The Impact of Procedural Knowledge Retrieval on the Architectural Design Process in Parametric Design Environments

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Given the rapid evolution of software, expertise has become increasingly transient forcing architects to keep learning after they have left educational institutions. Furthermore, complex tools such as parametric design environments (PDEs) are getting more popular. To mitigate the lack of expertise, architects can rely on information search systems. Even though, interactive information retrieval (IIR) has a rich literature, it is rarely addressed in architecture. This paper addresses knowledge retrieval and how it impacts the architectural design process in PDEs. Building on previous work on knowledge types in teaching parametric design, this article aims to bridge theory on IIR and searching as learning with architectural design through the Function Behavior Structure ontology. Data was collected through a long-term mixed approach of questionnaires and interviews during an elective course in computational design for graduate architecture students. Contrary to teaching, results show self-learning to rely mostly on procedural information which affects reformulation processes.

Introduction

Due to the rapid evolution of software, computational skills have become increasingly transient. Architects are put into a situation where they constantly must re-learn to master their tools, potentially during the design process. In order to address that situation, they rely on external information. Its rise in quantity, freedom of access and production has transformed human relationships with tools. Parametric design,

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which has become increasingly popular in architecture, is a prime example. The shift to process-based thinking where architects need to model functions and define relationships through parameters and functions brings a new kind of complexity [1]. Consequently, new tools such as visual programming interfaces have become unfamiliar and relying on external information turns into a necessity during practice. However, there is a lack of research in architecture and parametric design regarding information retrieval.

The paper presented addresses this empirical gap by proposing a theoretical base connecting interactive information retrieval and searching as learning to the function behavior structure (FBS) ontology. Novice designers were asked to complete 3 design tasks over multiple sessions and to report on their autonomous information search activity. A mixed approach combining questionnaires and semi-structured interviews was used to capture and discuss the data. Retrieval strategies are identified and finally their impact on the design process is discussed as well as perspectives fur further developments.

Background/Motivation

Parametric Design Environments

Parametric design in architecture describes a procedural process based on defined parameters that allows for automation and exploration. The designing takes place through a series of procedures translated into functions or components. It deals with form finding as well as managing all the metadata.

Visual programming tools like grasshopper have taken over as textual programming is quite unpopular among architects [2]. Visual programming is particularly interesting as complex forms can be described through a sequence of simple steps without the need for syntax. A specific geometry can therefore be captured through a series of components and relationships, then transcribed with other parameters to get variants of the original design (see Fig. 1). Those tools will be referred to as parametric design environments (PDEs). In terms of visual reasoning, information can potentially be as straightforward as a recipe compared to a more inspirational approach. Mental workload can therefore be reduced on both the tool and the design sides.

However, to go from a traditional representation tool to parametric design, architects need to translate the thought process into an algorithm. According to Woodbury, that kind of computational thinking requires new knowledge [3]. So, although working with PDEs can be seen as an epistemic action towards simplifying complexity, the tool itself is responsible for additional mental load leading to new cognitive investments and behaviors, themselves leading to other epistemic actions such as information retrieval during the design.

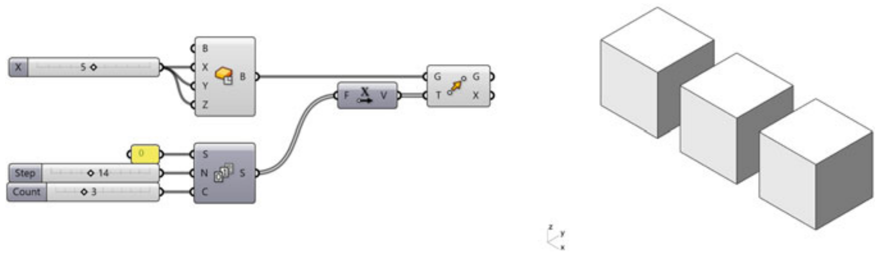


Fig. 1 Example of a visual script on Grasshopper, a popular visual scripting software

Function Behavior Structure Ontology

The function behavior structure (FBS) ontology [4] is a framework used to capture the design process and is one of the few popular cognitive models used in design and architecture.

In the original model, Gero defines 6 design issues: requirements, function, expected behavior, structural behavior, structure and documentation. Function (F) describes the designer's intentions, expected behavior (Be) is what is expected of the structure (S) and structural behavior (Bs) is the actual behavior of the structure put in place. Requirements (R) and documentation (D) are external issues triggering and ending a design episode. To transition from one issue to the other, Gero describes 8 cognitive processes: Formulation, synthesis, analysis, evaluation, documentation, and reformulation I (R1), II (R2) and III (R3). The 6 design issues and the 8 cognitive processes are presented in Fig. 2. According to Kan and Gero [5] reformulation processes are essential for innovation and creativity as they introduce new variables and/or directions.

Reformulation processes can be seen as follows. R1 is the reformulation of the structure within a defined design landscape and can be translated into an exploration through a given set of parameters. According to Erhan and colleagues [6] there is a risk of getting stuck into that process due to the sheer number of possibilities. R2 translates into the manipulation and addition of functions and their connections. The algorithm is modified and so is the expected behavior but always in line with the initial function. It triggers synthesis and possibly analysis and evaluation but can also induce subsequent R1s. In R3, the designer goes back to defining the problem space [7]. In addition to the formulation process, it might trigger the same processes as R2 and potentially other R2s and R1s. Formulation is determinant in PDEs. By setting up the algorithm or the necessary syntax to achieve the function, one formulates the boundaries of the design, or solution space. Eventually, exploring possible formulations leads to the selection of specific design spaces over others.

The FBS model has seen multiple improvements over the years as well as several superscripts' developments such as Yu and colleagues [8] which is concerned with PDEs. They distinguish 2 levels of design activities: The rule algorithm level and the design knowledge level. That study has provided a strong development basis for

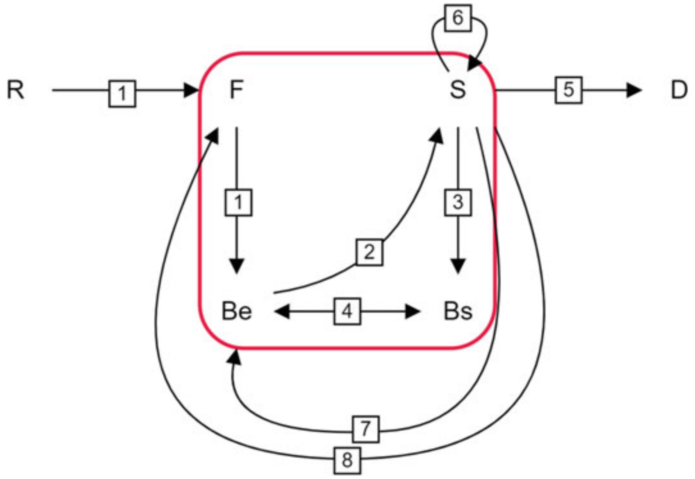


Fig. 2 FBS ontology based on the original model [4]. 1 = Formulation; 2 = Synthesis; 3 = Analysis; 4 = Evaluation; 5 = Documentation; 6 = Reformulation I (R1); 7 = Reformulation II (R2); 8 = Reformulation III (R3)

this research as it raised questions regarding the time constraints imposed by short protocols and consequently the lack of information retrieval possibilities. The FBS model informs on design cognitive pathways, but information retrieval has never to our knowledge been part of a study.

Therefore, this general model of design cognition seems like a strong basis. Given the very few papers specific to architecture, the model would enable to compare results with other design fields which is invaluable. Furthermore, the flexible nature of the model could potentially allow for a superscript taking information retrieval into account. Finally, using the FBS framework on PDE complements a growing basis of research for further development and discussion [8–11].

Knowledge in Interactive Information Retrieval

Interactive Information retrieval (IIR) is part of Human Computer Interaction (HCI) research and is concerned with the interaction between humans and information retrieval systems. Although we can trace back its history to more than 50 years, the term IIR only appeared in the 90 s with the advent of computational tools [12]. It revolves around the definition of information search tasks, but attention has been given to cognitive load and working memory because of the mental effort required to interact with search systems. There are many approaches to IIR, the one we are interested in is the characterization according to difficulty and complexity [13]. For this research we focus on Jansen's approach to searching as a learning (SAL) process that uses Krathwohl & Anderson (A&K) taxonomy of educational objectives to identify searchers' needs [14].

SAL is defined by the sense-making paradigm in IIR [15]. The term knowledge refers to information that is accessed via a storage medium and internalized. So, learning occurs in the searching process [16] and is conceptualized as a restructuring of one's knowledge. Consequently, accessing more information helps the stabilization process. Gero [4] describes designing as a goal-oriented constrained decision-making, exploration and learning activity. The learning aspect defined by Gero refers to the emergence of features in the design process. Because of the dynamic relationship designers have with retrieval systems, or more generally the Internet, emergence can also occur when searching for information.

The A&K taxonomy is a revision of Bloom's cognitive learning framework [17] and is widely used in pedagogy and learning design. It defines learning objectives through a 2-dimensional classification: The cognitive process and the knowledge type.

Cognitive processes are defined from least to most complex: remember, understand, apply, analyze, evaluate, and create. To each category correspond specific cognitive processes. For example, the "remember" category encompasses recognizing and recalling as specific cognitive processes. Based on A&K's revision, a design task would fall under "producing" within the "create" category. The latter is defined as "putting elements together to form a coherent or functional whole; reorganize elements into a pattern or structure". The "create" task is particular because it might require the learner to integrate the other cognitive processes [17]. As it corresponds well to the design task, this study naturally focuses on the "create" task.

Knowledge dimension is described through 4 types: Factual knowledge, procedural knowledge, conceptual knowledge, and metacognitive knowledge. Factual knowledge consists of the basic aspects a learner must know to be acquainted with one discipline. Procedural knowledge consists of methods on how to do something, and criteria for using skills. Conceptual knowledge is the ability to bring basic elements within a larger structure that enables them to function together. Finally, metacognitive knowledge is the awareness and knowledge of one's own cognition. Regarding the second dimension, few studies have been carried out [18] and none of them concerned with either design or architecture. For this paper, metacognitive knowledge will not be considered.

In a recent article, Vrouwe and colleagues [19] have conducted systematic research on "new knowledge" in parametric design and have described it as A&K's conceptual knowledge. That "new knowledge" is similar to what Yu and colleagues [8] describe as "rule algorithm level", which itself is based on Woodbury's definition of knowledge needs for computational thinking in PDEs [3]. Vrouwe and colleagues [19] have shown the consensus on the need for new knowledge and therefore identify conceptual knowledge as a learning objective for parametric design education. However there has not been any research on knowledge retrieval strategies adopted by architects or students while designing.

Urgo and colleagues [18] have recently reported conceptual knowledge retrieval task to be more prone to abandonment, to take a long time, to lead to less satisfactory results and to be perceived as more difficult than procedure-oriented knowledge retrieval tasks. Those results have yet to be applied in the architectural design field and in PDEs in particular. Empirical support from SAL in IIR tends to suggest that even though there is a consensus on conceptual knowledge to be the learning objective to aim for, the complexity of the design task might trigger other behaviors from autonomous learners.

Aims

The aim of this paper is to expose the information retrieval strategies of architecture students when dealing with PDEs and to explain how they affect the design process in the initial stages. The FBS ontology is used as a framework of reference for the definition of design. Our main hypothesis is that, given the complexity of parametric tools, novices will focus on procedural knowledge related to the tool, which will in turn guide subsequent design decisions by impacting design processes such as reformulation.

By adopting mental saving strategies, novices might be influenced by the information they consume to guide their design process. Eventually, this work should provide a basis for the refinement of the FBS model through the development of a potential superscript integrating IIR and SAL into the framework.

Significance

With the increasing transience of software, continuous self-learning through information retrieval has become common. In architecture, tools tend to be complex pieces of software, especially in PDEs which requires "new knowledge". This research is significant because it raises awareness concerning the impact of knowledge retrieval in the design process and is the first attempt at bridging IIR research with architectural design. The FBS ontology opens new perspectives for the development of a common framework to study that phenomenon. Given the quantity of information and the ease of access, raising awareness could be beneficial as there might be implications regarding the cognitive pathways used by architects to design and indirectly the final product. Therefore, the results of this study might prove useful for the architectural community dealing with new and complex tools, education, as well as provide foundation for further research.

Method

An elective class on computational design for graduate architecture students has been chosen. During one semester, students were given 3 design assignments, one every other week. The first assignment consisted in building a pedestrian bridge, the second assignment was to build a series of pavilions and for the last assignment, students were asked to design a multi-purpose high rise. They received basic constraints for each task, either related to the context or the function. Students worked in groups of 2 or 3 students. Eighteen students participated in the course, 17 of whom were surveyed as one was an exchange student and was not acquainted with the class language (French). The course was given on site at the faculty of architecture in accordance with the sanitary rules at that time.

The sample consisted of students with no experience in Grasshopper or PDEs in general. Given the elective status of the course, motivation levels were assumed to be similar across all students. During the in-class sessions, students were able to ask questions to the teacher/assistant, the student monitors, or the other students. There were 2 student monitors selected for their reliable knowledge of the parametric software used (Grasshopper) and they were asked not to intervene unless asked to do so by the students. The student monitors were also asked to keep an online conversation open in case students had issues outside of class.

A mixed approach was used to conduct this research. First, students were given 2 weekly pre/post task questionnaires. Then, based on the results, semi-structured individual interviews were conducted at the end of the semester.

Pre-task questionnaires were submitted right after the students received their assignments. The post-task questionnaires were submitted at the beginning of each session to reflect on the past working week. We collected a total of 3 pre-task questionnaires and 6 post-task questionnaires for both difficulty/knowledge and information sources. Students were given the questionnaires one week prior to the study on a sample assignment to get them acquainted with the format as well as the notion of knowledge type.

For pedagogical reasons, students were given theoretical sessions and hands-on exercises that were kept separated outside the scope of the 3 assignments (see Table 1). A typical lesson would last 4 h and be held as follows: First there was a presentation of each group work with feedback, then a theory session and the related hands-on practice task, finally the last 60 min were dedicated to the assignment. The collection of data started in week 2 as the first week was meant to get the participants familiar with the process. Week 5 was a holiday, which means that for the second assignment they had an additional week before the intermediary review. A global overview of the process can be seen in Table 1. All participants signed a use agreement regarding the use of the data collected.

The first pre/post task questionnaire followed a typical structure of pre/post task research in IIR. The goal was to collect quantitative information on the sources and the type of knowledge students would retrieve to complete their assignments.

Table 1 Semester course agenda

Week#	Course			Task#
1	Students 'presentation	Theory	Hands-on exercises	Introductory task
2				Task 1
3				Task 1
4				Task 2
5				–
6				Task 2
7				Task 3
8				Task 3
9				–

In both questionnaires, a Likert scale was used to go from *not at all* (1) to *very much so* (5). The pre-task questionnaire consisted of 6 questions meant to measure perceived difficulty (2 questions), perceived need for factual knowledge (1 question), perceived need for procedural knowledge (1 question), perceived need for conceptual knowledge (1 question) and motivation (1 question). The post-task questionnaire was identical except for one additional question on the satisfaction level. For this paper, however, only the first 5 questions, which concerned difficulty and knowledge type, are considered. Those questions can be found in Table 2.

Table 2 Questions asked in the pre/post questionnaires right after students received the assignments, and after one and two weeks of working

Q#	Interest	Pre-task questionnaire	Post-task questionnaire
Q1	Task Difficulty	How difficult do you expect the task to be?	How difficult was it?
Q2	Tool Difficulty	How more difficult will the tool render the task?	How difficult did the tool render the task?
Q3	Factual Knowledge	How inclined are you to look for factual knowledge?	What is the effort put into searching for factual knowledge?
Q4	Procedural Knowledge	How inclined are you to look for procedural knowledge?	What is the effort put into searching for procedural knowledge?
Q5	Conceptual Knowledge	How inclined are you to look for conceptual knowledge?	What is the effort put into searching for conceptual knowledge?
Q6	Motivation	How motivated are you?	How motivated are you to continue?
Q7	Satisfaction	/	How satisfied are you with the results?

The second pre-post task questionnaire was introduced to students to collect data on information sources. Through multiple choice, participants were asked to choose what sources they were planning to use (pre-task questionnaire) and what sources they actually used (post-task questionnaire). The choices available were course material; assistant; monitor students; group members; videos; blogs and other sites; forums; and other. If they picked the last choice, they were able to specify other sources manually. Course material is represented by the theory given in class as well as the support for hands-on exercises. Although the material is indicative of the type of knowledge they retrieved, nuances had to be discovered through further investigations.

The second approach consisted of semi-structured retrospective interviews that used a mix of deductive and inductive coding. Codes from the first questionnaire were used as the premise for the structured part of the interview. The rest of the conversation served as inductive material to foster for emergence of unexpected data for later improvements of the method.

Fifteen out of the 17 students were interviewed individually for 20 to 30 min. The questions were based on questionnaire results and aimed to nuance the results as well as identify opportunities for future research. Finally, they provided the necessary information to translate research behaviors into the FBS ontology. Each interview was recorded via a two-way microphone and was held the week following their last course.

Results

This section is divided in 3 subsections: Questionnaire results, interviews results and the FBS interpretation. Difficulty of the task is presented first, followed by the type of knowledge. Sources are presented afterwards to build on previous results. Interviews are then discussed I regards to questionnaires. Finally, knowledge retrieval strategies are outlined and discussed in terms of FBS.

Questionnaires

Regarding difficulty (see Fig. 3), the results of the first questionnaires show how working with PDEs (Q2) can be perceived as difficult compared to the design task itself (Q1). This result is expected and can serve as a manipulation check. Indeed, it confirms that design tasks are in the higher spectrum of complexity, as defined by A&K's revision of Bloom's taxonomy. Like "create task", design problems are ill-defined and the most complex ones [20].

Concerning knowledge types (Q3, Q4, Q5), the results in Fig. 4 show a smaller investment into conceptual knowledge (Q5) than factual (Q3) and procedural knowledge (Q4), which is in line with our hypothesis. Furthermore, there is a tendency to overestimate the investment into conceptual knowledge retrieval. Those results

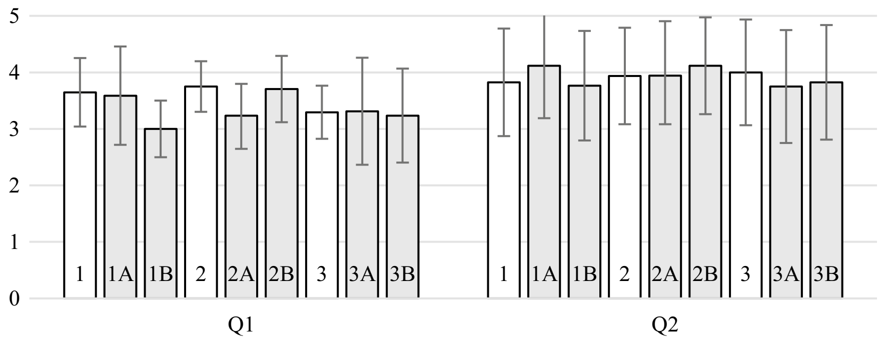


Fig. 3 Mean results for Q1 and Q2 for each step of each task

concur with research indicating that conceptual knowledge is more prone to lead to abandonment [18]. There is little difference between the investment in factual and procedural knowledge.

Results of the second pre/post questionnaires on sources are presented in Fig. 5. The first remark is that none of the participants picked the "other" option. The categories might either be sufficient or not detailed enough. During past semesters, books were sometimes used by students. This semester no one mentioned them even though they had a full library with a computational section at their disposal.

Video is clearly the preferred information source. If considered a source of procedural information, this is not consistent with the questionnaire results regarding the same investment into factual and procedural knowledge. Almost all students at every stage of every assignment used videos as source of information or had the intention to do so.

Student monitors were the second choice as a source of information. During the first week students did not rely too much on monitors, but the second week showed dependence. This tallies with former studies [21, 22] which concluded that the rise of complexity in a task tends to trigger people to rely more on people as source

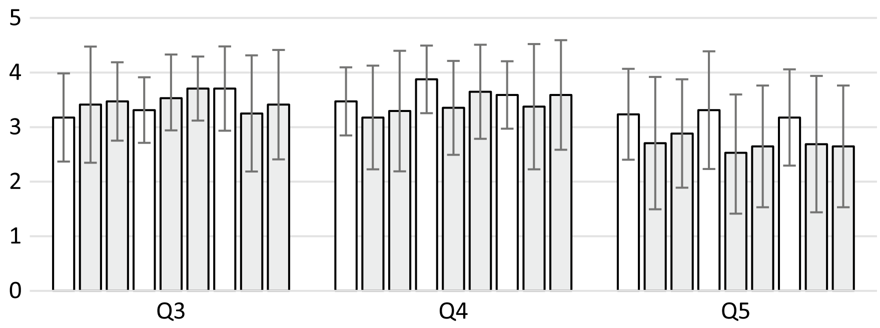


Fig. 4 Mean results for Q3, Q4, and Q5 for each step of each task

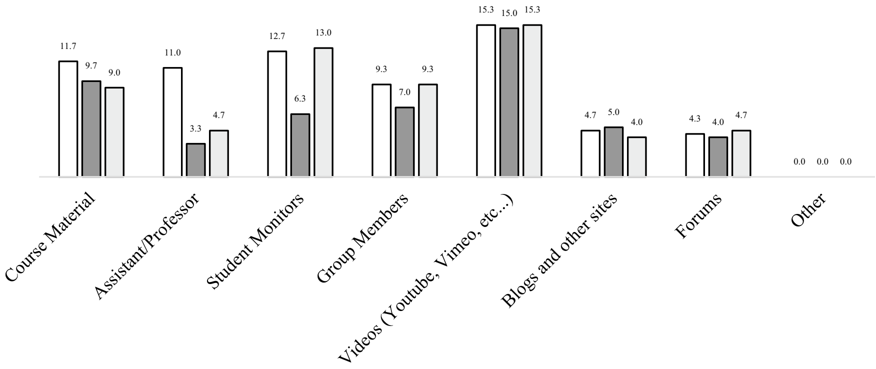


Fig. 5 Mean result for each step of the 3 tasks

of information. Although complexity does not increase throughout the assignments, students get eventually stuck, and complexity arises according to temporal pressure [22]. Another explanation is that formulating questions is not always easy and it might require some time before being comfortable enough with the material [16]. Finally, being stretched over a two-week period, students would rather try on their own during the first week before asking for help. Since monitors were available face to face during the course, students were able to explain their issues through sketching, gesture and talking while the rest of the week, they had to explain through written words and screenshots on the chat.

Course material was the third preferred source even though actual use dropped below group members after the first assignment. Given the lack of experience, it is not surprising that students rely on the little they know and get more autonomous as the course goes. However, those results do not convey the idea of autonomy as much as wanted for this research, but they are a good indicator for improvements in further developments.

Higher results regarding group members were expected as all students were all novices and working in groups would foster reliance on each other.

Assistants and professors were the last significant sources of information. Although expected use was quite high, actual use at the intermediate phase has the lowest average and the second lowest average for the second phase. Compared to monitors, the teachers were not in contact via chat during the week. Second, there might be potential fear of exposing weaknesses due to the fact that in this university context, students will eventually get graded for their work.

Finally blogs and forums were not used very much. As suspected, it is difficult to navigate those sources of information without prior knowledge.

All those observations served the structuring of the following interviews.

Additional Data from the Interview

Regarding difficulty (Q1, Q2), students expressed their effort towards the tools to be the center of their attention. At no point did any student mentioned difficulty concerning the design task. All groups referred to a similar strategy regarding their design process. First, they would generate ideas, and then they would look for adequate information to implement them in PDEs. Difficulty emerges first when translating an initial idea into a visual script. Students do not possess the adequate tool knowledge to do so. Moreover, they lack the conceptual knowledge required to do precise searches. Although it might be safe to think that this aspect would decrease along the 3 tasks, all members of one particular group explicitly mentioned the shift towards a more flexible approach to adapt to the material they would find more easily. This was in response to the struggle they faced during the first 2 exercises as they were trying to avoid reaching for external knowledge.

Regarding conceptual knowledge (Q3), interviews reveal that conceptual knowledge is indeed put to the side as students must deal with the new tool. It mainly concerns the design aspect of the task. Retrieval happened through image search but also through videos. A few students reported looking for references that seem programmable, even putting "parametric" as a keyword. One participant reported acting like that to legitimate the use of PDEs. Images were also mentioned to serve as visual support for the initial ideas or as references for creating them. Furthermore, students reported filtering images based on estimated feasibility rather than contextual value. It might be argued that the filtering of those reference images was based on the visual reasoning capabilities and computational knowledge of each student. Finally, several students mentioned looking at numerous videos unrelated to the design task to expand their tool related knowledge. Some of them mentioned however that this behavior eventually led to unexpected ideation. Eventually, students built conceptual knowledge through procedural knowledge.

For factual knowledge (Q5), student monitors are the preferred source of information. During the interviews, students mentioned how they wanted to tackle the design challenge themselves before relying on external help. Another aspect was that interactions outside the class varied between students. Formulating questions to the monitors was sometimes seen as an effort mitigated with time spent on the problem, which is in line with Li and colleagues' results [22]. This also explains why other resources such as forums, blogs or even the teacher were not exploited that much. Surprisingly, students also reported looking for factual information through video tutorials. When asked about the reason why they would adopt such a time-consuming strategy, they responded once again that formulating the search terms was difficult whereas searching through larger contexts was easier. Moreover, it was mentioned that video platforms such as YouTube provided visual cues, related content, as well as automatic translation of the titles from English into French. Those interviews revealed student's lack of skills when it comes to web searching. This was the conclusion of Rieh and colleagues' paper [23] that noticed: The struggle to find the right keywords, unsatisfying results not meeting needs and the reluctance to put efforts. Rieh and colleagues also observed that students tend to overestimate their search skills and effort put into it. Although the questionnaire results show a tendency to put effort into factual knowledge, the interviews reveal that it is marginal due to the difficulty experienced. By looking at videos, it might be argued students are not even looking for factual knowledge but rather procedural knowledge as the information is highly contextualized.

In terms of procedural knowledge (Q4), interviews revealed videos to be the main type of source. When asked to describe their design process, all participants mentioned "YouTube" as either the stage following the first concept ideas or a base for ideation. Monitors were also used as procedural knowledge sources. Some participants reported relying on the student monitors for procedural knowledge even outside the classroom. Later investigations revealed they had could physically meet and therefore did not have to rely on the chat discussion for support. Course material was mentioned as a source of procedural knowledge too. All students referred to the same video material that was part of a previous class and could be found online. Compared to the questionnaire results, this is more in line with our assumption of autonomy. Surprisingly, 3 students reported looking for images of visual scripts. A reference that would have required visual reasoning in more traditional means was delivered as visual step by step information. Images were not part of information sources as we did not consider them to be relevant in retrieving tool-related knowledge. However, they should be investigated in the future.

Relying on other students depended on the group dynamic and whether they were working together, which allowed for a collective memory [24] and all three types of knowledge.

The interviews revealed videos to be the main source for all types of knowledge. Assistants were also considered as sources of all knowledge but the interactions appeared less dynamic as students had to wait and potentially get no answer. Also, it came at the end of the design process as deadlines approached. Images were seen as conceptual knowledge sources although the filtering happened in order to serve either internal knowledge or the induction of video queries. In general, factual knowledge and conceptual knowledge served the building of queries for procedural knowledge found in video searching platforms, most likely YouTube. That nuance was not observable in the questionnaire results. Images should also have been considered independently.

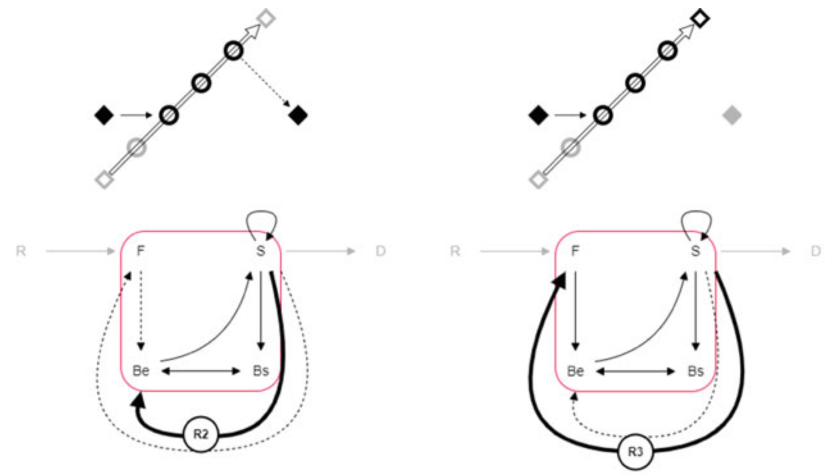
FBS Interpretation

With interviews data integrated, interpretation based on the FBS model is provided regarding the impact of procedural knowledge (Pk) on the design process. Students exposed 2 specific strategies regarding interaction with procedural information during their design process.

The first strategy consists of searching for Pk and integrating it into a larger conceptual knowledge scheme (see Fig. 6a, b). It can be time consuming and would potentially require considerable effort from the student [25]. Time constraint has been mentioned as schedules vastly varied between students. Two outcomes were observed. The first one integrates Pk to produce a structure without reconsidering formulation (see Fig. 6a). However, staying true to that initial formulation proved to be challenging and often forced students to rely on monitors. Finding adequate Pk required the retrieval from multiple sources. The more information was retrieved, the more conceptual knowledge grew as well as the ability to make queries for missing pieces of factual knowledge. However, time constraints limited retrieval. Synthesis of expected behaviors is therefore restricted to the retrieved knowledge. That would suggest an additional layer to Yu's superscript where a synthesis process (BeR > S) could be based either on external or internal knowledge. In terms of cognitive effort, Pk contains a free underlying synthesis process by providing the syntax for the algorithm. Analysis can also be free given the necessary information is supplied. Evaluation dictates whether the initial expected behavior is met or not and potentially leads to a subsequent R2 process. Therefore, the impact of displacement on the design process is mitigated by the amount of Pk retrieved. However, the lack of search effort after the initial formulation can lead to more displacement (see Fig. 6b). If the right information is given, Pk offers all the following processes for free: Formulation, synthesis and evaluation. Compared to R2 it also offers the formulation process for free. R3 can thus be triggered by the mental ease of Pk retrieval. Therefore, there could be an increase in the risk of displacement with the initial function.

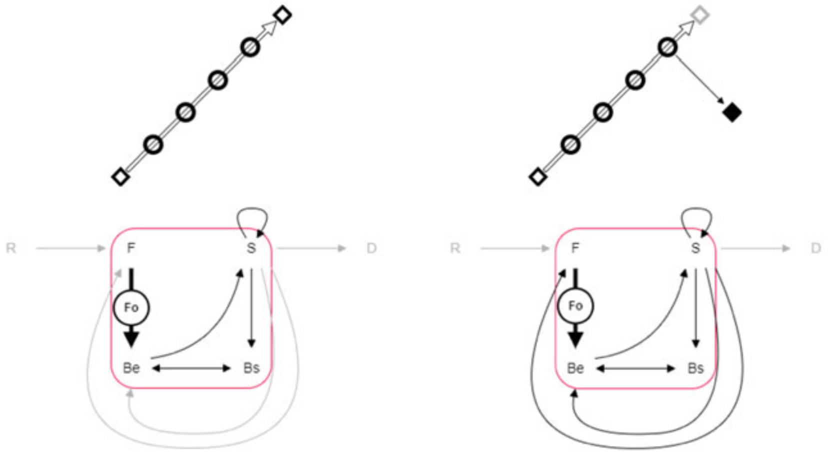
The second strategy relates to information-based ideation and affects the formulation process directly (see Fig. 6c, d). Ideation happens through the retrieved Pk without concerns for a more global conceptual knowledge to save effort and time. That Pk becomes a cognitive distribution device with the risk of architects falling into fixation and potential design displacement through what is called the worked example effect [26;27]. Even though there are advantages in education, the design of good, worked examples is challenging. Indeed, it requires the learner to put effort into integrating the knowledge rather than applying it directly as a completion problem (see Fig. 6c). This would shift the learning objective from "create" to "apply", which is described as a less complex task. Indeed, it is easier in terms of mental effort and therefore more prone to happen when saving mental load. Regarding FBS, this would translate into a cognitive free design process. Formulation as well as all subsequent processes would be integrated into the procedure and given the nature of PDEs, R1 would offer the possibility of design appropriation and thus the other reformulation processes wouldn't be considered. The other outcome would be to use Pk as a starting point and evolve from there either internally or using the first strategy of retrieval (see Fig. 6d). That behavior would be similar but would integrate further R2s and R3s. Either way, time constraint is the major factor for using the second strategy and would suggest integrating temporal pressure as a parameter in future studies.

Those strategies are not exclusive. There has been reconsideration across the different tasks but also during a single task. Taking the 1st strategy for example, the lack of information or experience in query can lead to mental overload and the adoption of strategy 2 without further reformulation. Moreover, flexible approaches to formulation have been mentioned to better accommodate the integration of retrieved



(a) Pk triggers R2. The initial function persists.

(b) Pk triggers R3. Function is influenced by the retrieved Pk



(c) Formulation and subsequent processes align with Pk

(d) Formulation aligns with Pk but reformulation 2 and 3 are still possible

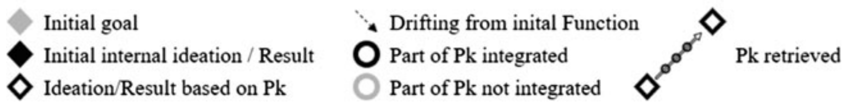


Fig. 6 Behaviors displayed in information retrieval strategy 1 (a, b) and retrieval strategy 2 (c, d)

Pk. This would indicate an initial loose formulation process to accommodate further R3. In that case only strategy one should be considered. Furthermore, retrieval can only happen if a query is made which would imply an initial formulation.

Conclusion and Further Research

Considering how fast software tools evolve and are created nowadays, architects are bound to rely on external information to keep up with their expertise. This phenomenon is accentuated in new complex computational tools such as parametric design environments. This paper proposes to integrate IIR and SAL into the FBS framework to study the impact of knowledge retrieval on the design process. To do so, we used a mixed approach using questionnaires and interviews to expose information retrieval strategies of graduate students in architecture. The participants had no previous experience with PDEs which fostered retrieval. The impact of procedural knowledge was of particular interest.

The paper shows that in a situation of autonomy, procedural knowledge is the preferred type of knowledge to search for learning while designing. The questionnaires and interviews suggest 2 strategies for knowledge retrieval: ideation support; and information-based ideation. The transcription of those results into the FBS model reveals procedural knowledge to have an impact on reformulation processes 2 and 3, commonly considered as triggers of innovation and creativity.

In summary, findings show that the retrieval of procedural knowledge can have a major impact on the design process. Methodology regarding quantitatively capturing behaviors should be investigated to support those results. The preliminary results also suggest the potential development of a superscript for the FBS model that would integrate IIR and SAL as part of the design process. There is an interest to further pursue that research into other digital tools for comparison and eventually in professional settings. In the future, we plan to implement theory on cognitive load and self-directed learning and to focus on video as a source as it was clearly demonstrated to be the preferred one.

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