Explorations of Designing Spatial Classroom Analytics with Virtual Prototyping

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ABSTRACT

Despite the potential of spatial displays for supporting teachers' classroom orchestration through real-time classroom analytics, the process to design these displays is a challenging and under-explored topic in the learning analytics (LA) community. This paper proposes a mid-fidelity Virtual Prototyping method (VPM), which involves simulating a classroom environment and candidate designs in virtual space to address these challenges. VPM allows for rapid prototyping of spatial features, requires no specialized hardware, and enables teams to conduct remote evaluation sessions. We report observations and findings from an initial exploration with five potential users through a design process utilizing VPM to validate designs for an AR-based spatial display in the context of middle-school orchestration tools. We found that designs created using virtual prototyping sufficiently conveyed a sense of three-dimensionality to address subtle design issues like occlusion and depth perception. We discuss the opportunities and limitations of applying virtual prototyping, particularly its potential to allow for more robust co-design with stakeholders earlier in the design process.

CCS CONCEPTS

• Human-centered computing → Visualization design and evaluation methods; **• Applied computing → Collaborative learning**.

KEYWORDS

virtual prototyping, spatial classroom displays, classroom analytics, mixed reality, augmented reality

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1 INTRODUCTION AND BACKGROUND

Current learning analytics (LA) research has identified that *classroom analytics* can support learning outcomes and teacher awareness [1, 4, 14, 17, 19]. These studies have investigated the importance of analyzing the interactions between the teacher, students, and the space during classroom instruction. The resulting analyses can provide meaningful feedback to teachers by making teacher-students' interactions visible [1, 5, 17], improving teachers' awareness and directing attention to struggling students [4, 12, 13], or giving early alerts about students' progress and engagement [5, 9, 13].

Considering the benefits of classroom analytics, there has been a growing interest in incorporating them in real-time systems, encoded as spatial classroom displays, through mixed reality devices [13] or ambient displays [5, 9]. We will refer to spatial classroom displays as a type of dashboard in which information is localized in the physical classroom space. Holstein et al. [14] deployed *Lumilo*, an Augmented Reality (AR) system for orchestrating classroom activities and alerting teachers about student progress and struggles in real-time as students interact with AI-based software. *Fireflies*, an ambient display system, spatially distributes student states and engagement information across the classroom while interacting with an AI-based software, supporting teacher awareness on students' needs [6, 9]. Similarly, Alavi and Dillenbourg [2] introduced *Lanterns*, a set of distributed lamps for the ambient display of information, which improved teachers' awareness of whether groups of students needed help. An et al. [4] implemented *ClassBeacons*, an extended version of *Lanterns*, by adding an indoor-localization system through beacons, enabling both teachers and students to visualize teachers' proximity distribution. To sum up, these works use the physical space as an interactive "dashboard", where students' status and teachers' positioning are shown through visual-spatial

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displays, which is often interleaved naturally within the classroom space without the need of an additional computer or tablet.

Existing design processes for LA dashboards suggest involving educational stakeholders (i.e., teachers, students) in co-design to get useful and contextual feedback [7, 14, 18]. Similarly, when designing for spatial classroom displays, it would be desirable to involve teachers in the early stages of the design, as this would give them the chance to experience several designs of visual-spatial elements. Engagement with teachers offer a valuable opportunity for designers and researchers to explore visual-spatial challenges that are inherent to the classroom space.

Prior works in this research area have used a range of prototyping methods to co-design spatial displays. Holstein et al. [14] and An et al. [4] demonstrated how low-fidelity prototypes can be used to support idea generation. Compared to mid- or high-fidelity prototyping, low-fidelity methods lack the capacity to demonstrate and test how spatial characteristics (e.g. teachers' position, students' location) and contextual information are essential when designing spatial classroom displays [14]. To overcome this limitation, mid- or high-fidelity LA prototypes are implemented to validate how users interact with the LA solution before moving towards a full implementation [18]. This solution may include more authentic and realistic data. For instance, Holstein et al. [14] used a modified version of HoloSketch and eventually a full mixed reality application with HoloToolkit and Unity to explore and validate design ideas of an orchestration tool using historical data in a simulated classroom scenario. Advantages of including mid- or high-fidelity prototypes include the possibility to validate spatial characteristics of visual elements and to quickly iterate over different design solutions. However, researchers considering mid- or high-fidelity spatial display prototypes must often reconcile with limited access to specialized hardware (e.g., AR headsets [12]) or the physical classroom space. Perhaps one of the most acute limitations for conducting research in educational contexts, which has only been exacerbated by the current COVID-19 pandemic, is the local and logistic constraints of soliciting stakeholder feedback and conducting user testing in classrooms. Teachers who participate in this work are often in close proximity to the research, which increases the likelihood that designs lack adaptability and generality to work in other contexts (e.g., classrooms in different countries).

Our work seeks to address the aforementioned constraints to the design process of spatial classroom displays by presenting a mid-fidelity approach called the Virtual Prototyping method (VPM), which follows industrial uses of virtual prototyping [23]. Specifically VPM refers to the process of constructing a 3D virtual classroom environment where spatial display prototype designs are simulated in the same environment. With VPM, contextual feedback is obtained by displaying the simulation and asking stakeholders to navigate the virtual space in person or via video conferencing software without needing specialized hardware. The virtual environment can be implemented using any 3D authoring tool. While virtual prototyping has been proposed as an approach for teacher training and professional development [10], to the best of the authors' knowledge, this is the first attempt in the LA community to explicitly outline a prototyping method for supporting the design of spatial classroom displays and extending the possibilities for co-design.

This paper demonstrates the feasibility of VPM through an exploratory case study. We report and discuss two main topics that emerged from prototyping sessions with five potential users, some with extensive teaching experience. First, we describe findings of the design prototypes regarding to spatial characteristics. Then we share insights about the VPM, as a method for idea generation and feedback to facilitate co-design throughout the development process. Separately, we discuss VPM's potential as a tool to examine paradigms like the hybrid classroom model .

2 VIRTUAL PROTOTYPING METHOD (VPM) FOR DESIGNING SPATIAL CLASSROOM DISPLAYS

The origin of virtual prototyping can be traced back to applications in industry as a way to easily and quickly iterate over several solutions in the design phase of complex products, before actually going deeper into the implementation phase [23]. In this context, virtual prototyping can have many forms, including simulation in Virtual Reality and Augmented Reality, but can also accommodate mock-ups in Computer-Aided Design (CAD) software. By taking a similar approach as industry research, virtual prototyping could potentially support the design of LA solutions that involve spatial classroom displays.

VPM's original motivation was to provide support for designers and researchers to create a prototyping environment that can be scaled and rapidly iterated upon to best fit the needs of stakeholders. We built on the notion that several spatial features should be validated before moving towards a more realistic high-fidelity prototype, such as i) choosing visual elements that encode the information specific to the problem, ii) determining the relevant physical space arrangement, and iii) identifying features that could influence the design of spatial displays, such as information load. Varying these features would help show the robustness and adaptability of candidate designs.

Utilizing VPM as a prototyping method in existing iterative design processes for LA visualizations [18] can take the following form. As an initial step, prior exploration and need findings of the problem should be available; some design ideas should have been initially generated from low-fidelity prototyping. Next, researchers and designers should decide the *design features* (i.e. visual elements, classroom layouts, information load) that are being validated in the 3D environment. Finally, these design features should be implemented in the 3D environment in preparation for the user evaluation.

3 EXPLORATORY CASE STUDY

3.1 Context: AI-based Classroom Technologies

Envisioning the classroom of the future, where AI-powered learning software plays an essential role in personalized learning, this case study has been set up using different classroom technologies for middle school students. In this study, we applied virtual prototyping in the context of AI-based Intelligent Tutoring Systems (ITSs), namely *Lynnette* [15] and *APTA* (Adaptive Peer Tutoring Assistant) [22], and a mixed reality orchestration tool called *Lumilo* [12].

Lynnette supports individual problem-solving practice, and provides step-by-step guidance in the form of hints and feedback as students progressively solve linear equations problems (e.g., solve for x: x + 3 = 9) [15]. *Lynnette* keeps track of learning mastery of math concepts and is implemented as a rule-based Cognitive Tutor within the CTAT/Tutorshop architecture [3]. *APTA* on the other hand, supports peer tutoring activities by assigning a student who will serve as a coach, or the tutor, to a student who might be struggling, also known as the tutee. *APTA* was implemented using two rule-based cognitive models: one that captures peer tutoring strategies and coaches the tutor and another that captures equation-solving mastery (this is done through *Lynnette*) [22].

Lumilo is a mixed reality orchestration tool implemented with *Lynnette* to enhance teacher's awareness of student struggle [12]. More specifically, *Lumilo* helps teachers to monitor a class that may be working on individual assignments by providing targeted assistance. In the mixed reality headset display, the tool directs the teacher's attention to students who might be needing most of the help, by projecting different real-time indicators of students' learning status. It does so by consuming students' mastery skills and actions from *Lynnette*; then automatically detecting states such as struggling, hint abuse, local errors, among others; and finally projects symbols over students' heads to represent those states, such as a smiley face suggesting that the student has been performing consistently well, or a question mark suggesting that the student might be struggling over students' heads [14].

3.2 Design Challenge: A Mixed Reality Orchestration Tool for Teaming Up Students

Prior research has investigated the use of *Lumilo* in K-12 education as an orchestration tool [12, 14]. In these investigations, middle-school students worked with *Lynnette* to individually practice linear equations, while teachers were wearing a mixed reality headset running *Lumilo*. Initial exploration with teachers pointed out a preference for hybrid control in which teachers *share the orchestration load* with students and AI-based agents [11, 14]. Therefore, our design goal is to provide support, within a new version of *Lumilo*, for dynamically switching students from individual (*Lynnette*) to peer tutoring (*APTA*) activities. We envision a tool that suggests and assigns students "on the fly" to serve as peer tutors. Thus, from students' performance in *Lynnette*, *Lumilo* indicators, teachers' prior knowledge, and students' preferences, we could generate AI-based suggestions for peer tutor-tutee pairings.

A particular design challenge when using mixed reality is to effectively display potential suggestions for pairing up students, taking into account the number of suggestions, teachers' location, and the correct use of visual elements for encoding tutor-tutee pairs. The design also needs to consider classroom characteristics (i.e., low-achieving, large classrooms) and spatial characteristics when rendering visual elements (i.e., depth, occlusion).

3.3 Mid-Fidelity Spatial Classroom Displays Prototypes

We implemented prototypes using Unity [20], a 3D graphics engine commonly used to build video games. Unity has been used frequently for creating simulations due to similarities in the development stages of making games. Unity provides a built-in Play Mode, enabling researchers to quickly build, test, and showcase new ideas. This, paired with virtual avatars included in many pre-built tools for simulating interactions, can serve as powerful tools for researchers.

We explored designs of spatial classroom displays (namely, for *Lumilo's* new functions for dynamically orchestrating collaborative learning episodes with *APTA*) throughout two iterations using VPM to understand how our designs might work concerning i) visual elements showing pairing suggestions; ii) classroom layouts; and iii) information load.

Visual elements: The first iteration consisted of three visual elements, including *arrows* that connect potential tutor-tutee pairs, *colored dots* above students' avatar heads, where green represented a potential tutor, and red represented a potential tutee, and a *panel*, which listed the names of the potential tutors and tutees in a two column format. These are shown in Fig.1. We showcased two new designs for the second iteration. The *arrows* were changed to a *gradient line*, gradating from green to red. Instead of an arrow, green and red colors were used to differentiate between a potential tutor and a tutee. The *colored dots* were connected with *black lines* to show explicit pairings. The *panel* design stayed the same across the iterations. These are shown in Fig.1.

Classroom layouts: In iteration one, we deployed three common classroom layouts that we observed in prior studies, a traditional row and column classroom, a layout geared towards group activities, and a layout similar to a computer laboratory. These three classroom layouts are illustrated in Fig. 1. The computer laboratory setting was removed from the study after the first iteration, because we discovered that participants were not as familiar with this arrangement.

Information load: We presented two options to explore the role that information load might play in showing pairing suggestions. We considered a *low information load* case showing fewer pairing options and a *high information load* with several pairing options, as illustrated in Fig. 1. The information load conditions were kept the same across the two iterations.

The prototypes were static, meaning that the pairing options being displayed did not change as teachers were interacting with the prototype, as they would in the wild. However, we plan to move towards an interactive version of the current prototypes using data from past studies.

3.4 Study Design, Participants, and Procedure

We conducted two iterations of design evaluation sessions. The first was a set of 3 visual elements × 3 classroom layouts × 2 types of information load permutations (18 total), while the second involved 3 visual elements × 2 classroom layouts × 2 types of information load permutations (12 total). Each of these variables can be seen in Fig. 1. These sessions were aimed at exploring the prototype designs described in the previous section.

Five participants (all females, avg. age: 29) were recruited. The three participants in iteration 1 (P1-P3) were college students. Later, two participants (P4-P5) were recruited for a second study; both

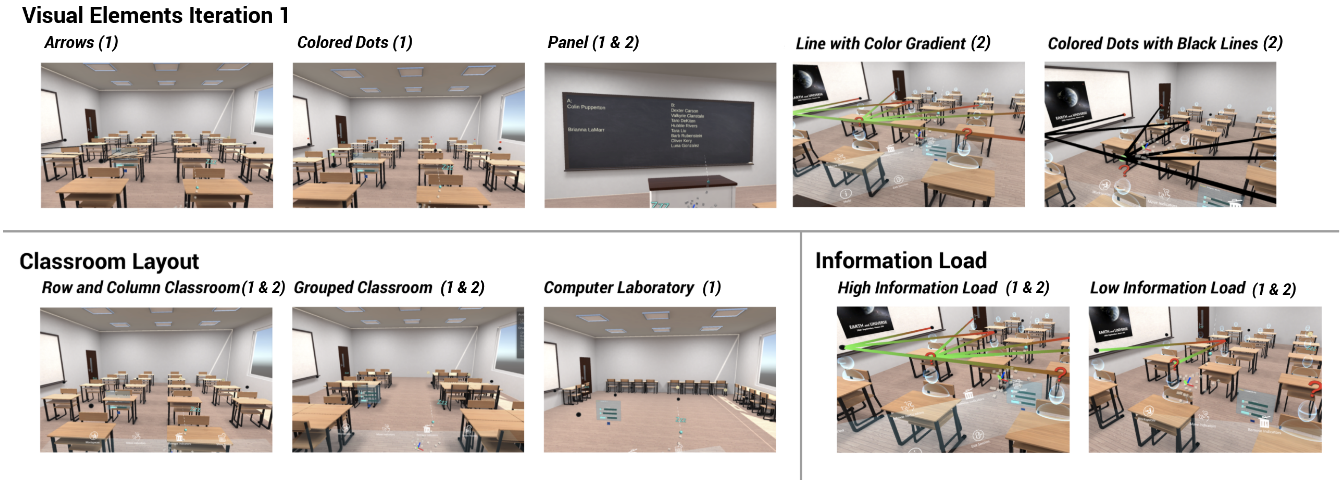

Figure 1: Examples of the virtual environment and spatial features validated across both iteration 1 and 2. Features which were only used in one iteration are denoted as such with (1) or (2), or (1 & 2) if they appeared in both iterations.

had prior teaching experience (avg. years of teaching experience: 16). None of the participants had prior experience with AR systems.

Each session from both studies were conducted using video conferencing software (i.e. Zoom), which allowed us to share the virtual environment created after applying the VPM.

The study consisted of the following steps. *First*, participants got familiarized with the context and the virtual environment. To provide some degree of interaction with the virtual environment, participants were instructed to move the virtual avatar (i.e., the teacher's view) around the classroom to three different locations. *Second*, participants explored each of the design prototypes. During the exploration, they were encouraged to provide feedback by externalizing their thoughts using a think-aloud protocol [16]. Overall questions about the designs were asked to participants in relation to the context and the design elements according to the different options displayed in the prototype (e.g., *"Can you tell which are tutors and tutees?; Which design did you like the most, and why?"*). *Finally*, follow-up questions were asked at the end of all explorations to draw conclusions across designs. Each participant session was recorded and approximately five hours of video recordings were transcribed for further analysis.

4 ANALYSIS AND FINDINGS

We aimed to understand what the experience told us both about 1) the designs for the orchestration tool, and 2) the VPM itself. We conducted a thematic analysis using Affinity Diagramming, a design method which summarizes patterns of responses by iteratively clustering quotes based on content from a grounded theory perspective [16]. The authors of this paper worked through the transcripts to synthesize findings. Over several interpretation sessions, we clustered 274 quotes across two themes, which were related to the two aims of this study. The first theme was aimed at exploring feedback and implications on our designs considering the spatial features (as defined in Section 3.3) about i) visual elements, ii) classroom layout, and iii) information load. Therefore, we clustered the quotes across these features. The second theme was focused on understanding the type of feedback that can be derived from the VPM. We started clustering similar quotes, from which three sub-themes emerged during the interpretation sessions, namely: 1) simulate occlusion, 2) observe depth; and 3) experience different perspectives. The next subsections provide a summary of findings from the two main themes and corresponding sub-themes.

4.1 What did we find out about our spatial classroom displays designs?

4.1.1 Visual elements. In the first iteration, two out of three participants found **arrows** to be effective because it displays tutor-tutee pairs explicitly. However, they noted that the thinning of the arrows towards the end made it difficult to see to which tutee the arrow was pointing. In addition, in scenarios with **high information load**, arrows often overlapped. Participants responded that the overlap felt overwhelming, as they could no longer decipher the possible pairings. Concerning the **colored dots**, all three participants agreed that it was a cleaner solution for displaying tutors and tutees. However, this design was not as effective as the arrows because it did not explicitly show pairings. One participant (P2) described, *"I think it's a little bit easier to tell which indicator represents which person, especially when you move around. But it's harder to, like automatically make associations, like this person needs to go with this person."* Lastly, two (out of three) participants liked the **panel** design because it summarized general understanding across students in the class. For example, P3 mentioned that the panel design displayed how many students are struggling in total, as well as the ratio between students who are struggling and those who are not. However, both of these participants agreed that the panel design would have been better if it was more spatially integrated. Four participants suggested that the panel should follow the teacher's view because a stationary panel was not visible at some angles. For instance, P2, who asked to move the teacher's view near the front door, said that the panel was *"kind of hard to read at this angle."*

Through the second iteration, both participants (P4 and P5) were pleased with **color gradients** throughout most of the scenarios. However, similar to findings found in the first iteration, during scenarios with **high information load**, both participants were overwhelmed by the number of lines in the space. In relation to **green and red dots with black lines**, this design received critical feedback because rather than diminishing flaws criticized in both designs (lines and colored dots), it combined them. Both participants (P4 and P5) expressed that using both visual elements worsened the information overload and the overlapping of visual elements. Also, as in the first iteration, both participants would have liked to see a **panel** that follows them around in the virtual space.

4.1.2 Classroom Layout. In the first iteration, the classroom layouts did not affect the panel design; limitations and affordances of the panel design persisted in all classroom layouts. However, the layout did have an impact on how participants perceived the arrows and colored dots. In the **grouped classroom**, participants expressed that the arrows did not show the pairing suggestions consistently. The location of students (i.e. four students sharing a desk) increased the likelihood that a line starts or ends at a similar location, which led to an increased occurrence of overlaps. For instance, P4 expressed that she *"did not understand how there's only one person helping and one who needs help, because there were four dots on the line,"* meaning that she saw two lines as one.

The colored dots received more positive feedback when placed in this layout. Participants described that the grouping of colored dots revealed whether a whole group was struggling or not, in addition to individual performances. In the second iteration, it did not appear that the classroom layouts had much effect on how participants viewed the designs. However, we note that P4 preferred the rows layout while P5 preferred a grouped layout, as it was the layout they chose to use for their own classrooms. P5 noted that, *"Being able to, [...] visualize how I would use it in the classroom setting that is similar to my own, it helps me evaluate the tool better [...] if I want to use it, I need to know how it's going to work for my situation,"*, which was similarly echoed by P4.

4.1.3 Information Load. Designs that were presented under the **high information load** condition had several drawbacks. All five participants expressed discomfort and confusion when the scenario involved high information load and described that it was the most significant hindrance to understanding classroom conditions. In particular, all participants expressed confusion with line-based designs under high information load because of how quickly the visual space became cluttered. This condition of the design study indicated that while spatial pairing displays can be useful for participants to understand who to pair, there is a limit to the number of pairings that can be suggested simultaneously in order to be interpretable.

4.2 What does VPM allow designers and researchers to do?

4.2.1 Simulate Occlusion. One key factor in determining the effectiveness of spatial displays is how its design deals with occlusion. Occlusion occurs when one object is blocking another object in a 3D environment and occurs naturally in the physical space. As such, it is imperative for designers to understand how their prototype exhibits occlusion and to minimize it as much as possible. Our designs in the VPM environment displayed occlusion to varying degrees, and the feedback from participants were crucial for mitigating occlusion. P3 stated several times, *"[the arrow design elements] blur into each other"*. This comment was also echoed by P1 and P2. When asked how we could improve the design to address this issue, P2 suggested *"a single width line [. . .] at one end of the line is green, and one end of the line is red, in a gradient,"* which was considered for the second iteration. The gradient line received a positive response from P4 and a mixed response from P5, representing progress from the unanimously negative feedback from the first iteration. Occlusion is difficult to envision, but the VPM environment appeared to help diagnose issues of this.

4.2.2 Observe Depth. Another important component of spatial dependence is depth, which is difficult to represent in a low-fidelity prototype. Our pairing designs in the VPM environment could occasionally be difficult to understand, as P3 noted, *"I can't tell if [the arrow] is pointing to this student [referring to a student near the arrow], the second student in the back row or the third one in that row, like it kind of looks like in between the two."* In the second iteration, P4 noted that ambiguity of depth in the *"ma[de] it a little more challenging to figure out who we're actually talking about."* Certain scenarios appeared to exacerbate depth perception issues. P2 remarked in the high information load with colored dots scenario, that the sheer number of dots led to bad depth perception, as *"usually, like the smaller [. . .] thing is farther away, but it might actually be closer here,"* while P1 and P3 made similar comments. Overall, we found that the classroom environment simulated in VPM was capable of displaying potential issues that may arise concerning depth.

4.2.3 Experience Different Perspectives. The last key factor was the ability to move and rotate within the virtual prototype environment. As the virtual classroom was constructed in a Unity scene, it was possible to navigate the first-person camera to different classroom locations, and to inspect visual elements from different perspectives. Participants, after being acclimated to moving around in the virtual classroom, often requested the researcher to navigate the camera view to different classroom locations, particularly the front (facing back), the back (facing the front), and the middle (rotate the camera around the room). Participants' requests for movement were key to discovering that our designs were easier to understand or were overwhelming in certain points of views from specific classroom locations. For example, P5 asked to move to the back of the room and discovered that the colored gradient lines were difficult to distinguish when viewed from far away. Over the course of two design iterations, the VPM environment appeared to allow subjects to fully experience the prototype from all angles, and as a result led to holistic feedback.

5 DISCUSSION AND CONCLUSIONS

This work aimed to explore virtual prototyping as a design method for spatial displays and understand what kind of feedback and interaction this method enables. We acknowledge limitations within the present study, including the small pool of participants to conduct rapid prototyping of our designs. One limitation of our use of VPM is the static nature of the displays. While virtual prototyping enables quick feedback of design elements in context, additional interaction features are still required to experience and reflect on the dynamic nature of these representations in space.

5.1 Directions for the Spatial Classroom Displays Designs

In this work, we were able to receive feedback on two iterations of our designs across the i) visual elements, ii) classroom layouts, and iii) information load. Using insights from our analysis, we will iterate on these design categories and conduct more testing to refine our designs. Future directions will explore additional representations that address issues of overlapping information (e.g., arrows crossing above the students' heads) and iterate on the positioning of visual elements so that the teacher can easily identify what information is aligned with which student. To enhance the authenticity of the feedback, we will explore the ability to vary classroom layout designs - including creating participant-preferred layouts before or during a design session. Some teachers expressed that certain designs worked better in the classrooms they were most familiar with. Giving teachers the ability to experience designs in contexts that are most familiar to them, may lead to more authentic feedback compared to other methods of prototyping. Further research on information load will use virtual prototyping to explore the amount of information to display to teachers. While high information load was overwhelming for participants, there are more incremental design decisions that can be explored regarding how many pairs can be shown at once. The VPM would allow us to easily visualize and manipulate pairing options; for example, we can show all possible pairings in the entire classroom or only show pairings for a particular student. By quickly mocking up these options in mid-fidelity prototyping we can explore teachers' feedback more quickly compared to refining a high-fidelity design.

5.2 Potential Uses for *Virtual Prototyping*

Our analysis sheds light on several factors that can be experienced during VPM, including depth, occlusion, and perspectives. Unlike in the real world, where researchers would have to physically reorient the classroom, virtual prototyping can adapt designs to different contexts quickly and at scale. This feature enables researchers to display different layouts and validate if those layouts are acting as confounding variables. It also enables flexibility to adapt the design that is most familiar to teachers and their teaching contexts. Because VPM enabled participants to experience spatial dependence and provide feedback on multiple elements, it also acted as a method to facilitate feedback and ideation. As such, we have reason to believe that virtual prototyping is conducive for designing and iteration of spatial classroom displays.

Future work will explore how virtual prototyping can be designed to be more interactive and flexible to adapt designs in real-time regarding the teacher's view. By making changes in the moment based on the feedback provided in co-design sessions, we can streamline the design process and explore options quickly without having to conduct multiple design studies. Further explorations can include the measurement of the user's visual and spatial perception to provide adaptive visual elements, in light of diverging comments about elements (i.e., *"I'm more a dot person"* - P5; or "*lines are a good way to get the whole classroom perspective*"- P4) [8]. Another question that remains open is how virtual prototyping may be useful to extend beyond traditional classroom layouts and explore how futuristic education settings might interact [21]. Designing novel classroom contexts with teachers and students could provide innovative insights about potential layouts and elements. The relative ease of conducting a user study with VPM also lends applications of exploring equitable classroom practices and how these provide equal opportunities to all students. Finally, other explorations could address current classroom challenges imposed by the COVID-19 pandemic, such as co-designing for a hybrid-classroom modality.

5.3 Concluding Remarks

This work presented VPM, a mid-fidelity prototyping method to aid designers to get contextualized feedback on visual spatial designs. Our study illustrated the potential of VPM to gather contextualized feedback on visual spatial designs, and that the interactions with different prototypes encouraged discussion on issues within the design. These opportunities are challenging to experience in low-fidelity prototyping. The VPM enables researchers to quickly build and switch between different virtual environments, which was helpful to show the effects of different classroom layouts and place participants in their natural surroundings. Through a two-step iterative design study, we show that a virtual prototype can draw out crucial evidence, such as perceived depth and occlusion, to support or reject spatial prototype designs.

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