through animation or providing an auxiliary 2D “bird’s eye” view could help designers keep up with the speed of iteration in generative space prototyping.

7.2 Working at Interactive Speeds

Many of the promising findings of our work also relied on the ability of the generative process to produce new designs in real time. This suggests a need for future work developing generative algorithms that can work at interactive speeds and are able to generate prototypes in high enough fidelity that users can get a rapid embodied sense of them. This contrasts with many existing generative design approaches, where the fidelity requirements may be much higher, but the system can take minutes, hours, or even days to compute design solutions or require GPU support to achieve interactive speeds. Related to the limitation discussed in the previous section, it could be beneficial to reduce the magnitude of change between iterations in order to help the user keep up with the system. When performing algorithmic optimization of design artifacts, some systems [19], [32] make only a single change to an artifact before re-evaluation. A successor to the DreamRooms prototype could introduce completely new designs after saving and introduce only a single furniture position/orientation change once the user has begun engaging with a particular design. Our findings also suggest that techniques that allow the user to subdivide a space into separate zones, where the activities of the generative process are localized, could be a useful general-purpose mechanism that would give designers a more malleable method of defining the problem to the generative process.

7.3 Reification of Human Engagement with Designs

Our results suggest the value of interaction mechanisms that allow the designer to communicate more human-centered and social goals to the generative process. For our test domain of room layout, this could take the form of representing knowledge of how objects such as desks, whiteboards, and couches are used by occupants of a space (e.g., the fact that someone sitting in a desk has a particular sight line when sitting at that desk) as meta-objects on top of the furniture objects themselves. This could allow designers to place constraints on these human-centered aspects of the objects in the space (e.g., prevent sight lines from pointing at one another) and their interaction with other objects in the space. Simulation of social activities in the space, or collaborative use of the design tool, could also potentially be used in this way.

7.4 Refining Subjective Preferences

In DreamRooms, subjective preferences are indicated to the system by a growing set of constraints imposed by the designer, but the system never has an explicit optimization function for selecting between designs that meet these constraints. This was by design, leaving it to the user to generate iterations for a current set of constraints until they find something they like (i.e., the designer’s judgement acts as the objective function), but it would be interesting to investigate how objective functions could be rapidly developed, represented, and selectively applied to supplement this approach. For example, participants in our study expressed several goals that could be turned into objective functions (e.g. flow of people through a space, importance of a given focal point, relations between certain pieces of furniture) – an interesting topic for future work is to investigate how these kinds of emergent user-created objective functions could be rapidly specified to the generative prototyping system, to complement our constraint-based approach.

7.5 Formal Evaluations

While our initial study was valuable to gain first insights into the experience of interacting with a generative process, it should be complemented by a controlled study comparing DreamRooms to prototyping on paper or using more traditional 2D design tools. In particular, it would be interesting to test whether DreamRooms is able to allow users to generate a wider variety of different designs, and to compare the speed with which designs can be generated using the different methods.

8 CONCLUSION

In this paper, we investigated *generative prototyping* – adapting existing generative design techniques to early stage prototyping, where the designer is still in the process of developing their subjective criteria for designs, and objective measures of design quality are not yet available. Through a prototype system and user study, we gained an initial understanding of the role that low-latency generation of prototypes and embodied evaluation can play in early-stage design. We believe this work demonstrates the immediate utility of user-directed generative processes and opens up a space of research on interaction techniques for defining measures of quality during the design process.

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