Exploring the Use of Digital Tools to Support Design Studio Pedagogy Through Studying Collaboration and Cognition

Julie Milovanovic and John S. Gero

Abstract This paper explores the effect of the use of digital design representation tools to support design studio pedagogy. We present the results of a case study of three types of architectural design critiques also called design reviews. The first one is a traditional desk critique where common design representations (plans, section, mock-ups) were used by tutors and students. The second case study investigates the use of a social Virtual Reality device, the Hyve-3D, that supports design collaboration through an immersive 3D sketch interface. The third case study involves the use of a digital desk utilizing the Sketsha interface to support remote design studio critiques. We used a video protocol analysis to study two characteristics of the design critiques: design collaboration and participants' interactions with design representations. Results highlight behavioral trends for each type of critique and provide insights on the potential of digital design representations to support design studio pedagogy.

1 Introduction

Designing and design representations are influenced and shaped by factors such as the evolution of digital technologies. It changes our design processes, the tools and ways to represent the design process and its result, the design artefact. The emergence of digital design tools and alternative, immersive and interactive design representations raises many questions about the integration of these tools into the pedagogical framework of design education.

The design studio is an essential part of design education in many design domains as it aims at teaching students how to design by doing design. We consider design as a reflective practice [1] that relies on a set of implicit cognitive processes.

J. Milovanovic (✉) · J. S. Gero
University of North Carolina at Charlotte, Charlotte, USA
e-mail: jmilovan@uncc.edu

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Students build design knowledge and skills as they learn by doing design, in a trial-and-error process, while being mentored by design studio tutors. During design critiques, also called design reviews, taking place in the studio, students present their designs to tutors and get feedback on their design in order to advance in their design process.

Design representations used during the critiques are important as they support the interactions between the participants. Common design representations vary from diagrams, sketches and drawings, to plans, sections, and perspectives, and include physical mock-ups, digital models, sometimes animated or immersive. All these design representations support communication between students and tutors and serve as an environment to discuss students' designs. Design representations have a triple purpose during design critiques. They provide a medium for students to express their design intentions and concepts to their tutors. They support collaboration as the participants in the design critique can negotiate, explain concepts, find solutions through the co-construction of an idea and reasoning with the help of design representations. Finally, they are used as a design tool: tutors and students will be able to propose a whole or partial solution to an unresolved design problem, by manipulating design representation.

In this paper, we explore the use of two different digital tools to assist design studio critiques. The first one, the Hyve-3D, is a social Virtual Reality device, that provides an immersive 3D representation of a design and an interface for 3D sketching and navigation. The second one is the remote Collaborative Design Studio (CDS) that uses an augmented tabletop with the SketSha software to organize remote design critiques between two European universities. SketSha supports 2D drawing on documents shared between the two sites. We compared those two types of design critiques with a traditional desk critique in order examine the effect of the use of these digital tools during design critiques by:

- exploring the behavior of tutors and students during the critiques: what are their roles in term of designing?
- studying how the digital tool is exploited during the critiques: what are the actions of the tutors and students on the design representations?

In the next section we build on references from the literature to develop the notions of collaboration and learning in design, and we discuss the importance of design representations, including digital ones, during the design critiques. Then, we present the methodology used to study our cases. The results will be described through two criteria: the role of each participant in the critiques' reflective practice and the use of design representations. The last sections of the paper discuss the results in the light of previous results found in similar studies and proposes directions for future work.

2 Background

2.1 Learning Design by Doing Design

Design critiques punctuate the temporality of the studio and the progress of the student's design. The format of design critique varies from one-on-one desk critiques involving a tutor and a student, to group reviews, peer discussions, pin-ups and juries [2]. One-on-one desk critiques provide, on a regular basis, a moment where students can present their design and get feedback from an expert, seek advices when faced with a specific design problem or are stuck in their design process [3]. The objectives of the critique are to evaluate the student's work, while providing constructive feedback on the design development. Design problems can be addressed during design critiques or simply pointed out to students so that they can reflect on them after the critique and adapt their design accordingly. Exploring, suggesting and proposing solutions can be considered as designing, where verbal and graphic formalization are intertwined. In *The Design Studio*, Schön identifies four types of actions in design critiques: telling (tutor) and listening (student); demonstrating (tutor) and imitating (student) [4]. The first set corresponds to the explicit formulation of design knowledge, such as specific instructions to be followed, design theories, requirements concerning the format of representations or design references; and the second refers to a design situation through the tutor's demonstration [4–6].

2.2 Importance of Design Representations During Design Critiques to Support Collaboration

Communication modalities and the relationship between tutors and students anchor design critiques in a social situation. The feeling of trust between tutors and students will allow them to feel comfortable to explain their design. Communication and collaboration appear as two important factors in order for the critique to be beneficial in terms of learning. In design critique situations, the concept of mutual responsibility for collaborative conversation applies between tutors and students. Everyone agrees that their interlocutor has a sufficient understanding of what they have just formulated before continuing talking [7]. The tutor/student team must understand what the other is referring to in order to co-construct the critique and the reflection on the design. Communication is essential for students and tutors to cognitively synchronize their own mental model of students' designs. The objective is to build a common design reference or common ground [8]. This first step of cognitive synchronization is important in collaborative design situations in order to integrate the point of view and reflection processes of each team member to make a collective decision [9].

The collaborative interaction between students and tutors is verbal, graphical and gestural and is channeled through design representations used during the critique. All the external design representations such as sketches, diagrams, plans, sections, physical models, digital models, simulations and animations form a representational ecosystem [10, 11] that acts as a support for communication, for an evaluation of students' designs and for an exploration of design proposals for inherent design problems. During design critiques, these activities are similar to a co-design activity between tutor and student. Indeed, the studio's pedagogical approach, project-based and by experience, implies that the design activity, which is the learning objective, is also the central activity during design critiques.

The externalization of design representations in a collaborative design framework serves to: leave a trace of the designer's mental effort in an external representation, represent elements that can give feedbacks (reflective conversation with the representations), and create an environment for criticism and negotiation [12]. In the situation of design critiques in architectural design studios, the pedagogical challenge of building design knowledge adds to the function of the representational ecosystem to support design and communication.

2.3 *Design Representations to Support Design Processes*

The production of drawings during designing, generating shapes and the relationship between these shapes, allows the designer to enrich their exploration space. Sketches are related to reasoning and reflecting during the design activity, where external and internal representations interact in a form of reflective conversation [1] or dialectic of sketching [13]. Designers externalize the concept of their design and explore new concepts by redrawing based on their design knowledge. If an idea appears in the representational ecosystem, it can be developed, revised and tested [14]. New design actions, anticipated or unexpected, may follow, which can be associated with the effect of surprise and creativity in the design activity. Sketching is often considered essential in the design activity, although some studies have shown little difference between designing with or without sketching [15].

Goldschmidt in [13] identified two modes of reasoning related to the way designer see their designs: "seeing as" (seeing as something else) and "seeing that" (seeing the element itself). A form of rationalization or generalization of decisions made in "seeing as" appears in the "seeing that" reasoning. For architects, sketching facilitates the interaction between design representations and the cognitive process of interpreting the concept. Ideas are transposed into sketches and can then be analyzed. In their study, Suwa & Tversky [16] use the concept of "focus shift" and "continuing segment" to study architecture students and professional architects only using sketching as a design tool. The "focus shift" pattern refers to Goel's lateral transformation [17] and is associated with the proposal of a new space, an emerging element in the design. In this study, it appears that sketching is not only

used to establish spatial relationships between the elements but also to support abstract reasoning.

Sketching isn't the only action on design representations that accompanies the design activity. Gestures are known to connect to thinking and reflecting [18, 19] and designing [20]. For instance, gestures in co-design can serve the purpose of communicating 3D and dynamic elements [21] or support interpretation and information actions [22].

2.4 *Using a Digital Representation Ecosystem to Support Design Studio Pedagogy*

Student/tutor interaction during design critiques are situated within the design representational ecosystem. The immersive characteristic of design representations potentially has an effect on designers due to the exploitation of external design representation as a thinking tool. The manipulation of virtual environments during the design process helps designers to better perceive space, for example its fluidity and functionality, without using 2D representations [23]. VR is widely used, from design itself to construction and project communication to collaborative decision-making [24, 25]. The use of VR in the studio can promote spatial understanding of the architectural design and improve students' self-assessment of their work [26], support the construction of design knowledge [27] and favor students' engagement in a co-design processes during critiques [28]. Other uses of VR in an educational context aim to enhance students' understanding of the structural parameters of their project [29], to enrich the modalities of representation [30] or to encourage remote collaboration between students [23], to name a few.

The use of augmented tabletops is an alternative use to VR that provides a way to reduce the cognitive load of students during the design process by bringing together different type of representation related to specific the design steps and represent rich environmental information such as wind flow, shadows, or traffic [31, 32].

We have emphasized the importance of collaboration between tutors and students during design studio critiques in order to support design learning by doing design. We have explained why the representational ecosystem is important during design critiques as it supports communication, design and teaching design. Design is the learning objective of the studio and it is also the main pedagogical strategy embedded in the learning by doing approach of studio teaching. We defined a design activity as an iterative reflective process of constructing mental and external design representations, where the designer navigates between different types of external design representations included in the representational ecosystem. We also highlighted that actions on design representations relate to specific design processes and type of reasoning. Digital tools like VR and augmented tabletops provides an alternative type of representational ecosystem to support design studio pedagogy and can have an effect on its users' design processes and interactions.

3 Methodology

3.1 Description of Case Study

This study aimed at exploring the effect of using digital representations in architectural design studio critiques. It specifically focuses on exploring the behavior of tutors and students during the critiques and how they interact with design representations. In order to address the research questions, a case study of three different type of design critiques is presented: desk critiques, Hyve-3D critiques and CDS critiques (Fig. 1). Observations were made in vivo, with no modification of the studio organization, design briefs, critiques' settings or timings.

The first case study is a traditional desk critique where students and tutors used printed plans and sections, as well as physical mock-ups during the critique. Students were master architecture students at the Graduate School of Architecture Nantes (France). The observations took place during the 2018 Spring semester. The requirements were to integrate public equipment into a housing complex, and to develop high environmental quality designs. The concept was developed by students individually using a series of conceptual mock-ups. The sessions observed took place following the selection of an architectural concept. During these critiques, students use concept mock-ups they had previously developed as a representational ecosystem as well as a set of other representations, plans, sections, perspectives drawings. Three students were observed during three critiques in a row. Each critique lasted between 30 and 60 min.

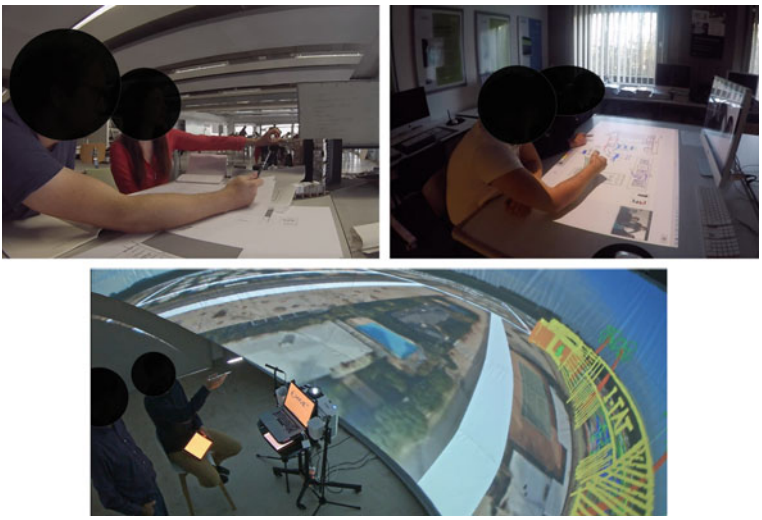

Fig. 1 Example each of the three critique type: a desk critique (up, left), a CDS critique (up, right) and a Hyve-3D critique (down)

The other two cases, Hyve-3D and the Collaborative Design Studio (CDS), offer entirely digital representational ecosystems. The Hyve-3D provides both a 3D drawing interface and an immersion in the design virtual environment. The critiques in the Hyve-3D were observed during the fall semester of 2017 in an architecture master level studio at the Graduate School of Architecture Nantes (France). Students from this studio worked on one of the two proposed briefs. The first brief is the development of a hotel on the theme of Jacques Tati's movies. The second brief proposes the development and production of a scenography inspired by Tati's work, which will then be used to shoot a short film and stage plays. Design critiques for this studio often take place with CAD models or with immersive representation devices (cardboard or immersive screen). For one of the critiques, a group of students participated in a Hyve-3D workshop. On the first day of the workshop, the students were trained in the use of the Hyve-3D. In the afternoon, students worked on their design, the hotel or the scenography, on a 45-min timeframe where they could go back and forth between CAD software (SketchUp) and Hyve-3D. The next day, each student individually presented the progress of their design to the studio tutor. The critique took place in the first half of the semester, i.e. in the conceptual exploration phase. Three of the critiques were analyzed. These critiques are quite short as they varied between 10 and 20 min. This timeframe is partly due to the format of the workshop. For this case study, a bias is due to the learning effects of the use of the Hyve-3D. Students had on a short amount of time to learn how to use this tool, and this probably had an impact on the way they presented their design. In addition, the tutor also spent a short amount of time to manipulate the Hyve-3D, which could lead to frustration during these design critiques.

The challenge of the CDS is to set up a remote design studio, integrating tools that support collaborative design [33]. Design critiques in the CDS differ from the others because the participants are spread between two sites. The representational ecosystem used is an interactive tabletop where users can draw in 2D on documents (plans, sections, perspectives). These documents, sketches and annotations appear simultaneously on both sites using the SketSha software [34]. The CDS is a master's studio proposing a group project including architecture/engineering students from the University of Liège (Belgium) and master of architecture students from the Graduate School of Architecture Nancy (France). This remote collaborative studio has been running since 2007 to support collaboration between both universities. Our observation took place during the fall semester of 2017. This multimodal remote collaboration environment operates with a verbal communication interface (Skype) and a drawing interface, SketSha. Both tutors and students were highly trained in using the digital tools. Three groups were observed, each composed of four to five students, two in University of Liège (Belgium) and two or three in Graduate School of Architecture Nancy (France) and two tutors, one at each of the sites. For this studio, students worked on the development of a community center including a boarding school, common rooms, an auditorium, a restaurant and a sailing club. In between studio critiques, students also used SketSha to work collaboratively. These critiques took place in the final phase of the studio and lasted around 40 min each.

Table 1 Information on cases observed in vivo

	Desk	Hyve 3D	CDS
Duration of critiques	30 to 60 min	10 to 20 min	41 min
Number of participants	1 student 1 tutor	1 student 1 tutor	4 to 5 students 2 tutors
Design brief	Housing complex and public equipment	Hotel or decor	Community center and boarding school
Design phase	Advanced concept	Concept	Final concept

In vivo observations provide a rich ensemble of design critique situations that carry a set of limitations. Each of the design studios is led by a different pedagogic team, with a different design brief. For one studio, within the same studio, design briefs vary. We also highlighted the differences in the number of participants in the critique, the different observation moments in the studios and the differences in critique length, from 10 min for the shortest to 60 min for the longest, Table 1. These observations were constrained by the real-life context of the studio: students wishing to withdraw from the study, students absent for a critique, or tutors not respecting the time defined for the critique. All these limitations should be taken into account when interpreting our results. Despite the limitations pointed out, the methodological tools used provide a unique framework to highlight similarities and differences between cases, as explored in other research using a similar methodology [35–37].

3.2 Methodological Tools

The protocol analysis methodology [38] is used to analyze each of the critiques as it aims at inferring a cognitive activity based on encoded collected data. The study explored design cognitive processes and designers' interactions with design representations. Therefore, the protocols, the video of design critiques, were coded with two coding schemes. The first one, dealing with design processes, is based on the Function Behavior Structure ontology [39], and the second, focusing on the manipulation of design representation, includes actions such as pointing to a representation or sketching. We used the Atlas.ti software to code our video protocols. Each protocol is coded twice and then arbitrated by the same researcher who is an experienced FBS coder, with 10 days between codings and between the second coding and arbitration, to obtain more reliable encoded data, on which the analysis is based.

3.3 Using the Protocol Analysis with FBS Ontology

The FBS ontology provides a description of design knowledge and design processes during a design activity [39]. This ontology represents six design issues and eight design processes at the ontological level: Requirement (R) include the design brief, client or regulation requirements; Function (F) is the design object teleology, i.e. what the design object is for; Behaviors represent how the design object performs, it can be an expected behavior (Be) or a behavior derived from the structure of the design object (Bs); Structure (S) is the description of elements or groups of elements of the design object and their relationships; and Description (D) represents externalizations representing the design object (Fig. 2). Eight transformations from one issue to another describe design processes as shown in Fig. 2. Formulation expresses a transformation of a requirement (R) into a function (F) or a function (F) into an expected behavior (Be). Synthesis is the transformation of an expected behavior (Be) into a structure (S). Analysis is the transformation of a structure into a behavior that is derived from it (Bs). Evaluation is the comparison between an expected behavior (Be) and a behavior derived from structure (Bs), and inversely. Documentation is the transformation of structure (S) or less often function or behavior into a description (D), which is the production of any external representation. Reformulation processes always start from a structure (S) that will redefine some variables in the design space. Reformulation 1 is a redefinition of a structure variable (S). Reformulation 2 is the redefinition of expected behavior variables (Be). Reformulation 3 is the revision of function variables (F).

The FBS ontology is relevant to explore design cognitive process as its descriptions of function, behavior and structure do not require any additional ontological concepts to describe design issues. Moreover, it has been used extensively to study diverse design situations [40–43].

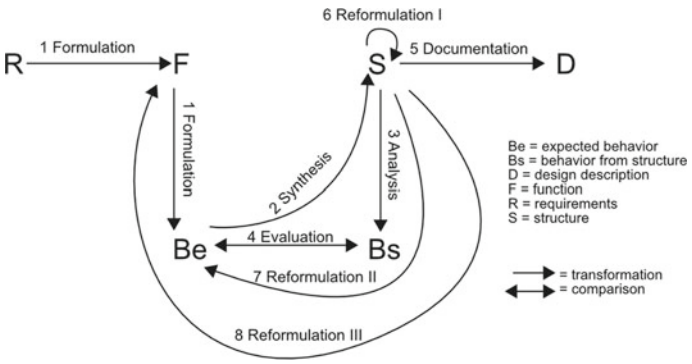

Fig. 2 FBS ontology based on [39]

3.4 *Analyzing Participants' Actions on the Design Representations*

The second coding scheme corresponds to the actions of the participants (tutors and students) on the representational ecosystem. References [14–23] and studio observations were used to define five categories of interaction with the representational ecosystem: point to a representation, represent a design element with a gesture, draw/sketch a design element, navigate in a representation and model a design element

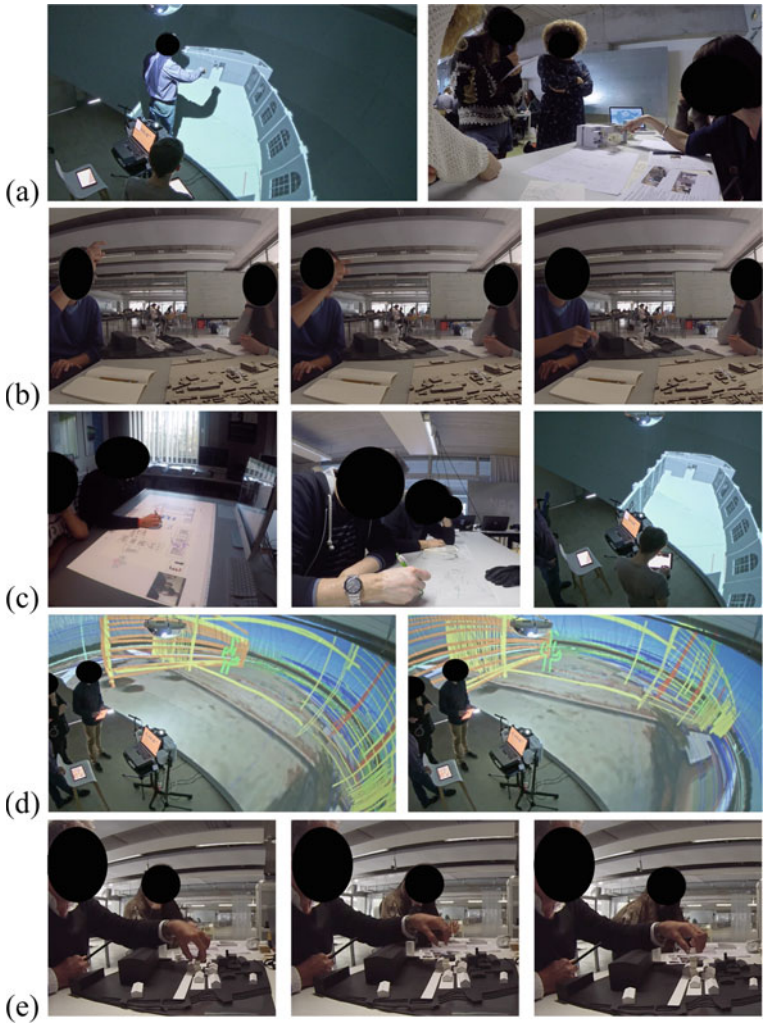

Fig. 3 Five types of interactions with design representations: (a) pointing, (b) gesture to represent a design element, (c) sketching, (d) navigating and (e) modeling

(with a mock-up) (Fig. 3). Two of our categories are a type of gestures as gestures support design and collaboration, particularly in the communication of 3D and dynamic elements [21]. We have identified two types of gestures in our videos: a deictic gesture, and an iconic gesture [44]. The deictic gesture is assimilated to the notion of pointing a representation and the iconic gesture aims to represent by a gesture an element of the project. Sketching and drawing are often used at the premises of the design process [45]. Those actions appeared in all the critiques. Navigation in a design representation implies the use of a 2D plan or a 3D model. This applies both to modeling with physical mock-ups and 3D digital models.

4 Results

4.1 Design Collaboration and Role of Participants

How tutors and students interact during the critique, how they co-design and what their roles are during the critique were initially analyzed. Each FBS design processes can be considered individual or collaborative based on the participants who formulated them. Four possibilities appear regarding the construction of processes: the student formulates FBS design processes individually (S > S), the tutor formulates FBS design processes individually (T > T), the tutor formulates the first element of the FBS design process and the student the second (T > S), and inversely (S > T). As mentioned above, some critiques involve several students or tutors, which have been grouped under two participant categories, student and tutor. In each critique, the FBS design processes formulated by the tutor dominated, Table 2. The tutor dominates the critique by verbalizing individual design processes. For critiques in the Hyve-3D, the dominance is the highest (M = 61.3%, SD = 9.8). The distribution of those processes decreases slightly for traditional critiques (M = 52.1%, SD = 12.5) and CDS critiques (M = 52.5%, SD = 16.9).

Table 2 Normalized distribution of design processes per interactions

	Individual S > S	Co-design S > T	Co-design T > S	Individual T > T
Mean desk critique	26.1	11.2	10.6	52.1
SD desk critique	10.7	3.1	2.8	12.5
Mean Hyve 3D	14.8	9.8	14.1	61.3
SD Hyve 3D	9.6	2.1	1.9	9.8
Mean CDS	27.2	10.2	10.1	52.5
SD CDS	11.7	3.9	2.8	16.9

The distribution of student > tutor co-design processes oscillates around 10% for all cases. The number tutor > student co-design processes is relatively higher in the Hyve-3D case than in the other cases with an average of 14.1% (SD = 1.9) compared to 10.6% (SD = 2.8) for traditional critiques, 9.9% (SD = 2.6) and 10.1% (SD = 2.8) for CDS critiques. It seems that in Hyve-3D critiques, students are more responsive to the tutor's verbalizations than in other critiques.

4.2 Actions on Design Representation

Between 40 and 70% of the verbalization of design critiques, for all types of ecosystems combined, are accompanied by an action on a representation or by the production of a representation, Table 3. For all design critiques except Hyve-3D ones, tutors are always more active in terms of actions on representations. Tutors dominate design critiques in all cases, which may explain why they are the most active in interacting with representations. In the Hyve-3D, students use sketching and navigation actions more frequently than the tutor.

The distribution of gestures to represent an element produced by the tutor increases in Hyve-3D (M = 16.3%, SD = 2.5) compared to their distribution in the desk critiques (M = 3.7%, SD = 3.4) and CDS (M = 4.6%, SD = 2.5). Pointing at a representation is more frequent, for both tutors and students, in the desk critiques than in the Hyve-3D and CDS.

For students in desk critiques and CDS, the dominant type of action is to point at a representation. For students in Hyve-3D critiques, the use of navigation in the 3D model is dominant, and interaction through sketching is important (M = 4.6%, SD = 8.0) compared to other representational ecosystems (Traditional M = 0,3% and CDS M = 1,1%).

Table 3 Standardized distribution (%) of participants' actions during design critiques

	Traditional		Hyve-3D		CDS	
	Mean	SD	Mean	SD	Mean	SD
Gesture tutor	3.7	3.4	16.3	2.5	4.6	2.5
Gesture student	2.2	1.3	3.5	2.5	1.3	2.5
Point tutor	27.3	11.0	13.3	9.6	13.7	9.6
Point student	20.7	5.2	2.6	2.6	13.4	2.6
Navigate tutor	*	*	3.6	3.7	*	*
Navigate student	*	*	9.2	6.1	*	*
Model tutor	1.6	2.6	*	*	*	*
Model student	0.6	1.3	*	*	*	*
Sketch tutor	3.7	4.6	1.7	3.0	6.9	3.0
Sketch student	0.3	0.6	4.6	8.0	1.1	8.0
No actions	39.9	9.5	45.2	25.8	59.0	25.8

*Action not possible

4.3 Connection Between Actions and Design Processes

We pointed out that design representations support multiple types of design processes. We explored how actions on design representation relate to specific design processes. In order to develop a qualitative representation of the associations between design processes and actions on the representations, correspondence analysis is used to represent relative relationship between an action and a design process. We synthesize all the results from the correspondence analysis in Table 4. We only looked at three types of actions since they are the only ones that occurred in all of our dataset. The action of pointing in the desk critiques and Hyve-3D ecosystem is associated with the evaluation processes while in the CDS, this deictic gesture is associated with design description and analysis. For the desk critiques, Hyve-3D and CDS cases, sketching is associated with the processes of reformulating design intentions, which reinforces the importance of this tool for the design critiques. Sketching is also associated with Synthesis for the Hyve-3D and CDS critiques. The use of the gesture to represent an element is associated with different processes depending on the representation ecosystems used: Reformulation 1 for the traditional ecosystem, Synthesis and Reformulation 2 for the mock-up ecosystem, Analysis and Evaluation for the Hyve-3D ecosystem and Synthesis for the CDS ecosystem.

Table 4 Summary of the connection between design processes and actions on design representations

	Desk critique	Hyve-3D	SDC
Processes link to pointing	Evaluation	Evaluation	Analysis reformulation 1
Pointing	••••	•	•••
Processes link to sketching	Reformulation 2	Synthesis reformulation 2	Synthesis reformulation 2
Sketching	•	•	••
Processes link to a gesture	Reformulation 1	Analysis evaluation	Synthesis
Gesture	•	••	•

The symbol • represents the connection of design processes for each action: • low connection; •• medium connection; ••• high connection

5 Discussion

This case study explored tutor/student interactions during design critiques when using different type of digital design representations. We saw how tutors and students engage in co-design processes, interact with design representations and use gestures and sketching to accompany cognitive design processes. These preliminary results are limited and cannot be generalized due to nature of the case study (small sample size, in vivo observations of studios in different universities, length of each critique varied, and different design briefs). However, these initial findings validate the usability and relevance of the methodology, and provide a base to develop larger and more representative studies in future work. In the following, the findings from this study are articulated and discussed in relation to findings from other studies.

5.1 Effect on Engagement in the Critique and Collaboration

The role of tutors and students in CDS critiques and traditional critiques is similar, while in Hyve-3D critiques, participants engage more easily in co-designing processes. The representational ecosystem used during design critiques can influence collaboration among participants. All participants should be able to communicate in a designerly way through the representational ecosystem to support design collaboration. In all the critiques we observed, students and tutors were able to engage in the critique. We saw in this study that the distribution of collaborative processes tends to be higher for traditional desk critiques and Hyve-3D critiques. Students in the Hyve-3D engage in responding to their tutor's questions more than the other representations. From this case result we develop the hypothesis that the immersive screen creates a design space that encourages collaboration between participants. The collaborative and rich dialogue between tutors and students during design critiques enhance the development of students' conceptual knowledge about their design [6]. This strengthens the potential of the use of immersive environment to support design studio critiques in order to enrich students' learning experience.

5.2 Effect on Interactions with Design Representations

Designing integrates the proposal of a spatial design organization while including a projection of a sensitive spatial experience or felt-paths [46]. In their study, Elsen and Heylighen [47] highlight the relevance of sketching and perspective representations with an egocentric view to communicate the sensory experience, which echoes the notion of felt-paths. Sketching, beyond its ability to provide a representation that communicates a sensitive experience, also supports the concept's

exploration [45, 48]. The Hyve-3D integrates an immersive 3D sketching interface than can enhance ideation [11] and the communication of the sensory experience. In our observations in the Hyve-3D, the action of sketching is not that frequent compared to the use of gestural actions (pointing and representing by a gesture). For a design session, the use of sketching tends to be more frequent [34]. The pedagogical dimension of the design critiques may be one reason for this difference in the use of sketching because the objective of the critique is to learn how to design and not to design per se. We saw in our case study that tutors tend to sketch more frequently in the traditional desk critique and CDS ecosystem (2D sketching), unlike the students who exploit sketches more frequently in the Hyve-3D (3D immersive sketching).

According to Détienne, Visser and Tabary [22], the action of sketching tends to be associated with solution-generation activities while the action of showing (pointing) corresponds to interpretation or information actions. In a study on the relationship between the design process and the manipulation of external representations, Cardella, Atman and Adams [49] showed that designers use sketching to frame the problem and to reformulate it as well. Sketching is used in the observed critiques to reformulate design intentions (Reformulation 2) for traditional desk critiques, Hyve-3D and CDS critiques, which is consistent with the study presented in [49]. For Hyve-3D and CDS ecosystems, where sketching is more widely used, this action is also associated with proposal processes (Synthesis), which are in line with the study presented in [22].

The importance of graphic representations, their manipulation and the use of gestures to communicate and design have been highlighted in many research studies [16, 19, 50, 51]. Gestures are important to support design and collaboration, particularly in the communication of 3D and dynamic design elements [21]. A link is suggested between the action of showing (pointing) and interpretation or information actions [22]. Spatial gesture actions are more frequent in the Hyve-3D design critiques and it tends to be associated with the Evaluation and Analysis processes. For the Hyve-3D, the action of pointing to refer to a design element is not dominant, which can be explained by the immersion of the participants in the design, and the possibility of navigating in the design virtual space. These two features of the Hyve-3D can reduce the ambiguity related to the object being discussed.

In summary, we have seen that the representational ecosystems studied here all support collaboration between the participants and provides an environment for participants to communicate in a designerly way in their reflective practice. Nevertheless, we observed differences in participants' behavior in each case, related to the prevalence of some actions over others and the function of these actions in the mentored reflective practice. The participants in the design critiques interact with the representational ecosystems with similar actions, such as the gesture of pointing or representing an element and sketching. Differences appear in the design function associated with these actions and in the distribution of their use.

6 Perspectives

This study explored several elements that have an impact on students' experience of the critique such as participants' engagement in co-design processes and the use of design representations during the critique. In our case study, different connections between types of gestures and specific design processes were found. Sketching tended to be associated with the synthesis of design concept or their reformulation. In this study, students in the Hyve-3D were more engaged in sketching during the design critique than in the other environments and were also more engaged in co-designing. Using a design representation environment that can support this behavior during the critique can promote co-ideation to enhance students' experience [28], and potentially augment their learning design skills.

Sketching is often the focus of studies of design activities but the analysis of gestures should not be discarded as it is an important part of the designing process [20]. During design critiques, communication and collaboration are essential for learning to take place, and gestures can support it. In this study, the use of gesture during the critiques varied in frequency and in the design process associated with this action. A deeper analysis of types of gestures and related processes will enrich the understanding of gestures' significance concerning students' learning experience during the critique.

Digital technologies such as VR and AR offer a potential to enrich students' learning experiences in the studios. To understand these potentials and how to exploit it, tools need to be assessed and refined to better support design learning pedagogy. This exploratory study is a first step in that direction and allowed us to test our methodology and tools used to support our analysis: protocol analysis and quantitative analysis. In future work, we will focus on increasing our sample size to statistically confirm the trends found in this study and provide reliable insights on the use of VR and AR digital tools to support design studio pedagogy.

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