ANALYZING THE SIGNIFICANCE OF PROBLEM SOLVING EXPERTISE AND COMPUTATIONAL TOOL PROFICIENCY IN DESIGN IDEATION

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ABSTRACT: This paper presents a pilot study to analyze the role of problem solving expertise (PSE) and computational tool proficiency (CTP) of expert and novice architects in the ideation process within a distributed cognition environment. To analyze PSE, we studied the frequency of occurrence of unique problem solving tasks per limited commitment mode (LCM) revisit. We also devised a quantitative measure for analyzing CTP based on the frequency of unique and normally distributed modeling activities per design process flows for a parametric modeling tool. In our study that involved freehand sketching and parametric modeling as two external representations used in the ideation process, we concluded that expert architects have higher levels of both PSE and CTP than novices.

KEYWORDS: Problem solving, distributed cognition, design ideation, parametric modeling, freehand sketching

RÉSUMÉ : Cet article présente une étude-pilote visant à analyser le rôle de l’expertise en résolution de problèmes (ERP), ainsi que celui des compétences numériques (CN) chez des experts et des novices pendant le processus d’idéation, dans le cadre d’un environnement de cognition distribuée. Pour analyser l’ERP, nous avons étudié la fréquence de la résolution d’une tâche unique pendant la révision en mode d’engagement limité. Nous avons aussi défini une mesure quantitative pour l’analyse des CN basée sur la fréquence des activités de modélisation uniques ou distribuées pendant le processus de design, et pour les outils paramétriques de modélisation. Au terme de cette étude, qui comprenait des esquisses à main levée ainsi que des modélisations paramétriques comme deux types de représentations externes pendant le processus d’idéation, il a été possible de conclure que les experts ont des niveaux plus élevés d’ERP et de CN que les novices.

MOTS-CLÉS : Résolution de problèmes, cognition distribuée, idéation, modélisation paramétrique, esquisse à main levée

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1. INTRODUCTION

The issue of cognitive processes in design problem solving activities between experts and novices has been widely discussed (Lawson 1979; Goldschmidt 1991; Akin and Lin 1995; Cross 2003). Cross (2004) defines expert strategies as relying on top-down and breadth-first approaches, while novice behavior usually has a ‘depth-first’ approach that relies on sequentially defining sub-solutions in depth. Experts can thus store and access information in larger cognitive chunks than novices, and focus on core principles rather than surface problem features.

This occurs when problem solving involves only one medium for externalizing design ideas, such as sketching (Goldschmidt 1991), or CAD (Bhavnani and John 2000). Studying more than one representation within the ideation process is significant in the context of distributed cognition (Hutchins 1995). In this context, we focus on cognitive processes distributed across external representations, where ideation is a result of not only designers’ minds, but also the interaction between designers and these representations, which are part of the designer’s extended mind.

In this study, we analyze activities in the ideation process across two representations; freehand sketching and parametric modeling. Parametric modeling has been used by designers at different design stages, including the ideation phase. Proficiency in using parametric modeling as a tool however is crucial in achieving the design task, as the level of proficiency is specific to the tool functions and attributes. The paper addresses the question: Does design problem solving expertise (PSE) and computational tool proficiency (CTP) affect the ideation process? Which is more significant? How can they be measured to reflect specific expertise in terms of problem solving or tool using abilities? How can we evaluate the process in a distributed cognition mode of integration between sketching and parametric modeling?

Using protocol analysis in our study, we focus on how both PSE and CTP can be inferred from activities of designers, taking into account how they perform problem solving tasks across representations. We also study how modeling activities are distributed and structured within design process flows. We describe how a parametric modeling environment can be viewed in terms of a design sketch. In this context, modeling activities can be considered similar to design moves in a freehand sketch, and different process flows would exist between these activities.

2. PROBLEM SOLVING EXPERTISE

Design problems in many disciplines are composed of large chunks that can be decomposed into modules and sub-modules (Cross 2004), allowing designers to develop problem solving strategies. We discuss one of these strategies;
the Limited Commitment Mode (LCM) control strategy (Goel 1995) and how we use it to infer expertise in design problem solving.

2.1. Redefining LCM control strategy

Goel (1995) defines the Limited Commitment mode (LCM) control strategy as a strategy that implies a level of expertise which does not require the designer to complete a specific module before beginning another one, but can rather “put that module on hold”, attend to other related or unrelated modules and go back to the first one later. Goel found that expert designers from many disciplines use this strategy in problem solving (Goel and Pirolli, 1989; Goel 1995). Kim et al. (2007) showed empirical data that experts use more LCM control strategy than student designers.

These studies relied only on designers’ verbal content. Goel segmented this content into meaningful components he defined as “topics of interest”. These are organized by what is known as the “attending order”. They represent ideas with specific content cues, syntactic cues and pauses. A designer is considered to be using LCM control strategy for some topic if he moves to another topic, putting the first one ‘on hold’, and revisits it in a later attending order. We believe it is crucial to consider the actual detailed activities rather than verbal data to accurately capture LCM control strategy.

2.2. Hypotheses and methodology

Our first hypothesis is that expert problem solvers would use more LCM control strategy than novices across all external representations. Second, we define a hierarchical structure for designers’ actions, regardless of the representation, to consist of three levels; detailed activities, higher level problem solving tasks and topics of interest. Detailed activities denote the lowest level that cannot be further decomposed. An activity here is specific to the type of representation. It can correspond to a pen stroke in sketching or a modeling command in parametric modeling.

Multiple activities that constitute a meaningful problem solving task are grouped together. In sketching, this can correspond to a group of strokes that define the boundary of a space. In parametric modeling, this can correspond to modeling commands that define a volume. Actions in this level are independent of the type of representation. Related tasks can be integrated to reflect a specific topic of interest for the designer. Defining the perimeter of an office space, its volume, color and materials are all tasks related to the same topic “office space”. The order of attention of these tasks within each topic determines the order and number of LCM revisits.

The third hypothesis is that the number of completed problem solving tasks in a session is not necessarily an indicator of PSE. The number of unique tasks
is more of an indicator, as they reflect the variety of methods the designer can use. A novice can perform many repeated tasks to achieve a solution, resulting in a solution space that lacks detail and diversity in data representation. For example, a novice can define a space boundary and extrude it to generate a volume. An expert however would incorporate a richer solution space for that same task (extruding boundaries, defining sectional profiles, assigning elevations and heights, assigning materials and glazing, etc.).

Although our focus is on ideation, we believe that the detail and variety expressed in the tasks early on illustrates deeper thinking and is a PSE indicator. Our approach in determining PSE thus involves the frequency of occurrence of two main factors along the process; LCM revisits, and unique problem solving tasks. The higher the frequency of unique problem solving tasks per LCM revisits for each topic is, the higher PSE is expected.

We organized the protocol data based on the LCM flow graph (Kim et al. 2007) to represent it textually and graphically. Many studies used graphs to visualize analyses of the design process (Goldschmidt 1990; Goel 1995; Kvan and Gao 2006). We use the LCM flow graph as it shows visually the location, order and frequency in the timeline where designers attended to topics of interest. The precise location and order of revisits in the LCM flow graph determine at which point the revisited topics occurred in relation to the representations. For quantitative analysis purposes, we developed a set of indices, serving as PSE indicators, which take into account problem solving tasks, unique tasks, LCM revisits, topics of interest and duration.

3. COMPUTATIONAL TOOL PROFICIENCY

Studies that deal with expertise in modeling activity focus on one of two aspects: iterative capabilities of tools at detailed levels (Bhavnani and John 2000), or how modeling aids problem solving at an abstract level (Akin and Moustapha 2004). We believe that CTP does not only lie in the knowledge of modeling commands but also in using it to structure and decompose design problems. With both aspects in mind, we explain what modeling activities imply in terms of design process flows. We draw on the idea of the design sketch; a platform of ideation that extends to include computational representations and where ideas are externalized in terms of processes.

3.1. Design process flows and modeling activities

In a previous study (Abdelmohsen and Do 2007), we devised a set of process flows to describe ideation development in sketching. We follow a similar approach to understand these process flows in the context of a parametric modeling environment. In doing so, we associated detailed modeling activities with concept development. We believe that parametric models embody a form
of semantically open design sketches (Chastain et al. 2002), which involves more concept exploration than solution description. This implies that designers would use parametric modeling tools reflectively to first ‘see’ then ‘move’ objects in a continuous process of reflection in action (Schön 1983). The functions, relations and constraints in parametric modeling provide many opportunities for continuous exploration, reflection and refinement.

3.2. Hypotheses and methodology

In this paper, our first hypothesis is that lateral and vertical transformations in the ideation process can be decomposed into further processes that can be inferred from detailed activities and the process flows between them. Here we adopt our previous definition in (Abdelmohsen and Do 2007), where promotion and propagation describe two classes of process flows in sketching. These denote processes that occur in successive design sketches; whether separate or traced (Figure 1). Promotion includes adding new elements (or strokes), or promoting them laterally or vertically for editing or emphasis purposes. Propagating strokes to the next sketch implies retaining a potential concept.

**FIGURE 1. REPRESENTING PROCESS FLOWS IN FREEHAND SKETCHING.**

The fundamental difference in parametric modeling lies in the definition of the term design sketch. The sketch here denotes one common platform for situating all activities that are internally linked through different views. This is in contrast to freehand sketching where interdependent activities are situated in multiple sketches. Modeling activities here include all types of objects such as lines, planes, pads, etc. In this integrated environment, designers can add, promote and propagate objects within the same sketch.
As shown in Figure 2, propagation includes adding, deleting or cross propagating objects. Drawing a new object or deleting it implies adding or removing an object (X) from the sketch, and thus adding or blocking a potential concept. Using an object as a reference for another instance denotes cross propagation into an object (Y), where (X) and (Y) become linked through cross propagation by reference. A potential concept is thus retained. Redefining the constraints or attributes of an object in a way that entails completely different characteristics (and consequently a possibly different concept) indicates a lateral promotion of an object (X) into an object (Y). Detailing or emphasizing an object (X) by e.g. assigning extrusion value, color or material indicates a vertical promotion of (X), thus reinforcing the potential concept embedded within that object.

**FIGURE 2. REPRESENTING PROCESS FLOWS IN PARAMETRIC MODELING.**

Our second hypothesis is that the number of modeling activities is not necessarily a CTP indicator. We believe that two factors control CTP; the frequency of occurrence of unique activities, and their distribution among process flows. Designers can perform many but inefficient activities. These activities can also be non-normally distributed among process flows. If designers focus on one class of activities, they do not make full use of tool capabilities (parametric edits, sketch references, etc.) A better scenario would consider more functionalities and a richer use of the representation. We thus define higher CTP as that which comprises normal distribution of unique modeling activities among process flows.

To evaluate CTP for subjects with different levels of expertise, we build on our study (Abdelmohsen and Do 2007) to develop a process flow graph. This graph shows visually the order and frequency where designers performed
processes along the flow of ideas. For the quantitative analysis, we used the Kolmogorov-Smirnov two-sample test (Siegel 1956) to acquire normal distribution values for unique activities, and to measure the significance of difference between their frequencies of occurrence.

4. PILOT STUDY

For this study, we used protocol data from the study by Sanguinetti and Abdelmohsen (2007) and analyzed it from a new perspective. Out of five participants, we selected two who were assumed to have the largest discrepancies in PSE and CTP. Both were graduate students in the design computing program at the college of architecture, and had undergraduate architecture degrees. Subject A was a teaching assistant for the Digital Project parametric modeling class, but had no professional experience. Subject B had both design teaching and professional experience and was assumed to have higher PSE. He was a student in the Digital Project class and so was assumed to have lower CTP.

The brief for the study included a main theater, 2 performance theaters, workshop studios, office spaces and seminar rooms. A special interest of the study was the use of parametric relations and constraints to stimulate the subjects to use specific functions of the tool within the problem solving process. They were asked to pay attention to 2 issues: describing the modular grid, and setting parametric relations between the building length and area of the performance theater. Figure 3 shows their final product.

**FIGURE 3. FINAL PRODUCT OF STUDY FOR SUBJECT A (LEFT) AND SUBJECT B (RIGHT).**

Both subjects sketched first then developed a parametric model. Subject A sketched the grid and main spaces in plan. He then did the same in parametric modeling and extruded the space boundaries. Subject B sketched the grid and masses in section. In parametric modeling, he created profiles for the structural frames and the main masses then extruded them and applied color and transparency. None of the subjects set parametric relations as required. Subject B, however, paid attention to the modular grid and used the frames as guidelines for the masses.
5. CODING SCHEME AND QUANTITATIVE ANALYSIS

We demonstrate here the analysis of PSE and CTP and their role in the ideation process. For each theme, we show the coding scheme, a graphical representation of the results, and quantitative analysis to evaluate the significance of both themes in ideation.

5.1. Problem solving expertise

The focus is to compare the frequency of occurrence of unique problem solving tasks per LCM activity for our subjects. This implies defining what we mean by LCM revisits, identifying tasks according to topics of interest, and extracting unique tasks that denote diversity in problem solving.

5.1.1. Constructing the coding scheme

We transcribed the protocol video segments into detailed activities. We recorded sketching activities such as “adding a new line” or “tracing previous” and modeling activities such as “assigning constraint” or “extruding pad”. We grouped the activities according to the different problem solving tasks defined by the subjects, such as “defining boundary” and “dividing space” in sketching, and “defining profile” and “defining volume” in modeling. These tasks were aggregated according to topics of common interest. Topics here denote the actual functional spaces defined by the subjects, such as the main theater, office, studio, etc.

Topics, problem solving tasks and unique tasks were coded according to their sequence in the session (Table 1). The codes in order were labeled T-X-n, H-X-n and U-X-n, where T denotes a topic, H denotes a task, U denotes a unique task, n denotes the serial number, and X denotes the subject. So H-B-02 for example is a problem solving task defined by subject B and it was introduced as the second task in the design session.

**Table 1. Extract from Coding Scheme for Tasks and Topics of Interest (Subject B).**

We recorded 127 tasks for subject A; 83 of which were in sketching, and 8 unique tasks. He performed activities in 8 topics while sketching, 3 of which
were not addressed later. For subject B, we recorded 124 tasks; 25 of which were in sketching, and 16 unique tasks. He performed activities in 5 topics while sketching, and addressed one more (the site plane) while modeling. We then added the order of attending and revisiting time for each topic. By revisiting, we mean any disjoint attending to the same topic. If the designer addressed topic T-A-02, moved to another one, then attended to T-A-02 (regardless of the task), the latter was recorded as the first revisit.

5.1.2. LCM flow graph

We adopt the LCM flow graph by Kim et al. (2007) and build a simpler version. Our graph maps unique tasks to the LCM revisits and topics. Revisits to a unique task are denoted by curved arrows from the last instance of the first topic to the first instance of the revisited topic which is circled. As shown in Table 2, an LCM strategy exists between attending 5 and 13 for topic T-B-03. The task in the revisit (defining space boundary) is a unique task. This is denoted by a curved arrow with a red circle at the first instance of the revisited topic. Another LCM control strategy is used between attending 13 and 17. The same task, however, is executed in the first instance of the revisited topic. The LCM revisit is thus denoted by a curved arrow with no circle at the end, indicating a non-unique task.

**TABLE 2. EXTRACT FROM LCM FLOW GRAPH FOR SUBJECT B.**

<table>
<thead>
<tr>
<th>TIME ORDER</th>
<th>UNIQUE HIGH LEVEL TASKS</th>
<th>CODE</th>
<th>TOPIC OF INTEREST</th>
<th>CODE</th>
<th>FLOW DIAGRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:01</td>
<td>Lay out main grid</td>
<td>U-B-01</td>
<td>Structural frames</td>
<td>T-B-01</td>
<td></td>
</tr>
<tr>
<td>0:15</td>
<td>Define boundary of space</td>
<td>U-B-02</td>
<td>Main theatre</td>
<td>T-B-02</td>
<td></td>
</tr>
<tr>
<td>1:44</td>
<td>Divide area of space</td>
<td>U-B-03</td>
<td>Performance theaters</td>
<td>T-B-03</td>
<td></td>
</tr>
<tr>
<td>2:36</td>
<td>Lay out main grid</td>
<td>U-B-01</td>
<td>Common area</td>
<td>T-B-05</td>
<td></td>
</tr>
<tr>
<td>3:02</td>
<td>Define boundary of space</td>
<td>U-B-02</td>
<td>Offices</td>
<td>T-B-04</td>
<td></td>
</tr>
<tr>
<td>3:18</td>
<td>Lay out main grid</td>
<td>U-B-01</td>
<td>Structural frames</td>
<td>T-B-01</td>
<td></td>
</tr>
<tr>
<td>4:28</td>
<td>Define boundary of space</td>
<td>U-B-02</td>
<td>Common area</td>
<td>T-B-05</td>
<td></td>
</tr>
<tr>
<td>4:29</td>
<td>Define boundary of space</td>
<td>U-B-02</td>
<td>Main theatre</td>
<td>T-B-02</td>
<td></td>
</tr>
</tbody>
</table>

5.1.3. Quantitative analysis

We calculated both the number of LCM revisits and unique tasks for each subject per representation. Subject A made 35 revisits for 8 topics of interest in 61 minutes; 34% of which were in parametric modeling. Subject B made 37 revisits for 6 topics in 57 minutes; 70% of which took place in parametric modeling. Subject A executed 8 unique tasks, 5 of which were in parametric modeling. Subject B performed 16 unique tasks, 12 of which were in parametric modeling. Most tasks for subject A involved defining the grid, space
boundaries in plan and volumes. Subject B executed additional tasks, including defining reference planes, sectional profiles, thicknesses and visual attributes. These generated a solution space richer in detail.

There was a difference in what revisits implied in terms of unique tasks for each subject. Subject B for example did not just define the boundary of spaces with simple extrusions or repeated commands, but went on to detail those by specifying elevations, adding external walls and partitions, and assigning color and transparency values. We thus needed to identify the number of unique tasks per LCM revisit per topic as a more accurate measure for PSE. This showed 21 unique tasks per LCM revisit for 8 topics of interest in 61 minutes for subject A, and 25 unique tasks per LCM revisit for 6 topics of interest in 57 minutes for subject B. We then identified a set of PSE indices (Table 3). Our main concern was to identify the average number of unique tasks per LCM revisit per topic and per duration. These were 2.63 and 0.34 for subject A, and 4.17 and 0.45 for subject B.

TABLE 3. INDICES OF PSE FOR SUBJECTS A AND B.

5.2. Computational Tool Proficiency

Our main focus for this study was to compare the frequency of occurrence of unique detailed activities per process flows for our subjects. This requires understanding what these process flows mean in parametric modeling, and describing unique activities that show diversity in using the tool proficiently.

5.2.1. Constructing the coding scheme

As per the hypothesis in section 3.2, we devised a scheme for process flows that consists of 2 types of flows: propagation and promotion. We subdivide propagation into 3 subtypes: propagation by adding (ADD), propagation by deleting (DEL), and cross propagation (CP). We subdivide promotion into 2 subtypes: lateral promotion (LP) and vertical promotion (VP).

ADD in parametric modeling refers to adding a new object in the sketch, such as creating a part or pad from scratch. DEL refers to deleting an object or cancelling a command. CP is where an object is referenced or copied to intro-
duce other objects, such as copying and pasting objects, or using reference planes for defining a sketch. LP refers to any act of editing parameters or constraints to indicate a shift of focus to a new object in the design. VP refers to retaining an object in the sketch without editing its main attributes, such as extruding a volume or assigning materials to an object.

5.2.2. Process flow graph

We constructed a graph that shows the time-stamped process flows between objects within each topic (Figure 4). In the graph, both unique and non-unique activities per topic can be identified. Subjects A and B developed two different strategies here. Subject A defined a sketch from a reference plane through CP. He drafted a rectangle through an ADD process and then performed 6 LPs, including 4 repeated commands for constraint assignment. He then performed 2 VPs to define space volume, followed by an LP to modify its height. This shows little diversity in using the commands across the process flows, due to the excessive use of LP processes in comparison to other processes, besides comprising mostly non-unique activities.

Subject B used ADD by adding a plane, then CP by taking a plane of reference for the sketch. He used ADD to define a sectional profile for the space. He defined the pad, extrusion and color of a volume using 4 unique VPs. Then he defined 2 LP processes by modifying a width attribute and an offset distance. The graph here is more condensed than subject A due to the uniqueness of activities per process flows which are more evenly distributed.

*FIGURE 4. AN EXTRACT FROM THE PROCESS FLOW GRAPH FOR SUBJECT B.*
5.2.3. Quantitative analysis

In parametric modeling, subject A made 42 unique activities out of 133 (32%). The largest fraction of unique activities per topic was the structural grid (36%) and per process was LP (52%). Subject B made 90 unique activities out of 226 (40%). The largest fraction of unique activities per topic was the main theater (28%), and per process was LP (31%).

As these were not strong CTP indicators, we used the Kolmogorov-Smirnov (KS) two-sample test to identify significant difference, where the subject with higher median for the number of unique activities per process flows was assumed to achieve higher CTP. A normal distribution of those activities would show higher integration within a process flow or topic, thus denoting more cohesion between commands to address the design issues.

We identified common topics that both subjects attended to: main theater space, performance theaters and office spaces. We conducted the KS test on the two datasets comprising 15 unique activities each. The test shows that the dataset of A is not normally distributed, where \( P = 0.09 \), the distribution has mean = 1.65 and standard deviation = 1.79. The dataset for B however is normally distributed, where \( P = 0.57 \), the distribution has mean = 3.07 and standard deviation = 2.10. This shows that B performed normally distributed unique activities, indicating proficiency in tackling the design problem via various modeling commands. The test also shows the maximum difference between cumulative frequency distributions (\( D \)) for A and B (Table 4).

<table>
<thead>
<tr>
<th>TABLE 4. CUMULATIVE FREQUENCY DISTRIBUTION DATA FOR A AND B (LARGEST DEVIATION OCCURS AT INTERVAL [1.00-2.00] AND [2.00-3.00] WITH MAXIMUM DIFFERENCE ( D = 7/15 )).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of total unique activities per process flows</td>
</tr>
<tr>
<td>St1a (X)</td>
</tr>
<tr>
<td>St1b (X)</td>
</tr>
<tr>
<td>St1a (X) - St1b (X)</td>
</tr>
</tbody>
</table>

The cumulative fraction plot (Figure 5) shows that values for unique activities of B are larger than A for the same cumulative fraction. The maximum difference in cumulative fraction is \( D = 13/15 - 6/15 = 7/15 \). According to the table of critical values of KD (numerator of D) in the KS two-sample test for small samples (\( n = <40 \)) (Siegel, 1956), when \( N = 15 \), a value of KD = 7 is significant at the \( \alpha = 0.05 \) level for a one-tailed test.
This indicates a significant difference between the unique activities per process flows for our subjects in favor of B (with the higher median). This demonstrates more proficiency for subject B in using a wider variety of modeling commands to achieve the required task within the design problem.

6. CONCLUSION AND IMPLICATION

In this study, we examined activities and process flows in the ideation process in a distributed cognition environment, and how they relate to PSE and CTP. We studied the role of LCM strategy in PSE, and process flows of modeling activities in CTP. Our results can be summarized as follows. First, expert problem solvers use LCM strategy more actively and frequently than novices regardless of tool proficiency. This was clear in revisits per duration, number of topics of interest, and number of problem solving tasks. Second, expert problem solvers perform unique tasks more frequently and efficiently than novices regardless of computational proficiency.

Third, expert problem solvers can maintain the ideas and topics they define in their solution space more than novices regardless of computational proficiency and no matter how far apart these topics are in the process. Novices tend to define more topics than they attend to in the final design product. Fourth, novices tend to perform prolonged activities and tasks to reach the same goal. This was observed in both sketching and parametric modeling despite their presumed high CTP level. Expert problem solvers tend to express more diversity and uniqueness of activities and tasks, especially in parametric modeling which holds the final product.

Finally, expert problem solvers demonstrate a normal distribution of modeling commands across process flows. Novices tend to pursue one line of process flows while disregarding others, and repeat many activities within one process flow. This is insignificant for the solution space, as laborious efforts are made to achieve a goal that can be attained easier and faster otherwise. Experts
act in a precise and diverse way, even if this entails leaving unfinished activities for later revisits with more fresh perspective.

According to the observations in this pilot study, expert problem solvers who may be less proficient computationally use their expertise to frame modeling commands in meaningful chunks of activities and tasks through specific strategies. They do not express proficiency only in problem solving but also in computational tool use eventually. Their counterparts, who lack problem solving expertise, could not use their knowledge of modeling commands to achieve better solutions. We conclude that PSE was seen to be more significant than CTP in the ideation process and in achieving richer design solutions regardless of the used external representation.

This study is just the beginning of a larger effort to analyze the ideation process. Extending it to include larger sample sizes with a wider spectrum of expertise and larger pool of external representations would allow for further exploration. Our methods in this study relied on recording and encoding design activities, and extracting them right off the external representation, unlike verbal analysis for example. We envision applications that use these methods to provide objective and tailored evaluation in educational contexts based on the ongoing ideation process rather than the final design product.

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