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SUPPORTING DESIGN REVIEWS WITH PRE-MEETING VIRTUAL REALITY ENVIRONMENTS

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SUMMARY: *The purpose of this paper is to explore how design reviews can be supported with pre-meeting virtual reality environments. Previous research has not systematically investigated how virtual environments can be used to communicate the design intent (to clients) and to communicate feedback (to design professionals) in advance of review meetings within real-world projects. A prototypical virtual environment that enables clients to individually navigate through and comment on a design-in-progress, aimed to be used before a review meeting, was therefore studied in two typical architectural and engineering design projects. A pattern-matching strategy was applied for the qualitative analysis of the data collected. It is concluded that theoretical expectations and pragmatic realities about the support of pre-meeting virtual reality environments for design review match (yet in varying degrees) in the areas of: exploration from a user perspective, participation in solution-finding and feedback on a design proposal. This paper thereby offers an in-depth understanding about the potential of virtual environment usages in advance of review meetings, which may help design professionals to make a more informed choice about how and why to support design reviews with pre-meeting virtual reality environments.*

KEYWORDS: *Design management, Design review, Information transferability, Pattern-matching, Virtual environment*

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1. INTRODUCTION

Design review is one of the most important processes in architectural and engineering design (Cárcamo et al. 2014). It is the process of evaluating a design solution to detect any possible failures with respect to program, function of spaces or overall performance (Castronovo et al. 2013). Typically, design reviews take place during regular meetings in which designers/engineers and clients (i.e. building owners and/or end-users) convene to reflect on an unfinished design and decide upon any necessary changes (Le Dantec and Do 2009). The design is then talked about in relation to more-or-less clearly defined client judgments, needs, desires, or pre-existing conditions of other stakeholders (Oak 2011). Visualization techniques such as sketches, architectural drawings, mockups or photomontages play an important role in these complex designer-client interactions (Rwamamara et al. 2010). Design reviews are crucial for timely detecting and identifying discrepancies, errors and inconsistencies in design (Shiratuddin and Thabet 2007) and they allow participants to accept and commit to decisions made as a group (Garcia et al. 2005; Le Dantec and Do 2009). However, these objectives are complicated due to profound problems in exchanging and communicating building design information.

Design reviews are often supported with traditional visualizations that provide limited information transferability. It is, by nature, very difficult to convey how a design will look and feel once it is realized (Conniff et al. 2010). Particularly inexperienced clients find it often hard to extrapolate the scale of the design to their own scale (Castronovo et al. 2013), while different types of visualizations can easily alter perceptions of a design (Bassanino et al. 2010). Traditional approaches to visualize the design intent have concentrated on static pictures or three-dimensional (3D) scale models, which face expensive design evolution, lack of communication and limited reusability (Wang et al. 2014). The dependency on these visualization approaches in a meeting setting can pose additional problems, including a lack of confidence to express comments in a group (Shen et al. 2013) and constraints in aligning participants' agendas. Altogether, the information flows in design are considered insufficient (Woksepp and Olofsson 2008), which can result in incomplete understanding of proposed design solutions, a lack of involvement in the evaluation process and biased feedback on the design.

This research proposes to address these problems with virtual reality environments that are deployed before a design review meeting. Virtual reality (VR) offers an intuitive medium in which a 3D view can be manipulated in real-time and used collaboratively to explore and analyze design options and simulations of the construction process (Bouchlaghem et al. 2005). Numerous studies have highlighted the potential of virtual reality for design review (Dunston et al. 2011; Kumar et al. 2011; Shiratuddin and Thabet 2011), but have not yet explored its possibilities for communicating the design intent (to clients) and subsequent feedback (to design professionals) in advance of actual review meetings. Hence, we aim to provide insights and recommendations on supporting design reviews with pre-meeting virtual reality environments through (I) hypothesizing about their potentials, (II) organizing empirical data collected from real-world projects and (III) attempting to match these theoretical ideals and pragmatic realities.

2. THEORETICAL FRAMEWORK

Virtual reality simulates physical presence in an interactive, three-dimensional setting. Whyte (2002) argues that virtual reality has three defining characteristics: it is (1) interactive, enabling users to manipulate a design model, (2) spatial, with those models being represented in three spatial dimensions and (3) real-time, with feedback from actions given without noticeable pause. These characteristics make it possible to experience a model from the inside, which is substantially different from viewing a 3D (or even 2D) representation on a screen. The latter gives the sensation of looking through a window into a miniature world on the other side of the screen, with all the separation that sensation implies, rather than a feeling of depth and immersion (Shiratuddin and Thabet 2007). 3D CAD systems assist design specialists in creating precise 3D representations of real objects with certain features (such as volume, weight, etc.), whereas virtual reality allows users to display and manipulate these objects (modeled with surfaces and spaces for realistic representation) in a virtual environment (Woksepp and Olofsson 2008). Those virtual environments require the 3D design models to be imported into virtual reality systems, which are often based on technologies from the computer games industry (Kumar et al. 2011).

Virtual reality has been an area of increasing research and development activities in construction. Scholars and practitioners initially focused primarily on immersive wall-mounted displays (Bowman et al. 1997; Cruz-Neira et al. 1993; Roussos et al. 1999), but improvements in computing technology have later shifted the attention to non-immersive virtual environments running on desktop computers (Koutsabasis et al. 2012; Merrick et al. 2011) and immersive head-mounted displays (Froehlich and Azhar 2016). Iorio and Taylor (2014), for example, demonstrated the mediating role of boundary objects for conflict management in virtual environments used by globally dispersed teams. Woksepp and Olofsson (2006) argue that the use of virtual reality had a positive effect on the final project costs and quality in a large-scale industry project. Other scholars have also successfully demonstrated the potential of virtual environments to support planning construction site activities (Gül 2009; Hartmann and Fischer 2007; Li et al. 2008), coordination between different design disciplines (Merrick et al. 2011; Rosenman et al. 2007), collaboration in globally dispersed teams (Dossick 2014; Dossick et al. 2012; Iorio et al. 2011) and teaching/training efforts (Sacks et al. 2013; Sampaio and Martins 2014). Accordingly, virtual reality environments may be "meaningful, valuable and affordable" (Mobach 2008) for use within the construction industry.

Virtual environments have been proposed for design review accordingly, but with limited attention for asynchronous and remote information transferability in actual projects. Germani et al. (2012) discuss four dimensions of design collaborations based on time (synchronous/asynchronous) and space (co-located/remote) combinations. Related works on the topic have mostly focused on virtual reality systems to support design interactions during meetings in which participants meet at the same place (i.e. synchronous and co-located) or at different sites (i.e. synchronous and remote). For example, Majumdar et al. (2006) report on a study where key professionals and decision-makers met inside a Computer Assisted Virtual Environment (CAVE), a room with six projectors optimized for viewing 3D environments in real-time, to review the design of a courtroom. Such expensive and high-end virtual reality solutions are, however, not always available and can be difficult to use in day-to-day design practices. In addition to that, many studies have overlooked the possibilities of virtual environments to enable clients evaluating a design proposal and communicating feedback from their own time and place (i.e. asynchronous and remote). Indeed, Kim et al. (2013) conclude that very few studies have actually involved industry practitioners. Most studies on virtual environments for design review mainly deal with technical aspects of developing virtual design review systems and lack any empirical evaluations of those systems in use (cf. Chionna et al. 2015; Kumar et al. 2011; Shiratuddin and Thabet 2007; Yan et al. 2011).

Surprisingly, previous research has not systematically investigated how virtual environments can be used *to communicate the design intent* (to clients) and *to communicate feedback* (to design professionals) *in advance of* review meetings within *real-world projects*. Those works have addressed only one or few of these (italicized) aspects – not all of them together. The extant literature nevertheless allows us to hypothesize about the potential of virtual reality environments, which we thematically group in three categories: exploration from a user perspective, participation in solution-finding and feedback on a design proposal.

2.1 Exploration from a user perspective

To start with, some studies indicate that exploring a design proposal from a user perspective may be beneficial for clients. Virtual environments have the capability to present spatial information in a more engaging manner, giving users a better sense of spatial (scale, distance and adjacency) and visual (appearance and view) factors (Eastman et al. 2011; Shen et al. 2012). They could thus be used to offer clients a glimpse of a possible future (Mobach 2008), supporting them in becoming familiar with the look and feel of a realized design (Conniff et al. 2010). That enables clients to recognize how a design proposal meets a problematic situation (Paton and Dorst 2011) and facilitates discovering any problematic design issues (Dossick 2014). Previous works of Shen et al. (2012) and Shen et al. (2013) have, for example, revealed that clients reported to gain a better "overall understanding" of a design when they used a specific tool for visualizing and simulating end-user activities instead of using 3D modeling software. Similarly, Castronovo et al. (2013) argue that virtual reality attributes enable a more qualitative representation of spaces from a user perspective. Based on these studies, we expect that:

- *Clients will discover problematic design issues while navigating through a virtual environment*, and that;
- *They can imagine what the design will look like once it is realized*;

2.2 Participation in solution-finding

Other studies also hint at the potential of virtual reality environments to foster client participation in solution-finding. To achieve efficient and effective design collaboration, it is essential that clients participate in the process of finding solutions for design problems (Gül 2009). Participation nevertheless varies per individual and may also alter during the course of a design project due to the change process and the nature of human behavior (Thyssen et al. 2010). Virtual environments aimed at clients may stimulate their participation in the process, since such tools increase their access to design information (Shiratuddin and Thabet 2011) and because the possibility to navigate in an as-yet-unbuilt environment is appealing in itself (Conniff et al. 2010). Users of the review tools of Shen et al. (2012) and Shen et al. (2013) also reported to be "more willing to work together with designers to improve a design" than people specifying feedback on a design with conventional paper-based methods. That willingness may manifest itself in the engagement in discussing and optimizing design issues (Jensen 2011). Earlier work furthermore demonstrated that more introverted persons are more comfortable with the possibility to give feedback individually (Shen et al. 2012; Shen et al. 2013). In line with that, Bassanino et al. (2014) conclude that the possibility to evaluate a design proposal on one's own screen provides users privacy, which may encourage clients' willingness and confidence to collaborate with designers. Based on this, we expect that:

- *Clients feel empowered to contribute building the design solution further with their feedback*;
- *They participate actively in discussions about design issues they previously identified themselves during virtual walkthroughs,* and that;
- *Those clients who regard themselves as introverted feel comfortable to express feedback*.

2.3 Feedback on a design proposal

Literature also suggests that virtual reality environments could be utilized to capture feedback of clients. Cross (2008) argues that a client generally "does not know what the 'answer' [to a design problem] is, but they will recognize it when they see it." With feedback, a client indicates that the right answer is not yet found: it points to key areas for improvement (Salter and Torbett 2003). Useful feedback provides new insights with the potential to impact on the subsequent design process (Følstad et al. 2013). A previous study with an immersive virtual environment revealed that most of the feedback expressed there dealt with forward looking actions such as suggesting changes for important parts of the design (Majumdar et al. 2006). Similarly, the experiment of Shen et al. (2013) revealed that the use of a visualization and simulation tool led to significantly more suggestions for improvement of the proposed design. Designers can use such feedback to determine whether the proposed design is what the client envisioned (Shiratuddin and Thabet 2007) and to plan on taking action for ensuring acceptance and appreciation of the building design (Jensen 2011). Based on this, we expect that:

- *Feedback expressed in a virtual environment considers a key part of the design and is suited to contribute to a change in that design,* and that;
- *Designers regard the feedback expressed in a virtual environment as helpful to guide the design process*.

3. RESEARCH METHODOLOGY

The goal of this research is to explore how design reviews can be supported with pre-meeting virtual reality environments. We developed a tool ourselves based on jMonkeyEngine 3.0, a Java-based game engine coupled with an integrated development environment. The non-immersive tool runs on a laptop with average processing power and does not require a head-mounted device. It essentially enables clients to navigate in first-person through a design-in-progress using keyboard and mouse and then to type feedback in a textbox that appears when they click on an object somewhere in the model. The feedback that is stored consists of information about the object that was clicked on, a screenshot and the text entered. While this tool is novel in itself, we were here interested in how it supports actual design reviews in terms of the aforementioned categories: exploration from a user perspective, participation in solution-finding and feedback on a design proposal. We thus implemented and studied the use of this virtual environment in two typical architectural and engineering design projects. Subsequently, we applied a pattern-matching strategy for the qualitative analysis of data collected in these two cases.

3.1 Case I: draft design of a parking garage

The first case concerns the draft design of a parking garage in Amsterdam, the Netherlands. At the time of our study, the draft design phase was finished and no decision had been taken yet to proceed to the preliminary design phase. Two (out of three) client representatives in this project were nevertheless available and willing to evaluate the draft design like they would do if the design would be elaborated into a preliminary design. We thus collected the design files (non-parametric model and 2D CAD drawings) from the designers and prepared a virtual environment: we imported these files in the game engine, set up an interactive, navigable scene and applied basic colors and textures to the 3D geometry – corresponding to the conceptual level of the draft design stage. We then organized two individual review sessions, with the clients making a virtual walkthrough and commenting on certain objects in the design. We also combined this feedback in a report and handed that over to the designers. Although no review meeting could be scheduled afterwards, the data collected yielded important insights on the use of the virtual reality tool that justify the inclusion of this case in our study. During earlier review meetings, not included in this study, the designers had nevertheless predominantly relied on 2D representations to convey the design intent.

3.2 Case II: definitive design of water production plants

The second case concerns the definitive design of three plants for the production of drinking water: a pump, filter and softening plant located in the South of the Netherlands. While the scheduled design review dealt with these three plants, we only imported the first two in the virtual environment so that we could make some comparisons. A few days before the review meeting, we received the design files (Building Information Model (BIM) and 3D CAD drawings) and consequently prepared the virtual environment in a similar way as described above. The focus of the subsequent review meeting was here on engineering features, with colors of pipes, installations and other engineering systems indicating certain production steps, and thus little attention was paid to the rendering quality. Before the review meeting, we held individual review sessions with six persons having different roles and backgrounds in the design project – most of them would eventually work in the renewed production plants. We combined all their feedback in a report for the designers. They could use that report to prepare for the review meeting. A few days later, twenty persons attended that meeting – three of them had used the virtual environment. The designers here used 3D viewing software to show the definitive design on a projection screen. All of the designers were familiar with the design and would each verbally introduce some parts of the design, but only one of them was in charge of manipulating (e.g. zooming in/out or rotating) the view shown on the projection screen. During the consequent design discussions, both clients and designers referred to these 3D views.

3.3 Data collection: using multiple sources from case studies

In an attempt to achieve data triangulation, we collected data from multiple different sources – for which these two cases provided abundant opportunities. In both cases, we visited the clients participating in our study in their own offices and observed them making a virtual walkthrough and commenting on design proposals. After these individual sessions, we asked them to reflect on their software use during semi-structured interviews. We recorded the review meeting that (in the second case) followed these sessions, thereby following video research guidelines of Derry (2007) and Jordan and Henderson (1995). As such, we applied a coding scheme based on the hypotheses to the video data; essentially splitting the review meeting in distinct parts and then coding the content (i.e. 'design discussion', 'taking stock of progress' or 'coordination activity'), noting the specific persons contributing to that meeting part (i.e. marking names) and identifying whether a review topic was previously identified with the use of the prototypical virtual environment or not (one or zero). The coding resulted in an extensive case-by-variable matrix of the video data (Bernard and Ryan 2010), which turned out to be an illuminating data source. Data was also collected with short, qualitative pre- and post-meeting questionnaires to capture perceptions that could not be observed or recorded directly. Finally, a few days after the review meeting, we collected the meeting's minutes and other project documentation and held eleven telephonic semi-structured interviews with (six) persons who had used the virtual environment in advance of the meeting and (five) who had not. With the permission of the respondents, all these interviews were recorded on audiotapes and transcribed verbatim thereafter for further analysis.

3.4 Data analysis: applying a pattern-matching strategy

For the analysis of the data collected, we applied a pattern-matching strategy. Pattern-matching is one of the most desirable strategies to deal with the relatively unstructured nature of qualitative data (Trochim 1989; Yin 2009). It is about comparing the 'theoretical ideals' with the 'pragmatic reality,' which will enhance critical understanding

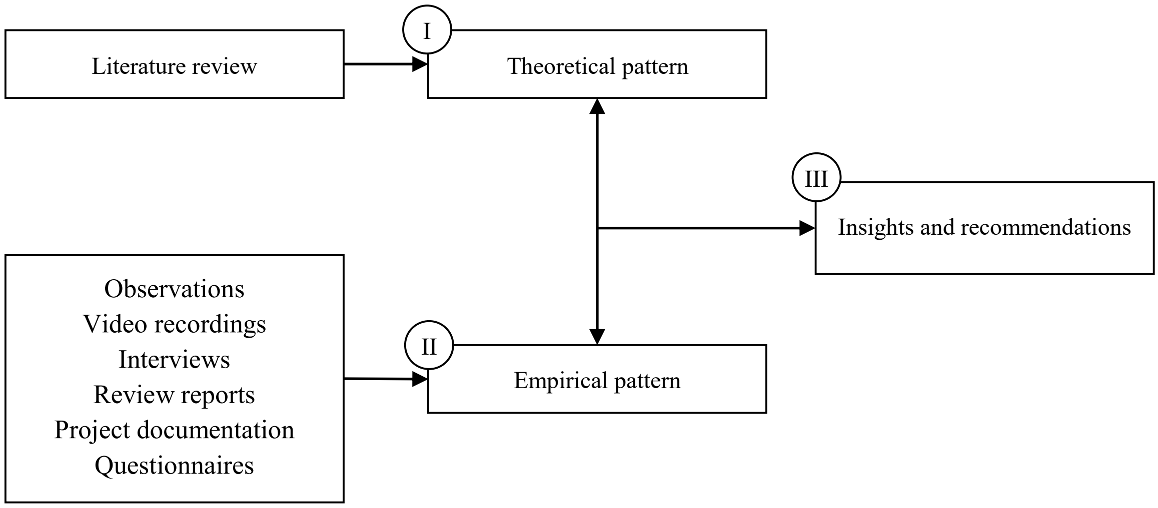

Figure 1: Research model visualizing how this study (I) specifies a theoretical pattern, (II) organizes the data in an empirical pattern and (III) compares both with each other

and learning (Cao et al. 2004; De Graaf and Dewulf 2010). Pattern-matching involves (I) the specification of a theoretical pattern, (II) the acquisition of an empirical pattern, and (III) an attempt to match those two (Figure 1) (Trochim 1989). A theoretical pattern describes what is expected in the data (the theoretical ideal), while an empirical pattern consists of the actual data found in real-life cases (the pragmatic reality). For the latter, we examined, categorized and recombined the multiple data sources “in search for patterns in the data and for ideas that help explain why those patterns are there in the first place” (Bernard and Ryan 2010). Provided that the theoretical and empirical pattern are parallel in structure, they can be compared with each other to assess whether the theories predicting the observations receive support. Both the theoretical pattern (as specified above) and the empirical pattern (as specified in the upcoming section) are therefore structured in three categories: exploration from a user perspective, participation in solution-finding and feedback on a design proposal.

4. RESULTS

This section organizes the findings from the two real-world case-studies in an empirical pattern that is parallel in structure to the theoretical pattern.

4.1 Exploration from a user perspective

The first part of the empirical pattern considers exploration from a user perspective. From observing the usages of the pre-meeting virtual reality environment, we found that clients discovered issues in the design that could potentially be problematic. In the parking garage case, for example, the technical advisor noticed “a strange corner” when making a virtual walkthrough (Figure 2-left). He was so surprised that he looked for an explanation in some drawings he brought with him, but eventually left the next comment in the virtual environment: “Strange corner, seems not socially secure! Is this a parking lot?” Similarly, the project leader found out what it will look like if cars are parked on a small slope of 7% (Figure 2-right). Although that design feature had been a major topic of discussion in previous design review meetings, the virtual walkthrough offered a user perspective, which helped him recognizing the implications of parking on a slope for the first time.

The virtual environment usages in the water production plants case resulted in similar discoveries. The project employee Service & Maintenance, for example, found that one large pipe section was incomplete (Figure 3-left). However, from his comment in the virtual environment it appears that he realized this might not be an error at all, but a result of a change in the water production process: “there are valves missing from the basement (maybe this becomes single filtrate, then this is not necessary).” Other persons knew that removing this pipe was correct and – independent of the previous person – commented in the virtual environment to “take out” the remaining pipe and wall piece. Another issue discovered in the virtual environment was a potential error in the number of tubes for the air intake, being either four or five (Figure 3-right). When the process technologist noticed this, he walked back and forth and looked around in the virtual environment to count the number of tubes and to see how they ran through the corridor. During the review meeting, this person referred back to his earlier discovery and asked the designers to clarify this part of the design – which demonstrates that he had become more familiar with the design than most of the other attendees who had not used the virtual environment.

Clients using the virtual environment also reported being able to imagine what the future building would look like in reality. One client in the water production plants case said that he "gained a very good mental image [due to the virtual environment]. We could walk properly through the buildings. I could see the technical aspects […] very well. Visually, the colors and the like, it is powerful, and also the details were visible." Another client said that he had gained a good mental picture of the buildings because he could navigate through them himself this time, "which is easier than evaluating 2D drawings." Similarly, a client in the parking garage case argued the following:

> *"One can also see certain design features, like parking on a slope and the fact that there are no structural columns, at a drawing. But if you see those things in such a [virtual environment], you get a better impression of it."*
>
> Project leader

In both cases, the interview data reveal that the clients attributed their understanding of the design proposal to their individual walkthroughs in the three-dimensional space.

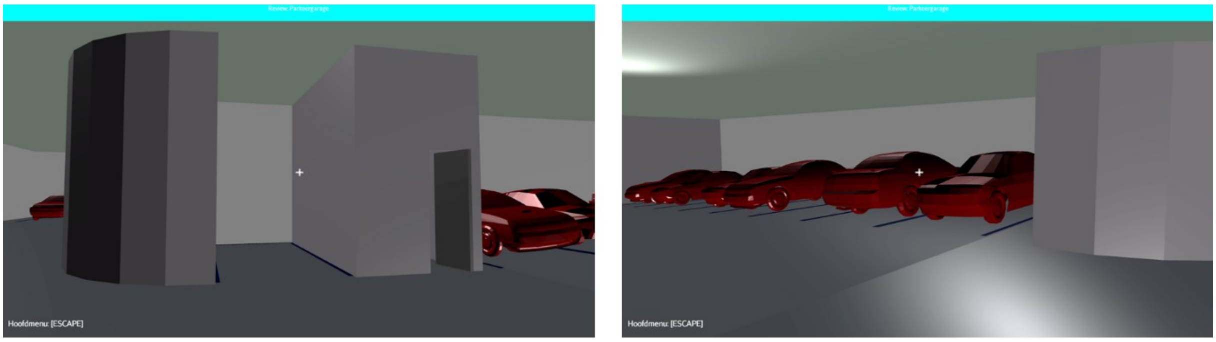

Figure 2: Discoveries in the parking garage case: a "strange corner" that is actually a parking lot (left) and parking lots on a slope (right)

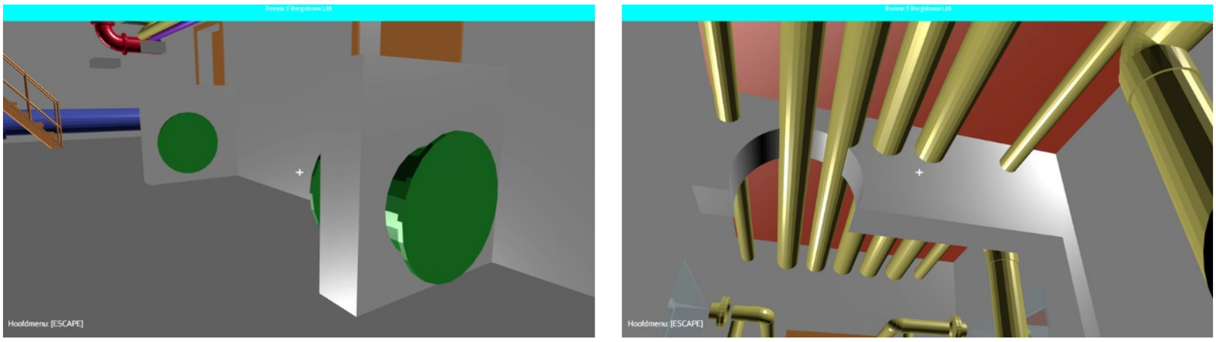

Figure 3: Discoveries in the water production plants case: an unconnected pipe section (left) and a potential error in the number of pipes (right)

4.2 Participation in solution-finding

The second part of the empirical pattern deals with the participation of clients in solution-finding. Our interview data reveal that users of the pre-meeting virtual reality environment expected that designers would respond properly to their feedback on the design. These clients were all enthusiastic about making a virtual walkthrough, making comments like "it is actually fun" and "nice that you can see all of this." They were also pleased with the feedback functionality that the tool provides them; one client in the parking garage case described this as "a really surprising feature." Several clients in the water production plants case believe that the designers will handle the virtual environment feedback carefully. As such, one client in the water production plants case could not attend the review meeting, but recognized from the meeting's minutes that his virtual environment comments were nevertheless "put into work carefully." Other users of the tool also thought that their comments would be meaningful to further improve the design. As such, one client said the following:

> *"We are men of the work floor and we see other things. It seems to me that [the designers] will do at least something with those suggestions of us. Especially when also other people of our workplace talk about the same, I expect [they] are going to do something with it."*
>
> Project employee Service & Maintenance

And another client in the same case formulated his expectations as follows:

> *"I expressed my comments [in the virtual environment]. I don't decide about those comments myself, but I assume [the designers] will do something with my comments. Not all comments will be accepted, but some will. […] Because of that, I feel more involved with the project."*
>
> Process technologist

These clients also joined (and occasionally started) discussions about issues they had identified in the virtual environment before the meeting. The video transcription revealed that sixty-three design issues were raised during the meeting. Although three users of the virtual environment were not present at the design review meeting, the other users participated (six times) in such design discussions. As an example, one said: "I understood the shape of the rungs [of the cage ladders] is rectangular" and then started a discussion about the ease of holding such a shape. In the virtual environment he had already identified the shape of the rungs as an ergonomics issue (Figure 4-left). As another example, one process technologist did not understand what some "barrels" in one of the buildings were meant for and subsequently formulated a question in the virtual environment (Figure 4-right). While an answer had initially not become clear during the review meeting, he brought the subject forward again and learned that these 'barrels' need to reduce the effects of 'water hammer': a pressure-wave resulting from the sudden closure of a valve. Contrasting evidence was nevertheless found as well: some earlier identified issues (e.g. on the location of lifting beams or the spatial layout of the corridor) were only implicitly addressed during the meeting and the participation of the reviewing client was there rather limited.

It nevertheless appeared that clients felt at ease with sharing their concerns during the design review meeting. Most of them said they "did not feel uncomfortable" to share their feedback on the design proposal during the meeting with the designers. Only one person explicitly confirmed feeling a barrier to talk in large groups:

> *"I am not someone who likes to be in the picture and takes the initiative. I always let other people have their say first. I am biding. I always think that there are other people who like to say something first [during a meeting]. Oftentimes, the points I would like to discuss are then already brought forward. In that case, I don't have to say them myself."*
>
> Project employee Service & Maintenance

When we asked this person what could make him more comfortable in these situations, he answered that individual sessions, "like you just did," could work for him. "For me that is more efficient than working in a big group." This statement was also backed up by the designers, who explicitly mentioned that this particular person "had come out of his shell" and "contributed much more" than they were used to from previous meetings (without the use of a virtual environment beforehand). Our finding is furthermore supported by the views of most other clients, who suggested "individual sessions" or "smaller groups" as a way to increase the participation of introverted people during the design reviews. Even though few clients felt a barrier to express their concerns during a review meeting, individual review sessions with a virtual environment are still seen as helpful for introverted persons to collaborate with designers for improving a design.

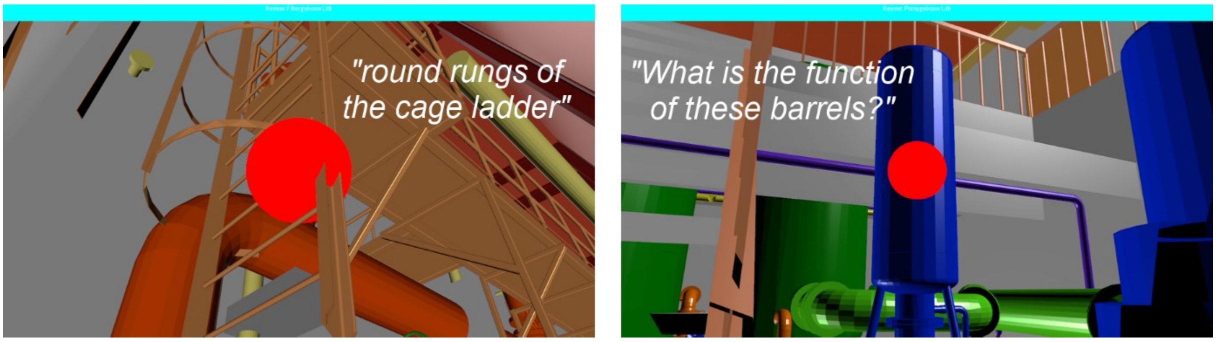

Figure 4: Examples of feedback on a design proposal (text pasted on original screenshots). Clients participate in design discussions about issues they previously identified in the virtual environment: the ergonomics of holding a specific type of rungs of a cage ladder (left) and the function of some "barrels" in the basement of the proposed design (right)

4.3 Feedback on a design proposal

The third part of the empirical pattern considers feedback on a design proposal. From analyzing the review reports, it seems that a large part of the feedback points to a key part of the design and may lead to a design change. The individual review sessions with the virtual environment each resulted in one to twelve comments (thirty-three in total). A large part of the feedback pointed to details that would only be addressed in a later design phase or did not build the solution further (e.g. feedback concerning the position of emergency exit signs or fire extinguishers). Other feedback given in the virtual environment was nevertheless considered as relevant and could contribute to a change in the design. One comment on the design of the filter plant, for example, suggests to "include a sliding gate so that it will be easier to lift heavy materials or equipment." As employees need to perform lifting operations quite regularly and ergonomics had been an important design concern, this comment has great potential to lead to a change in the design. Similarly, other comments in the same case raised attention to undesirable working conditions for (some of) the clients' future workplace, such as high noise levels of eight air blowers (Figure 5-left) and the lack of partitions to protect from falling down (Figure 5-right).

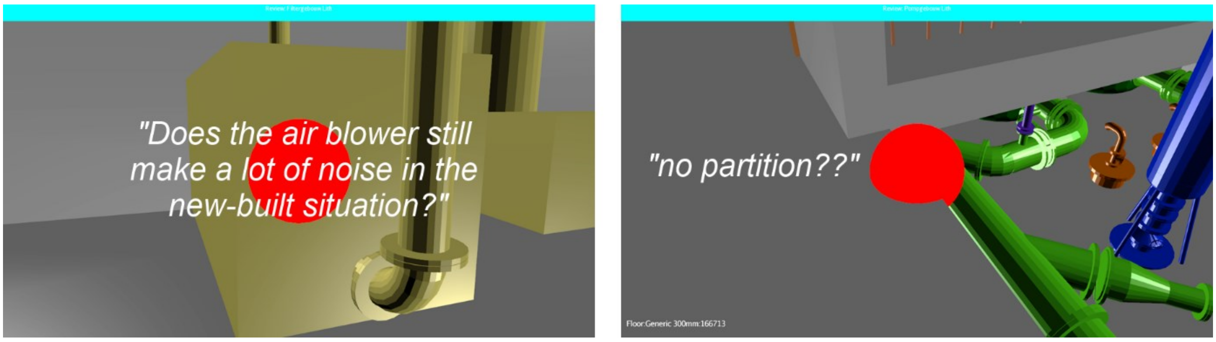

Figure 5: Examples of feedback on a design proposal in the water production plants case (text pasted on original screenshots): a comment about the noise level produced by a number of air blowers (left) and a comment about the absence of partitions to protect from falling down (right)

In the parking garage case, most of the comments also seemed relevant with the potential to impact on the design. These individual review sessions resulted in four and five comments (nine in total). As such, one of the clients noted that the ceiling is "quite high" at some point in the garage and suggested that this height could be used at ground level, for example for trees or mechanical, electrical and plumbing (MEP) systems (Figure 6-left). Since the construction site is exceptionally small in this particular project, the comment provides a new insight for dealing with an important constraint. Another comment dealt with the entrance of a stairwell that is not clearly visible according to the client. He suggested relocating it "so one will approach it directly" (Figure 6-right). An important requirement is the accessibility of the parking garage for pedestrians, for which this comment makes constructive input.

In line with this, the interviews revealed that designers consider the feedback expressed in the virtual reality tool as helpful. We observed that the feedback on the design proposal for the parking garage was seen as supportive for the design process as a whole. One of the designers in the water production plants case, on the other hand, regarded most of the comments as "actually too detailed," and thus not appropriate for the related design stage, "but we will deal with those anyway." Another designer also believed that some comments dealt with "minor issues," but similarly revealed that those were still very valuable. He argued that the virtual environment feedback was "helping [him] a lot to understand the [clients] well." Because he already read the virtual environment review reports before the start of the meeting, he could "respond well, listen to them carefully and retort properly" during that meeting. Indeed, a comparison of the video transcription and the review reports revealed that designers and clients agreed upon a solution for twenty-four (out of sixty-three) issues that were raised during the meeting, while the other thirty-nine were noted for future consideration. Ten issues had already been identified in the virtual environment before the start of the meeting. Although the last-mentioned designer was initially a bit skeptical about the virtual environment reviews, he later admitted that resulting comments exceeded his expectations: "it could result in an unmanageable amount of bottlenecks that would need to be resolved. […] I was a little bit afraid for that, but this appeared not to be the case. It actually had a very positive effect." It thus turns out that the designers considered feedback on the design proposals as helpful for the design process, even though they find some comments too detailed for the then current design stage.

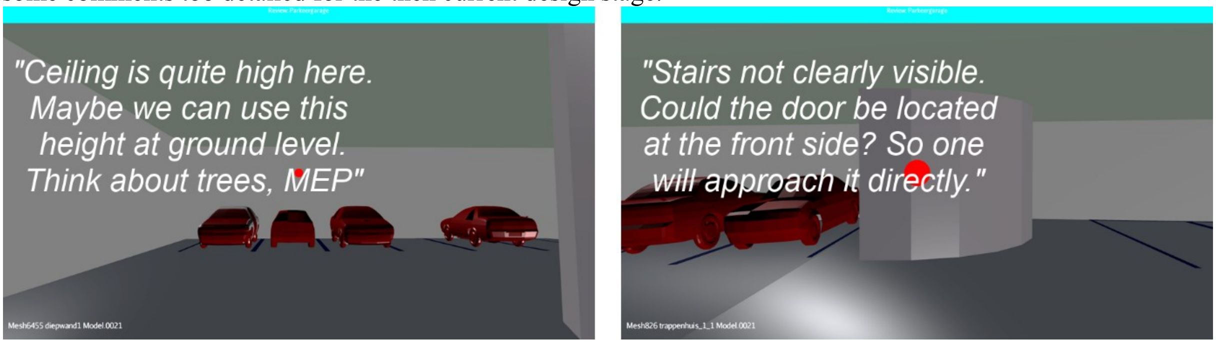

Figure 6: Examples of feedback on a design proposal in the parking garage case (text pasted on original screenshots): a suggestion to lower the ceiling of the parking garage (left) and a suggestion to relocate the door of the stairwell to the front side to make it better visible (right)

5. DISCUSSION

In this paper, we explored how design reviews can be supported with pre-meeting virtual reality environments. Unique to this research are the in-depth insights of actual virtual environment usages before a design review meeting that are contrasted with hypothesized usages. The novel tool that we developed and implemented in two real-world projects aimed to assist in communicating the design intent (to clients) and in communicating subsequent feedback (to design professionals) in advance of actual review meetings. As our contributions, we here provide insights and recommendations through systematically matching our findings (organized in an empirical pattern) with our previously formulated expectations (organized in a theoretical pattern). We then discuss the limitations and suggest directions for future research.

5.1 Contributions: insights and recommendations from pattern-matching

As this study's first contribution, pattern-matching is applied in terms of exploration from a user perspective (Table 1). Starting with the theoretical pattern, we expected that clients would discover problematic design issues while navigating through a virtual environment and that they would be able to imagine what the design will look like once it is realized (cf. Castronovo et al. 2013; Conniff et al. 2010; Paton and Dorst 2011). For the empirical pattern, we found that clients using the virtual environment discovered issues in the design that could be problematic. An example is the identification of an isolated parking lot that "seems not socially secure" (technical advisor, case I) and needs to be resolved before the design is finalized. The discovery of an incomplete pipe section was only potentially problematic since the reviewing client realized that the water production process could "become single filtrate – then [solving the issue] is not necessary" (project employee Service & Maintenance, case II). Next to this, our interviews and observations of clients using the virtual environment both suggest that clients were able to imagine what the future building would look like in reality. Through virtually experiencing the proposed building from the inside, clients recognized the implications of design decisions such as parking on a slope (case I) or production process changes (case II).

As for the second contribution, pattern-matching is applied in terms of participation in solution-finding (Table 2). The theoretical pattern outlines our expectations that clients using the virtual environment before a review meeting would feel empowered to contribute building the design solution further with their feedback, would actively participate in discussions about design issues they previously identified themselves during their virtual walkthroughs and that those who regard themselves as introverted would feel comfortable to express feedback (cf. Bassanino et al. 2014; Jensen 2011; Shen et al. 2012; Shen et al. 2013). Organized into an empirical pattern, we found that clients welcomed the feedback functionality and expected that designers would respond properly to their feedback. The virtual environment offered individuals to comment on the design proposal from their own perspective. The individual comments were sent around with the review meeting's minutes (case II), from which it was already concluded that the designers would deal with comments properly. We also presented evidence that clients sometimes joined (and occasionally started) design discussions about issues they had already identified in the virtual environment. An example is that a client had typed feedback about a specific type of cage ladder in the virtual environment, referred to that feedback during the meeting and participated in a resulting ergonomics discussion about the issue at hand (case II). Finally, we found that clients saw individual review sessions with a virtual environment as helpful for introverted persons, even though most people did not feel uncomfortable to share concerns during a meeting with the designers. One interviewee argued that he experienced a barrier to talk and join discussions, but that preparatory sessions with a virtual environment could work for him. Observations, video-recordings and interviews with others support his contributions to the design review (case II). Accordingly, preparatory review sessions were considered beneficial to acquire client input (case I, II).

Table 1: Pattern-matching: exploration from a user perspective

Theoretical pattern	Empirical pattern	Exemplary evidence	Match
Clients discover problematic design issues while navigating through a virtual environment	Clients using the virtual environment discovered issues in the design that could be problematic	Discovery of a strange corner that is actually a parking lot (observation), statement of having found a "strange corner" during the virtual walkthrough (interview), and a screenshot with written comment "Strange corner, seems not socially secure! Is this a parking lot?" (review report) [technical advisor | case I]	yes
		Discovery of a large incomplete pipe section (observation), statement that a possible error in the design was found (interview), and a screenshot with written comment "there are valves missing from the basement (maybe this becomes single filtrate – then this is not necessary)" (review report) [project employee Service & Maintenance | case II]	
Clients can imagine what the design will look like once it is realized	Clients were able to imagine what the future building would look like in reality	Noting the implications of design decisions such as 'parking on a slope' during the review (observation), the comment "One can also see certain design features, like parking on a slope and the fact that there are no structural columns, at a drawing. But if you see those things in such a [virtual environment], you get a better impression of it." (interview) [project leader | case I]	yes
		Recognition how the design changes the already existing building (observation), comments of having "gained a very good mental image" and "I could see the technical aspects […] very well. Visually, the colors and the like, it is powerful, and also the details were visible" (interview) [project leader (1) | case II]	

As for the third contribution, pattern-matching is applied to feedback on a design proposal (Table 3). According to the theoretical pattern, we expected that feedback expressed in the virtual environment would concern a key part of the design and be suited to contribute to a change in that design, as well as that designers would regard that feedback as helpful to guide the design process (cf. Følstad et al. 2013; Majumdar et al. 2006; Salter and Torbett 2003; Shiratuddin and Thabet 2007). Structured into an empirical pattern, we found that some feedback expressed in the virtual environment pointed to details that are only relevant in a later design phase. Examples are screenshots and written comments related to details such as emergency exit signs and fire extinguishers (case II). Other feedback dealt with novel insights that could lead to a change in the design though, such as the suggestion to use part of the parking garage's floor-to-ceiling height at ground level (case I) or the suggestion to include a sliding gate in the production plant to ease lifting of heavy equipment (case II). We also found that designers considered the feedback expressed in the virtual environment as helpful for the design process, even though some of the feedback is considered as too detailed for the relevant design stage. Designers considered the feedback as supportive for the design process as a whole (case I, II) and particularly to prepare better for the design review meeting (case II).

Table 2: Pattern-matching: participation in solution-finding

Theoretical pattern	Empirical pattern	Exemplary evidence	Match
Clients feel empowered to contribute building the design solution further with their feedback	Clients welcomed the feedback functionality and expected that designers would respond properly to their feedback	Expectation that individual comments are meaningful: "We are men of the work floor and we see other things" (interview), sharing of individual review reports with minutes of the design review meeting (project documentation) and the related remark that the individual comments will thus be "put into work carefully" (interview) [project employee Service & Maintenance | case II] Appreciative comments that making a virtual walkthrough "is actually fun" (observation) and the comment that the feedback functionality "is a really surprising feature" (interview) [technical advisor | case I]	yes
Clients actively participate in discussions about design issues they previously identified themselves during their virtual walkthroughs	Clients joined (and occasionally started) discussions about issues they had previously identified – yet sometimes their participation was limited	Screenshot with comment "round rungs of the cage ladder" (review report), meeting comment "I understood the shape of the rungs [of the cage ladder] is rectangular" (video recording) and subsequent ergonomics discussion (observation, video recording) [project leader (1) | case II] Screenshot with question "What is the function of these barrels?", similar question and answer during the review meeting (observation, video recording) [process technologist | case II)	partly
Clients who regard themselves as introverted feel comfortable to express feedback	Clients saw individual review sessions with a virtual environment as helpful for introverted persons, even though most people did not feel uncomfortable to share concerns during a meeting with the designers	Comments of "not feeling uncomfortable" or "no barrier to join discussions" (interviews) [process technologist, safety expert | case II] Comment "I always think that there are other people who like to say something first [during a meeting]. Oftentimes, the points I would like to discuss are then already brought forward. In that case, I don't have to say them myself." (interview), client participation in the meeting (observation, video recording) and designer comment that this person "had come out of his shell" and "contributed much more" (interview) [project employee Service & Maintenance, project leader (2) | – case II] Comment that "individual sessions" are most beneficial to acquire input (interview) [project employee Service & Maintenance | case I]	yes

The three main research contributions above have important implications for practice. Through contrasting ‘theoretical ideals’ with ‘pragmatic realities,’ we provided detailed insights into how virtual reality environments can be used by designers and clients in advance of design review meetings. Design and engineering firms can benefit from those insights by making a more informed choice about how (and why) to support design reviews with pre-meeting virtual reality environments. Such firms can expect comparable information transferability potential in upcoming design reviews that are more proximally similar to the settings, places and times of this study (Trochim 1989). When designers offer their clients to individually evaluate a design-in-progress some days before a review meeting with them, they can expect benefits related to explorations from a user perspective, participation in solution-finding and feedback on a design proposal. However, this comes at the expense of additional time needed to import design files in a virtual environment and to organize individual design reviews.

Table 3: Pattern-matching: feedback on a design proposal

Theoretical pattern	Empirical pattern	Exemplary evidence	Match
Feedback expressed in the virtual environment concerns a key part of the design and is suited to contribute to a change in that design	Some feedback expressed in the virtual environment pointed to details that are only relevant in a later design phase, but another part seemed relevant and could contribute to a change in the design	Contradictory screenshots and written comments related to emergency exit signs or fire extinguishers (review report) [process technologist, safety expert | case II] Screenshot and written comment “Ceiling is quite high here. Maybe we can use this height at ground level. Think about trees, MEP.” (review report) [technical advisor | case I] Screenshot and written comment to “include a sliding gate so that it will be easier to lift heavy materials or equipment” (review report) [process technologist | case II]	partly
Designers regard the feedback expressed in the virtual environment as helpful to guide the design process	Even though some feedback is considered as too detailed for the relevant design stage, designers considered it as helpful for the design process	Opposing comment that some feedback is “actually too detailed” (interview) [project leader (1) | case II] Comment “but we will deal with those [too detailed comments] anyway” (interview) [project leader (1) | case II] Comment that the virtual environment feedback was “helping [the designer] a lot to understand the clients well” and “respond well, listen to them carefully and retort properly” (interview) and answers to issues identified in the virtual environment (observation) [project leader (2) | case II] Feedback considered as supportive to the design process as a whole (observation) [building information manager | case I]	yes

5.2 Limitations and future research

As far as the research limitations concerned, this study dealt with individual cases without reference to a comparison group. We did not try to control for independent variables that account for variations in the observed phenomena. Instead, we chose for in-depth explorations of multiple real-world building design reviews in an attempt to expand and generalize theories (i.e. we aimed for analytical rather than statistical generalization). That approach is most appropriate here, since we dealt with a ‘how’ question, had little control over the events studied and the focus was on a contemporary phenomenon within a real-world context (Yin 2009). Flyvbjerg (2006) argues that contextually rich case descriptions (as we aimed to provide here) can be even more valuable as a source of scientific development than predictive theories and universals. An inherent drawback is, however, that we cannot generalize the findings to a wider ‘population’ (of building design reviews) because we cannot know whether the two cases are ‘representative.’ This research is thus limited to the generation of preliminary support for a number of hypotheses: additional research is needed to test, refine and extend the theory that we built here. Albeit at the expense of losing the connection with a real-world setting, more experimental research would allow to systematically control for certain variables and could thus identify cause-and-effect relationships at hand.

Deploying the novel virtual reality environment also came with its limitations. The prototypical tool only visualizes geometric design information such as shape, size and location. To take decisions on how to proceed with a design project, clients will, however, also need non-geometric information such as design specifications or maintenance data. As also observed by Wang et al. (2014), research (including ours) is rarely concerned with visualizing such information. An additional problem here is that it was time-consuming to organize individual review sessions. Importing the relevant design files and preparing them for use in a virtual environment turned out to be laborious, since 3D design models lack, by nature, information that can be visualized and interacted with in virtual environments (Conniff et al. 2010; Majumdar et al. 2006; Yan et al. 2011). That can be particularly challenging when time pressure is high, as in the second case that was studied. We dealt with this challenge by applying only basic colors and textures to the building objects, which saves time but unavoidably results in rather mediocre graphical quality. This was acceptable here as aesthetics were not yet (case I) and not (case II) a primary design concern, but may be problematic when they are. Future research thus needs to investigate novel approaches for quicker visualization of both geometric and non-geometric design information in virtual reality environments.

The issue of timing of feedback is another topic worthy of future research. We found that the level of detail of some of the feedback expressed in the virtual environment was inappropriate for the then current design stage. On one hand, some comments in the second case, which dealt with the definitive design stage, seemed too detailed – even though designers considered them as 'helpful.' On the other hand, the comments from the first case seemed more appropriate for the then current draft design stage. That may be explained by the corresponding levels of realism with which these design proposals were represented in their virtual environments: the (more) rough shapes and basic colors of the draft design essentially (better) indicate that the design is not yet finished. This fits with the observation of Conniff et al. (2010) that "the greater the level of realism, the more obvious [is] the absence of the final ingredients that make an environment actually real." Since realistic design representations apparently elicit more detailed comments, deploying a virtual environment offers opportunities to improve the timing of feedback. To verify whether that feedback does not lead to additional design rework, we propose a (longitudinal) study with multiple implementations of a pre-meeting virtual environment in different design stages of a single project.

Finally, it would be interesting to investigate why clients were more engaged within the review process. We provided an example of a self-identified introvert that, according to the designers, "contributed much more" during the review meeting he attended. On a broader basis it remains, however, unclear why clients would do that: is it because they have pre-identified design concerns that enable their engagement or did they have more confidence in their own knowledge arising from the use of a virtual environment? We speculate that it is a mix of both, but more research is needed to uncover the underlying mechanisms at hand.

6. CONCLUSIONS

This paper offers in-depth insights into (and recommendations for) supporting design reviews with pre-meeting virtual reality environments. A prototypical virtual environment was developed and implemented in two real-world design projects. Both our theoretical expectations and empirical findings about this are organized into a pattern consisting of three main categories: exploration from a user perspective, participation in solution-finding and feedback on a design proposal. Through systematically attempting to match these patterns with each other, we can draw the following conclusions.

Regarding exploration from a user perspective, we conclude that the theoretical and empirical pattern match: clients using the virtual environment discovered (problematic) issues in the design and were able to imagine what the future building would look like in reality.

Regarding participation in solution-finding, we firstly conclude that there is support for the proposition that clients would feel empowered to contribute building the design solution further with their feedback. Secondly, the proposition that clients would actively participate in discussions about design issues they previously identified themselves during their virtual walkthroughs is partly supported with empirical evidence. Thirdly, there is empirical evidence for the proposition that clients who regard themselves as introverted feel comfortable to express feedback.

Regarding feedback on a design proposal, we firstly conclude that the proposition that feedback expressed in the virtual environment would concern a key part of the design and is suited to contribute to a change in that design is partly supported with empirical evidence. Secondly, there is a match for the proposition that designers regard the feedback expressed in the virtual environment as helpful to guide the design process.

Overall, we conclude that theoretical expectations and pragmatic realities regarding the support of pre-meeting virtual reality environments for design review match (yet in varying degrees) in the areas of: exploration from a user perspective, participation in solution-finding and feedback on a design proposal. The insights and recommendations of this paper provide a next stepping stone for fellow scholars and practitioners to further develop and exploit virtual reality environments for architectural and engineering design reviews.

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REFERENCES

Bassanino, M., Fernando, T., and Wu, K. C. (2014). "Can virtual workspaces enhance team communication and collaboration in design review meetings?" *Architectural Engineering and Design Management*, 10(3-4), 200-217.

Bassanino, M., Wu, K. C., Yao, J., Khosrowshahi, F., Fernando, T., and Skjærbæk, J. "The impact of immersive virtual reality on visualisation for a design review in construction." *Proc., Information Visualisation (IV), 2010 14th International Conference*, IEEE, 585-589.

Bernard, H. R., and Ryan, G. W. (2010). *Analyzing qualitative data: Systematic approaches*, SAGE publications, Thousand Oaks, CA.

Bouchlaghem, D., Shang, H., Whyte, J., and Ganah, A. (2005). "Visualisation in architecture, engineering and construction (AEC)." *Automation in Construction*, 14(3), 287-295.

Bowman, D. A., Koller, D., and Hodges, L. F. "Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques." *Proc., Virtual Reality Annual International Symposium, 1997., IEEE 1997*, IEEE, 45-52, 215.

Cao, G., Clarke, S., and Lehaney, B. (2004). "The need for a systemic approach to change management—a case study." *Systemic Practice and Action Research*, 17(2), 103-126.

Cárcamo, J. G., Trefftz, H., Acosta, D. A., and Botero, L. F. (2014). "Collaborative design model review tool for the AEC industry." *2014 Virtual Concept International Workshop*Medellin, Colombia.

Castronovo, F., Nikolic, D., Liu, Y., and Messner, J. "An evaluation of immersive virtual reality systems for design reviews." *Proc., 13th International Conference on Construction Applications of Virtual Reality*.

Chionna, F., Cirillo, P., Palmieri, V., and Bellone, M. (2015). "A proposed hardware-software architecture for Virtual Reality in industrial applications." *Augmented and Virtual Reality*, Springer, 287-300.

Conniff, A., Craig, T., Laing, R., and Galán-Díaz, C. (2010). "A comparison of active navigation and passive observation of desktop models of future built environments." *Design Studies*, 31(5), 419-438.

Cross, N. (2008). *Engineering design methods: Strategies for product design*, John Wiley & Sons, West Sussex, England.

Cruz-Neira, C., Leigh, J., Papka, M., Barnes, C., Cohen, S. M., Das, S., Engelmann, R., Hudson, R., Roy, T., Siegel, L., Vasilakis, C., DeFanti, T. A., and Sandin, D. J. (1993). "Scientists in wonderland: A report on visualization applications in the CAVE virtual reality environment." 59-66.

De Graaf, R. S., and Dewulf, G. P. M. R. (2010). "Applying the lessons of strategic urban planning learned in the developing world to the Netherlands: A case study of three industrial area development projects." *Habitat International*, 34(4), 471-477.

Derry, S. J. (2007). "Guidelines for video research in education." Data Research and Development Center, Chicago.

Dossick, C. S. (2014). "Messy work in virtual worlds: exploring discovery and synthesis in virtual teams." *Cooperative Design, Visualization, and Engineering*, Springer, 134-142.

Dossick, C. S., Anderson, A., Iorio, J., Neff, G., and Taylor, J. "Messy talk and mutual discovery: exploring the necessary conditions for synthesis in virtual teams." *Proc., Engineering Project Organizations Conference*, Working Paper Proceedings.

Dunston, P. S., Arns, L. L., Mcglothlin, J. D., Lasker, G. C., and Kushner, A. G. (2011). "An immersive virtual reality mock-up for design review of hospital patient rooms." *Collaborative design in virtual environments*, Springer, 167-176.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM Handbook: a guide to Building Information Modeling*, John Wiley & Sons, Hoboken.

Flyvbjerg, B. (2006). "Five misunderstandings about case-study research." *Qualitative Inquiry*, 12(2), 219-245.

Følstad, A., Hornbæk, K., and Ulleberg, P. (2013). "Social design feedback: evaluations with users in online ad-hoc groups." *Human-centric Computing and Information Sciences*, 3(1), 1-27.

Froehlich, M. A., and Azhar, S. "Investigating virtual reality headset applications in construction." *Proc., Proceedings of the 52nd ASC International Conference, Provo, UT*.

Garcia, A. C. B., Kunz, J., and Fischer, M. (2005). "Voting on the agenda: the key to social efficient meetings." *International Journal of Project Management*, 23(1), 17-24.

Germani, M., Mengoni, M., and Peruzzini, M. (2012). "An approach to assessing virtual environments for synchronous and remote collaborative design." *Advanced Engineering Informatics*, 26(4), 793-813.

Gül, L. F. (2009). "Evaluating design behaviour when using emerging collaboration technologies." *Architectural Engineering and Design Management*, 5(3), 107-123.

Hartmann, T., and Fischer, M. (2007). "Supporting the constructability review with 3D/4D models." *Building Research & Information*, 35(1), 70-80.

Iorio, J., and Taylor, J. E. (2014). "Boundary object efficacy: the mediating role of boundary objects on task conflict in global virtual project networks." *International Journal of Project Management*, 32(1), 7-17.

Iorio, J., Taylor, J. E., and Dossick, C. S. (2011). "A bridge too far: examining the impact of facilitators on information transfer in global project networks." *Proceedings Editor*.

Jensen, P. A. (2011). "Inclusive briefing and user involvement: Case study of a media centre in Denmark." *Architectural Engineering and Design Management*, 7(1), 38-49.

Jordan, B., and Henderson, A. (1995). "Interaction analysis: Foundations and practice." *The Journal of the Learning Sciences*, 4(1), 39-103.

Kim, M. J., Wang, X., Love, P., Li, H., and Kang, S. C. (2013). "Virtual reality for the built environment: a critical review of recent advances." *Journal of Information Technology in Construction*, 18, 279-305.

Koutsabasis, P., Vosinakis, S., Malisova, K., and Paparounas, N. (2012). "On the value of Virtual Worlds for collaborative design." *Design Studies*, 33(4), 357-390.

Kumar, S., Hedrick, M., Wiacek, C., and Messner, J. I. (2011). "Developing an experienced-based design review application for healthcare facilities using a 3D game engine." *Journal of Information Technology in Construction*, 16, 84-103.

Le Dantec, C. A., and Do, E. Y. L. (2009). "The mechanisms of value transfer in design meetings." *Design Studies*, 30(2), 119-137.

Li, H., Huang, T., Kong, C. W., Guo, H. L., Baldwin, A., Chan, N., and Wong, J. (2008). "Integrating design and construction through virtual prototyping." *Automation in Construction*, 17(8), 915-922.

Majumdar, T., Fischer, M. A., and Schwegler, B. "Conceptual design review with a virtual reality mock-up model." *Proc., Building on IT: joint international conference on computing and decision making in civil and building engineering. Montreal, Canada: American Society of Civil Engineers*, 2902-2911.

Merrick, K. E., Gu, N., and Wang, X. (2011). "Case studies using multiuser virtual worlds as an innovative platform for collaborative design." ITcon.

Mobach, M. P. (2008). "Do virtual worlds create better real worlds?" *Virtual Reality*, 12(3), 163-179.

Oak, A. (2011). "What can talk tell us about design?: Analyzing conversation to understand practice." *Design Studies*, 32(3), 211-234.

Paton, B., and Dorst, K. (2011). "Briefing and reframing: A situated practice." *Design Studies*, 32(6), 573-587.

Rosenman, M. A., Smith, G., Maher, M. L., Ding, L., and Marchant, D. (2007). "Multidisciplinary collaborative design in virtual environments." *Automation in Construction*, 16(1), 37-44.

Roussos, M., Johnson, A., Moher, T., Leigh, J., Vasilakis, C., and Barnes, C. (1999). "Learning and building together in an immersive virtual world." *Presence: Teleoperators and Virtual Environments*, 8(3), 247-263.

Rwamamara, R., Norberg, H., Olofsson, T., and Lagerqvist, O. (2010). "Using visualization technologies for design and planning of a healthy construction workplace." *Construction Innovation*, 10(3), 248-266.

Sacks, R., Perlman, A., and Barak, R. (2013). "Construction safety training using immersive virtual reality." *Construction Management and Economics*, 31(9), 1005-1017.

Salter, A., and Torbett, R. (2003). "Innovation and performance in engineering design." *Construction Management and Economics*, 21(6), 573-580.

Sampaio, A. Z., and Martins, O. P. (2014). "The application of virtual reality technology in the construction of bridge: The cantilever and incremental launching methods." *Automation in Construction*, 37, 58-67.

Shen, W., Shen, Q., and Sun, Q. (2012). "Building Information Modeling-based user activity simulation and evaluation method for improving designer–user communications." *Automation in Construction*, 21(0), 148-160.

Shen, W., Zhang, X., Shen, G. Q., and Fernando, T. (2013). "The user pre-occupancy evaluation method in designer-client communication in early design stage: A case study." *Automation in Construction*, 32, 112-124.

Shiratuddin, M. F., and Thabet, W. (2007). "Information rich Virtual Environment (VE) design review." *24th W78 Conference & 5th ITCEDU Workshop & 14ht EG-ICE Workshop*Maribor, Slovenia.

Shiratuddin, M. F., and Thabet, W. (2011). "Utilizing a 3D game engine to develop a virtual design review system." *Journal of Information Technology in Construction*, 16, 39-68.

Thyssen, M. H., Emmitt, S., Bonke, S., and Kirk-Christoffersen, A. (2010). "Facilitating client value creation in the conceptual design phase of construction projects: A workshop approach." *Architectural Engineering and Design Management*, 6(1), 18-30.

Trochim, W. M. K. (1989). "Outcome pattern matching and program theory." *Evaluation and program planning*, 12(4), 355-366.

Wang, J., Wang, X., Shou, W., and Xu, B. (2014). "Integrating BIM and augmented reality for interactive architectural visualisation." *Construction Innovation*, 14(4), 453-476.

Whyte, J. (2002). *Virtual Reality and the built environment*, Elsevier Science, Oxford.

Woksepp, S., and Olofsson, T. (2006). "Using virtual reality in a large-scale industry project." *Journal of Information Technology in Construction*, 11(43), 627-640.

Woksepp, S., and Olofsson, T. (2008). "Credibility and applicability of virtual reality models in design and construction." *Advanced Engineering Informatics*, 22(4), 520-528.

Yan, W., Culp, C., and Graf, R. (2011). "Integrating BIM and gaming for real-time interactive architectural visualization." *Automation in Construction*, 20(4), 446-458.

Yin, R. K. (2009). *Case Study Research: Design and Methods*, Sage, Thousand Oaks.