

IS THERE ANYTHING TO EXPECT FROM 3D VIEWS IN SKETCHING SUPPORT TOOLS?

Abstract. This paper describes a research project which aims at studying the ergonomic and cognitive value of EsQUIsE, a freehand design environment for architects. This sketch-based modeling software is implemented on a Tablet PC. The EsQUIsE software provides architects with the possibility to generate automatically 3D views from the freehand drawings.

The first part of the paper deals with the usability of such a digital environment for sketching, and especially the use of the drawing areas. The second part of the paper is dedicated to the analysis of how 3D views are generated and used for exploring alternative solutions. Although in interviews architects rate 3D highly, in fact they do not produce a large volume of 3D sketches. Issues about visual and spatial reasoning in design are thus highlighted. Finally, the benefit of such a tool for creativity is questioned.

1. Introduction

It is now asserted that sketches play an essential role in generating creative outcomes (Purcell and Gero, 1998). Researchers investigate the nature of sketching tasks with two objectives: On the one hand, understanding and modeling the cognitive processes involved in sketching (Goldschmidt, 1991; Scrivener, Ball and Tseng, 2000). On the other hand, providing computer tool supports and digital environments that could better support this specific phase of the design process (McGown and Green, 1998).

Two different rationales can be distinguished in the attempts to support the transition from paper-based sketching to a digital environment. One is to transform selected freehand-sketched concepts to digital input. The other one is to mimic the natural sketching activity with computer-based methods. The EsQUIsE design environment which is reported in this paper belongs to the second category.

EsQUIsE is a freehand design environment for architects, which is able to capture and interpret in real time digital drawings. The architect works freely, creating his/her drawings with an electronic pen. No keyboard and no menu are needed to depict the building. The EsQUIsE interface is designed to be as close as possible to the architect's traditional and usual way of working, that is to say, a sheet of paper.

Among various functions provided by EsQUIsE, the one which consists in generating automatically - from a 2D view – a volumetric view of the envisioned building is especially striking (see Figure 1, next section). Bench studies have pointed out that this function is highly-rated by practicing architects. But its added value for sketching had not been assessed yet. This is one of the objectives of our study.

The other objective is to conduct a systematic user-centered study of EsQUIsE's digital environment with practicing architects. As a matter of fact, previous user-centered studies have been conducted, but they were either informal design trials or experimental studies with advanced students (Safin, Boulanger and Leclercq 2005; Decortis, Safin and Leclercq 2005).

The study reported here is conducted with 7 practicing architects. The aim is two-folds: to evaluate the device from an ergonomic point of view and to assess the principles adopted to build EsQUIsE's sketching digital environment.

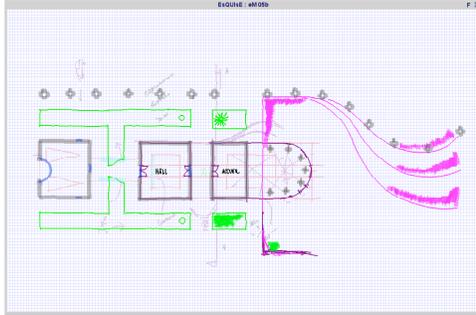
2. EsQUIsE, a Freehand Design Environment For Architects

EsQUIsE is a freehand design environment which captures and interprets in real time digital drawings. The architect draws with an electronic pen on a digital layout. Sketches can be drawn at any place on the layout. Suitable tools and functions for sketching (colors selection, digital eraser, sketch transformations, rooms labeling) are displayed in a menu at the left of the tracing surface. The successive layout are indexed by the architect and stored in an easy-access area at the right of the layout. The architect can generate as many layout as he/she wishes and can choose to superpose them or not, in any order.

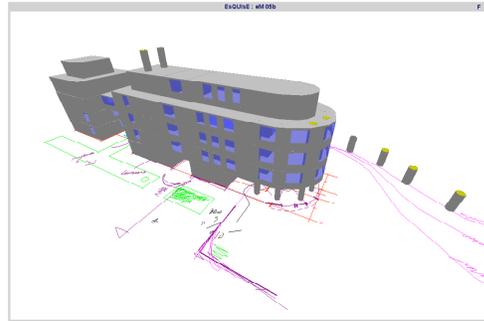
Once the sketch is completed, EsQUIsE can recognize the drawn components. These are used to generate a 3D model of the building. Characteristics which were not explicitly described by the designer are then completed on the basis of an architectural knowledge base. For example, as window heights are rarely specified in the preliminary design, EsQUIsE automatically selects relevant heights according to the type of room.

The data can be imported by all CAD tools belonging to the downstream production phase of the architectural process. The 3D model is composed of faces which can be easily translated into OBJ, DXF, DWG or VMRL files.

This 3D model provides the architect with a volumetric view of the artifact (see Figure 1). This view can be oriented in any direction so as to highlight a specific viewpoint. Scale options can also be changed. Other functions (e.g. evaluation of energy needs, topological representation of the building) are also provided. We do not describe them here since they are out of the scope of this paper.



Digital 2D sketch



View of the 3D model automatically generated by EsQUIsE

Figure 1. An overview is drawn on a digital layout with an electronic pen. Each layout is seen as a floor. The architect can then select those of the layout which are relevant to him and ask for an automatic generation of the 3D view (at the right).

EsQUIsE can be used either on a virtual desk (see Safin *et al.* 2005 for further description) or on a Cintiq graphics tablet (see Figure 2). This latter device is the one which we used in our study. It includes a 21" LCD into the tablet (36 x 29 cm²) which can be rotated or lay flat down so that the user can work as he/she would do on a A3 slate. This choice was made because such a device is easy to install and is likely to be adopted by practicing architects.



Figure 2. EsQUIsE is used on a graphic tablet.

3. Sketching Support Tools

Many CAD tools make it possible to design and manipulate digital sketches. However, most of these tools fail to help the designer in the very first design phases, when the outlines of the project have to be defined and the space of solutions must be explored. This failure is often due to the principles adopted for the user interface, which force architects to implement data that are not relevant when sketching and compel them to choosing among a set of limited actions with the mouse.

In order to preserve the specific properties of sketching activity - especially the vagueness, incompleteness or ambiguity of sketches -, the research community in pen-computing started in the 90th with pioneers like the Electronic Cocktail Napkin (Gross 1996), SILK (Landay 1996) or EsQUIsE (Leclercq 1997; Leclercq 1999). More recently, many prototypes were developed for different design applications: interpretation of electrical schemas (Gennari, Kara and Stahovich 2004), sketch-based query in graphical database (Ferreira, Fonseca, Jorge and Ramalho 2004), graphic user interface design (Coyette, Faulkner, Kolp, Limbourg and Vanderdonkt 2004), generic recognition systems (Alvarado and Davis 2004; Hammond 2004) or architectural sketches interpretation (Juchmes, Leclercq and Azar 2005). The feasibility of employing multimodal input, by combining speech input, gesture input and menu-driven inputs, as a means of supporting the rapid dialogue between the designer and the sketch has also been explored (Sedivy and Johnson, 1999).

4 Sketching As The Dialectics Between Internal And External Representations

Sketches play a major role in the upstream phases of design, when decisive choices among design principles have to be made. During these very first phases of the design process, a sketch is not only an externalization of the design ideas, the role of which being to communicate the design principles. Ferguson (Ferguson, 1992) distinguishes these “prescriptive” sketches from the “talking” sketches. These latter enable designers to build a “conversation with the situation” (Schön 1983). In other words, the “description” of envisioned ideas goes along with a “depiction” of the design (Fish and Scrivener 1990, cited by Suwa and Tversky,1997).

At the same time, since they are acting as “stakeholders” in the design process, sketches provide the designer with a basis for a “conversation with one’s self” (Scrivener, Ball and Tseng 2000). The reasoning process is thus elaborated through the interaction between the external representation and the

cognitive processes of interpreting it (Purcell and Gero 1997). The cognitive strategies (such as generate solution, select and evaluate goals and constraints, generate alternative goals and solutions, build the constraints network, retrieve domain knowledge, etc.) are experienced and assessed through the sketch. This dialectics was formulated by Goldschmidt (1991) as an intertwined reasoning between “seeing-as” (aimed at extracting new meaning from the sketch, on the basis of its figural properties) and “seeing that” as (aimed at using the sketch as a basis for discovering non-figural elements).

5. Visual Reasoning And Spatial Representations In Sketching

Thus, what do architects see in their sketches which make these drawings irreplaceable “partners” of the design cognitive processes ?

Suwa and Tversky (1997) claim that sketches allow architects to “read-off” non-visual functional issues from visual features. According to these authors, three explanations could be further investigated to account for the fact that sketches enable and facilitate this act of “reading-off”:

- Sketches are visual; certain configurations of line drawings would visually cue the architect’s background knowledge about functional issues;
- A spatial relation between things that have been drawn on the sketch irrelevantly to each other becomes emergent all of a sudden; this could suggest a certain functional issue;
- Freehand sketches afford re-interpretation of line drawings.

The way that designers manipulate graphical information in design drawings is investigated by research on visual reasoning (Oxman, 1997 ; Kokotovich and Purcell, 2000; Do, 2005). But, as stressed by Bilda, Gero and Purcell (2006, p.588), “there is anecdotal literature about designing with the use of imagery”. Of course, designers are assumed – and feel as – they use imagery in the conceptual phase of design. The dialectics between internal and external representations is likely to be, for a large part, supported by volumetric reasoning.

Kokotovich and Purcell (2000) have tried to understand the mechanisms of creative 3D mental synthesis, by contrasting 3D designers and 2D designers. They investigate whether flat two-dimensional forms would be or not of practical value to 3D-designers, such as engineers or architects. However, the experimental material was quite simple, contrary to the complexity of architectural sketches as studied in this paper.

In another research conducted by Kavakli, Scrivener and Ball (1998) and Scrivener, Ball and Tseng (2000) in the field of furniture design, the specific role of structural parts in mental imagery and object recognition processes are put forward. According to the authors, idea sketching is structured along the

volumetric structure of envisioned ideas. The authors focus on the role of parts in object recognition and mental imagery. They stress that sketches were predominantly drawn part by part and based on simple volumetric primitives.

6. Issues

Considering the previous state of the art, it can be assumed that architects would much appreciate using a CAD tool capable of generating volumetric views of their sketches. The exploration of new ideas would be made easier and their creativity would thus be enhanced. However, the expression of creativity could be impeded by a bad drawing interface.

This is the reason why the study is divided into two complementary parts. The first one deals with the usability of the tablet, regarding the complexity of the drawings which are to be made. The second part investigates the use of 3D views.

7. The Study

7.1. THREE SUCCESSIVE STEPS

The study was divided into three sequential steps. The *first* one consisted of preliminary interviews (about 30 min.) during which architects were asked about their practices of sketching, and their familiarity with CAD tools. They were also asked to describe how they usually communicate their first blueprints to the customers. The *second* one was aimed at solving an architectural design problem, using the device EsQuise+Tablet. The *third* step of the study consisted in evaluating the software, on the basis of a usability questionnaire. This took about 45 minutes. This paper only reports the results of the second phase.

7.2. PARTICIPANTS: PRACTICING ARCHITECTS

As described above, the study aimed at performing a user-centered evaluation with practicing architects. The opportunity of using an attractive freehand digital environment helped a lot in convincing seven architects to give one half day of their working time. Among them, two trial sessions could not be fully recorded. They were not included in the results. Table 1 summarizes the architect's profiles. It can be noted that two novices were recruited so as to assess the role of experience in using EsQUIsE.

All of them are used to draw their first sketches by hand on tracing paper. Excepting for the architect *A1* who relies upon his/her assistant to transform the blueprints into CAD files, other architects use CAD tools (such as Autocad, Archicad, Arc+ or Architriion) for the downstream design phases.

	Level of experience	Main job
Ae1	Expert (31 years)	Co-manager of an agency (5 people)
An2	Novice (1 month)	Unemployed yet
An3	Novice (1 year)	Assistant - architect
Ae4	Expert (40 years)	Works alone in his agency
Ae5	Expert (40 years)	Manager of an agency (2 people)

Table 1. Architects' profiles

7.3. A REALISTIC ARCHITECTURAL PROBLEM

The problem to solve was elaborated in order to enable architects to carry out a first design cycle within two hours. The instructions given to them were: (i) to stop when they feel like having a blueprint sufficient enough to communicate the key ideas about the envisioned building; (ii) to transmit this blueprint through a sketch *and* at least one volumetric 3D view generated by EsqUIsE.

The problem was elaborated by an architect-engineer. Its feasibility was tested before the experiment. It was required to build a high school in a urban area. Other detailed requirements were given on a paper document, such as the size of the plot, the number of pupils to host, some of the functional dependencies (e.g. to have the director's office near to the entrance) and functional requirements (a restaurant, a playground of a specific size, etc). Architects are asked to use the graphic tablet but they have also some sheets of paper, rulers and rubbers at their disposal.

8. Method

8.1. DATA COLLECTION

Design sessions were audio and videotaped. Backup files were recorded. A simultaneous verbalization method was used, which benefits and limits are known (Ericsson, K.A. and Simon, 1984). We will not discuss this point here. Verbal recording was not aimed at providing data for verbal protocols but only to support further interpretation of specific sequences. Verbal records were thus not fully transcribed.

8.2. CODING SCHEME

The first coding scheme was elaborated to highlight the *time duration of the drawing tasks*, regarding two factors:

- *Type of drawing* (3D view, drawn perspective, 2D overview, cross-section, frontage, text). This latter modality (*Text*) is made up of annotations, calculations, rewriting or interpretation of requirements (note that room

labeling is not counted in this category). An “*Document*” category was dedicated to the reading tasks, during which architects examine the requirements list;

- *Location of the drawing* (main area of the tablet, peripheral area, outside the tablet).

According to this coding scheme, videotapes were cut into significant units (clips) using iMovie (a Macintosh application). The duration of each clip is automatically computed.

8.3 . GRAPHICAL REPORTS

On the basis of this coding, we have drawn graphical reports which provide a temporal view of the design session. An example is given in Figure 3 below. The type of drawing is written in the left column. The clips are numbered (in the example, from number 23 to 42). Each color is for one digital layout. Cell surrounding is for the localization (bold in on the *main area* of the layout, hatched lines are for identifying *peripheral area*). Time duration is written into each cell.

N° clip	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	
3D																					
Plan	1' 30''	21''	10''	4' 28''	13''	5' 14''					16' 63''			10''	36''	5' 14''			1' 80''		
Persp				2' 47''		58''		10''													
Coupe														29''	26''	16''	2' 14''				
Façade																					
Texte																				23''	
Doc.																					
Layout (floor)	Layout 1 (Ground floor)										Layout 3 (Ground floor)		Layout 2 (First floor)								

Figure 3. Graphical report (extract) elaborated on the basis of the video recordings.

9 . Phase 1: Assessing the Usability of the Digital Environment

Before all, it was necessary to evaluate whether the digital environment, made up of EsQUIsE and the graphic tablet, would not prevent architects from performing the design process in a satisfactory way.

9.1 . GENERATING DIGITAL LAYOUT

We first wanted to check that the digital device, based on the layout principle, is easy to use. The system must allow the architects to generate as many layout as necessary to find out their “best” solution.

As presented on Table 2, the duration of the design session varies a lot. It is comprised between 1 hour (Ae5) and more than 2 hours (An3). Because of these important disparities, the average time (1h30min) is not meaningful.

	Number of layout generated during the design session	Number of alternative solutions	Duration of the design session
<i>Ae1</i>	5	6	91'47''
An2	9	2	73'
An3	8	9	138'59''
Ae4	12	6	88'50''
Ae5	4	4	67'43''

Table 2. Heterogeneous practices among architects.

The number of solutions which are explored can be quite low (only two solutions are explored by An2) or quite important (up to 9 for An3). Since both of these architects are novices, we explain this discrepancy by the style of designing rather than because of the level of expertise. Excepting for architect An2, the architects generate about 6 different solutions.

It seems that architects do not restrain themselves into a narrow exploration of the solution space when using the digital environment. However, is this exploration easy to perform or not, considering the limited size of the graphical tablet? This is answered in the next section.

9.2. MANAGING THE DRAWING AREAS

The question is to know whether or not the various external representations needed to accomplish the design process (sketches, annotations, notes, computations) can all be handled on the tablet itself. If too many of these artifacts were to be dealt with outside the tablet, the usability of the digital environment would have to be questioned. In any case, the sketching tasks which cannot be performed on the device must be identified. It may not be relevant to support all of them, though. For instance, the manipulation of the requirements document, the re-interpretation and re-writing of the constraints may be better processed outside the main drawing space. Regarding the other tasks, additional functions could be required to expand the interface.

Figure 4 provides us with an excellent instance of the richness of sketching which is allowed by the device. Architect *Ae1* draws on a sole layout but uses both the central area (2D floor overview) *and* the peripheral area (which is itself divided into two parts: calculations on the top of the area, and a perspective on the bottom).

Results presented in table 3 stress that :

- In most cases, external representations are drawn or written *on the main area* of the tablet.
- Except for Ae1, the peripheral area is almost never used. We will report later what it is used for.

Two groups can easily be distinguished, related with the duration of the work on each area and especially, by the use of the area “*outside the tablet*” (no statistical test was done because of the small number of subjects). Contrary to our expectation, these groups do not correspond to the level of expertise, since novices are *An2* and *An3*.

Architects	Group 1			Group 2	
	Ae1	An2	Ae4	An3	Ae5
Main area	82	88,5	88	72,50	62,50
Periphe-ral area	15	4	6	0	0,5
Outside	3	7,5	6	27,50	37
Total	100	100	100	100	100
	91'47''	73'	88'50''	138'59''	67'43''

Table 3. Duration of work on each area (%)

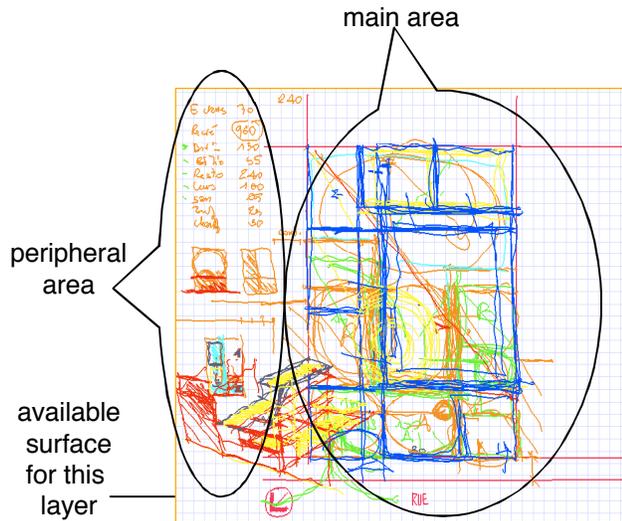


Figure 4. Diversity of sketches drawn on the different areas of the tablet

9.3. WRITING AND PROCESSING DOCUMENTS

Group 2 spend one third of the design session “outside” the tablet. We have to identify which artifacts are dealt with in this working area. As shown in Table 4 below, there are only two types of external representations which are manipulated outside the tablet:

- Texts written on the available whitepaper sheets (such as annotations, calculations, rewriting the requirements);
- Documents which support the requirements list reading.

There is an important discrepancy between *Group 1* and *Group 2*. These latter architects spend much more time reading the documents and writing texts than the former. We were surprised that experience does not seem to play a role in this way of doing. From observations and interviews, it seems that *Group 2* architects were much more concerned than others to follow precisely the requirements given by the experimenter. This could explain why they spend so much time reading these documents, rewriting and interpreting them into additional texts.

Type of external	kGroup 1			Group 2	
	Ae1	An2	Ae4	An3	Ae5
Text	0	0'58"	0	20'20"	9'50"
Doc	3'	4'30"	5'30"	17'51"	15'12"

Table 4. Type of external representation manipulated *outside the tablet* and duration of work on these representations (min/sec)

This important use of *Texts* by *Group 2* architects do not mean that *Group 1* never writes down a note. But, as highlighted in Table 5, *Group 1* architects do not write so much (5 to 10 times less) and prefer to write down annotations or calculations on the *peripheral area* rather than on a whitepaper sheet.

Texts areas	Group 1				
	Ae1	An2	Ae4	An3	Ae5
Outside	0	0'58"	0	20'20"	9'50"
Peripheral	3'40"	2'53"	2'32"	0	0'29"

Table 5. Area where *Texts* are manipulated and duration of work on these representations (min/sec)

Regarding text writing, the usability of the tablet is thus satisfactory for a classic use. Its peripheral area allows architects to write down usual annotations

and calculations. As suggested by some of the architects, a computation function could be added in the interface.

But it is noteworthy that the peripheral area is only dedicated to writing. Excepting for *Ae1* who often draws perspectives and cross-sections in the peripheral area (and a few seconds for *A4*, for a sole frontage sketch), this area of the tablet is never used to sketch. As a matter of fact, it is quite surprising that there are so few drawings in this peripheral area, since it is quite easy to access it. We hypothesize that it is a question of designing style. This interpretation is supported by *Ae1* preliminary interviews and post-evaluation. This architect said that he proceeds here as he usually does at his office, by drawing various viewpoints of the artifact on a sole sheet of paper. This provides him simultaneously with different abstraction levels on the same artifact. We will present in section “Results 2” which categories these external representations belong to.

10 . Phase 2: Use of 3D Views in the Sketching Process

As stated before, the easy use of 3D CAAD views in EsQUIsE was highly rated by the architects in the evaluation system questionnaire. Interviews also revealed that this functionality was much appreciated as a support for designing. Accordingly, it was assumed that many 3D CAAD views were to be generated during the sketching process. We hypothesized that 3D CAAD views would be generated to evaluate partial solution (for instance, to evaluate the location of stairs) or to evaluate a completed solution, leading on either detailing it further or exploring an alternative conjecture. This section investigates this hypothesis.

10.1 . TYPE OF ARTIFACTS REPRESENTATIONS GENERATED WITH THE SYSTEM DURING DESIGN: POOR USE OF 3D VIEWS

Table 6 shows the diversity of drawings and design actions which are performed by the architects. It is striking to note that, in both groups, the great majority of sketches are *2D overviews*. Only two architects over the five drew perspectives, cross-sections and frontages. This result is surprising, but it is in accordance with a study conducted by Leclercq [16]. The author examines 39 sketches drawn by six practicing architects. He stresses that 80% of the drawings are made of 2D overviews.

The use of 3D in general - that is to say manually sketched or automatically generated -, is very poor. There are only 2 occurrences of a sketched perspective (drawn by *A1* and *A5*). The use of 3D CAAD views is rare, as shown on Table 6, since it does not exceed 10% of the sketching activity.

This is a very low result, regarding the fact that architects much appreciate this functionality, as highlighted in the post-interviews. Moreover, it has to be said that the generation of 3D CAAD views was somehow compelled for architects A1, A2 and A5, since the instructions of the experiment prescribes to generate at least one 3D CAAD view at the end of the process in order to present the project their client (see section “The study”).

How can we interpret this lack of success of 3D CAAD views generation?

A first explanation could be searched for in the type of design problem given to the architects. Let us remind that the problem to cope with consists of finding the best way to superpose various floors. It could be assumed that reasoning in such a problem space would give an advantage to 2D reasoning and would not lead to handle volumetric mental representations nor 3D external representations.

		Architects				
Type of external representation		Ae1	An2	An3	Ae4	Ae5
3D	3D CAAD view	5	1,5	9,5	4	2
	Drawn perspective	4	0	0	0	0,5
2D	Plan	82	87	63	84	60
	Cross section	1	0	0	0	0
	Front-age	0	0	0	1	0
Other	Text	4	5,5	14,5	3	15
	Doc	4	6	13	9	22,5
Total		100 91'47''	100 73'	100 138'59	100 88'50''	100 67'43''

Table 6. Duration of work on each external representation

Two facts come against such an interpretation. The first one is that the architectural problem to be solved was highly constrained because of the very big size of the schoolyard (960 m²) compared to the available building area (1200 m²). Such a constraint likely compels architects to cope with the combination of the various floors and their conceptual, structural and aesthetic consequences for the designed building. There is no doubt that volumetric simulation must be triggered in such a problem solving process.

The second fact to go against this interpretation is that a very different problem was given to two advanced students in architecture [3]. These latter had to design a school in a place where the relief was the highest constraint (the site was sloping steeply, with a specific recess in the relief). One of the student solved the problem using EsQUIsE on a virtual desk, the other one had only pen and paper. The former student did not generate any 3D CAAD view, while the latter drew only 2 sketches related to 3D perspectives. This single observation cannot be a basis for generalization. However, it goes along with our assumption that the poor use of 3D sketches and the poor use of 3D CAAD view is not related to the type of architectural, but rather to a specificity of the reasoning process.

Another explanation is suggested by the work of Kavakli, Scrivener and Ball [25]. These authors have studied whether sketching reflects the geometric structure of the objects represented. They have highlighted the superiority of part-to-part recognition processes over holistic objects recognition in spatial reasoning. The superposition of floors to be dealt with in our architectural problem could be seen as different parts of an artifact. 3D CAAD views available in EsQUIsE could be characterised as holistic external representations. These would thus be less relevant in spatial reasoning than superposed 2D overviews.

So, the issue which arises from these results is the question of spatial reasoning. Two lines can be investigated. First, is spatial reasoning not well supported by EsQUIsE and the digital environment? Second, what is the importance and the role of spatial reasoning at this stage of the design process? This is investigated in the next section.

10.2 . VOLUMETRIC REASONING INFERRED THROUGH GESTURAL AND VERBAL CUES

This part of the study stems from the results presented in the previous sections. It was highlighted that, although well-appreciated by all architects, 3D CAAD views were (almost) not generated during this sketching phase. These results lead us to investigate two hypothesis:

- Hyp.1: There is no (or poor) 3D external representations (either drawn or CAAD generated) because there is no spatial reasoning at this phase of the design process. This of course goes against the common designers' feeling, those claiming that they "think in 3D". However, as stressed in our state of art, there are few researches investigating this issue in the domain of architectural design.

- Hyp.2: There is no (or poor) 3D external representations (either drawn or CAAD generated) because the EsQUIsE digital environment does not fit to the level of abstraction required for handling mental volumetric representations which are cognitively handled by the designers. This latter assumption seems more realistic but must be tested.

10.2.1. Method

To infer how spatial reasoning is conducted, we came back to the design sessions videos. The objective was to identify where volumetric reasoning is performed in the course of the design process and what it is about. This was done by two experimenters, one of them being an architect and the other one a psychologist.

Since this dimension of reasoning cannot be observed but only inferred, we based our inferences on two categories of behavioral cues which likely account for spatial cognitive representations:

- *Gesture cues*: there were made with one or two hands, sometimes with the pen. To be considered as an indicator of spatial reasoning, a gesture must be “3D-shaped”. That is to say that some gestures, such as underlining a shape or circling a room, are not considered as indicating a “volumetric thought” (in the rest of this paper, we will use the term “volumetric internal representation”). An example of a gestural indication of a “volumetric thought” is a stairway, described with the pen by a circular gesture finishing as an ascending loop. The mass ratio between the surrounding buildings is simulated with both hands encompassing the whole space.
- *Verbal cues*: simultaneous verbalization was used to infer the intention of the architect when performing the gesture.

These two cues point out where and what about a “Volumetric Internal Representation” (VIR). Each VIR is thus qualified as follows in Table 7.

VIR coding scheme	Example
Type of the gesture	Tiny and fuzzy gesture with the pen forming an ascending loop
Simultaneous verbalization	“Stairs in the frontage ... it is not so great ...”
Aim	Simulation of the ascending stairs
Previous action	Generation of the 3D CAAD views which presents the building mass ratio
Following action	Realizes that he did a wrong appreciation of the number of stairs of the neighbouring buildings and starts correcting data.

Function in the design process	Evaluation of a form, in relation with the aesthetic perception of the solution
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Table 7. Volumetric Internal Representation coding scheme

10.2.2 . Data analysis

Data analysis rationale is based on the fact that time cannot be the unit for a quantitative comparison, since it is not possible to know how long a “Volumetric Internal Representation” is handled in mind. Furthermore, comparing the number of VIR to the number of other architectural units generated during design was not in accordance with our objective.

Indeed, we are more interested in understanding at what level of abstraction these VIR are handled, so as to specify better what kind of 3D CAAD views should be presented to architects.

10.2.3 . Results

Results are presented in the following tables. First (Table 7), a comparison of the two types of volumetric representations is done. It is first stressed that there are a number of volumetric thoughts which back up the design process. But there is no homogeneity among architects, nor in the ratio between the number of 3D CAAD views and the VIR. The amount of VIR is much higher than the 3D CAAD views (except for one of the architects). So, how can we explain that the VIR are not externalized into a CAAD view or a 3D drawing ?

Volumetric representations	Architects			
	Ae1	An2	Ae4	Ae5
3D CAAD view	1	9	2	3
Volum. Internal Rep.	27	20	30	5

Table 8. Comparison of the volumetric representations

To answer this question, we have characterized all these volumetric representations along an abstraction hierarchy (Table 9). There are many proposals in the literature to qualify this hierarchy (see for instance (Burns and Vicente, 2000 ; Suwa and Tversky, 1997 ; Purcell and Gero, 1998) . Here, we propose to qualify the 3D views according to how they were driven. They can be :

Concept-driven, in relation with:

- an aesthetic criteria (for instance: “with the huge surface of this schoolyard, I would have to raise the things in such a way ...”
- an architectural choice (“I think about some stairs *à la française*”)

- the evaluation of the mass or volume ratio between the surrounding buildings

Form-driven, in relation with:

- the structure of the artifact (“classrooms will be on piles”)
- aesthetic criteria (“the patio is too cornered”)

Function-driven, in relation with:

- the use which is foreseen
- the circulation
- the feeling or the need of space

3D CAAD view is :	Architects			
	Ae1	An2	Ae4	Ae5
Concept-driven	1	2	1	2
Form-driven	0	6	0	1
Functional-driven	0	1	1	0
	1	9	2	3

VIR is :	Architects			
	Ae1	An2	Ae4	Ae5
Concept-driven	11	8	15	3
Form-driven	9	5	8	1
Functional-driven	7	7	7	1
	27	20	30	5

Table 9 Comparison of the volumetric representations

These tables must be interpreted keeping in mind that this study is a pilot one. This is the reason why we did not try to apply any statistical treatment on the results. It is worth to note that, among the 3D CAAD views, when they are generated (An2) are used to evaluate the global shape of the conjecture rather than to externalize a concept or a function. On the contrary, VIR seem to be driven by the concepts more than by the functions or the form.

This may explain why 3D CAAD views are not so often used by the architects whose mental representations are more conceptual than the volumetric view generated by the digital environment.

11 . Discussion and Conclusion

In this paper, we have presented a user centered evaluation with practicing architects. The study was two-folds. We now discuss each of them and draw perspectives for carrying on the study.

11.1 . USABILITY OF THE DIGITAL ENVIRONMENT

We first assessed the usability of the digital environment for sketching. The results point out that the principle on which the sketching device works is well suited to the architects' needs. The potential of simultaneously sketching on various drawing areas enable architects to keep their own style of designing. The layout principle is flexible enough and easy to use.

Our results show that architects do not restrain themselves into a narrow exploration of the solution space. Some of them do not hesitate to generate up to 9 design solutions.

Beyond the electronic pen based interface, the observations show that, in terms of interaction process (layouts management and work area management) and in terms of graphical production (sketch content : strokes, symbols, annotations), the tablet seems suitably supporting architectural design activities.

The usability assessment was done in more details in the third step of this study (see section "The study"). It consisted in a questionnaire (45 minutes long) in which architects had to rate the device (sketching interface, 3D interface and navigation between each interface), according to the conventional criteria of usability (Nielsen, 2001): *effectiveness* (the user can carry out its task), *efficiency* (it consumes a minimum of resources), and *satisfaction* (the system is pleasant to use). These detailed results are not presented in this paper, since they focus on this particular interface and are most likely useful for improving this specific system.

11.2 . USE OF 3D VIEWS IN THE SKETCHING PROCESS

The study then investigates the use of 3D views for generating and exploring alternative solutions.

Our study highlighted that, although in interviews architects rate 3D CAAD highly, in fact they do not produce a large volume of 3D sketches. Two related explanations were given:

- There are poor 3D external representations (either drawn or CAAD generated) because there is no spatial reasoning at this phase of the design process.
- There is poor 3D external representations (either drawn or CAAD generated) because the EsQUIsE digital environment does not fit to the level of abstraction required for handling mental volumetric representations which are cognitively handled by the designers.

Our results clearly confirm that there spatial reasoning may is conducted when sketching, even if not as often as we would have expected. If these spatial

thoughts are not externalized through the interface, it is likely to be because of the level of abstraction of the 3D CAAD representation. These are mainly form-driven, since the architects' internal volumetric representations are mostly concept-driven .

Other possible explanations could be formulated. For instance, it could appear that 3D representations are more important in architectural culture than they are in fact in architectural design practice. Another explanation may also be that the use of 3D varies widely among architects, this particular group being on the low-use end of this spectrum.

As a conclusion, it appears that some exciting issues are stressed in this study. It opens towards further research regarding the creativity features of our tool. We have to measure how much (and in which ways) the application impact the design process, and especially, how creativity is enhanced thanks to such a digital environment. We cannot use the study presented in this paper to answer this issue. We propose to cope with it through an experimental comparison of digital versus manual sketching.

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