

Exploring the effect of a visual constraint on students' design cognition

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Abstract

This paper presents the results of a study that explores the effect of a visual constraint on design behaviors of architecture students. To examine this effect, twenty-four second-year architecture students volunteered to participate. Each of them undertook similar conceptual design briefs in two different conditions, one with and another without a visual constraint. Retrospective reporting was used to collect the verbalization of participants. The FBS ontology was used to model the design cognition of the participants by coding their design protocols. A dynamic analysis was used to study the differences between the two conditions based on the Problem-Solution index. A further index, the Pre-Structure–Post-Structure Index, was proposed to measure design behavior differences between the two conditions. Correspondence analysis was used to explore the effect of gender. We found statistically significant effects in design behavior of the visual constraint group, such as a decrease in behavior used before structure and also in the processes related to it. In the visual constraint condition, participants focused on both problem framing and solving from the beginning of design session and did not change this behavior during the session. They had almost the same attention to pre- and post-structure design processes during designing. The gender of participants had a statistically significant effect on their design behavior in the without visual constraint group. The distribution of design issues was not the same for male and female students. The order of experiencing the two design sessions did not have any statistically significant effect.

Keywords: *Visual constraint, design cognition, FBS ontology, Design students*

1 Introduction

1.1 Constraints in design Ideation

There is a dichotomy in using freedom or constraints in design ideation. Freedom provides conditions to explore new experiences without limitations (Tversky & Chou, 2011). Constraints are essential in design ideation in order to introduce the limitations related to situational realities of design problem (Clinton & Hokanson, 2012; Lawson, 2006). Constraints cover a broad range of concepts such as time, cost, social and organizational issues or seeing any representation that can be used for design solution (Onarheim, 2012) and can be classified as visual and non-visual. Since designing is situational, designers have interactions with the environment, which consists of different visual representations. They use the visual representations of others as well as their own representations, which are generated during designing.

Empirical studies of design behaviors show that visual constraints have important roles during design ideation and designers produce design solutions by interpreting those visuals (Purcell & Gero, 1992; Schon & Wiggins, 1992). Both students (novice designers) and experts generate design solution by using visual representations. Experts generate less drawings with more cognitive behavior related to interpretation of representations, while novices generate more drawings with less interpretations (Suwa & Tversky, 1997). This implies that experts thought about more different attributes of representations. Prompting designers to use representations during designing might affect their perception. The effect of visual representations on students' perception could change their interpretation of further representations (Webster, 2015). As such, students need more skill in interpreting representations during the ideation phase of design, which can be provided by prompting them through design practices with visual constraints (Casakin,

2010; Casakin & Goldschmidt, 2000; Fu, Cagan, & Kotovsky, 2010; Goldschmidt & Sever, 2011; Goldschmidt & Smolkov, 2006; Heylighen & Verstijnen, 2003).

In design education, constraints are presented in the design brief. Teachers provide design briefs generally in a form of text to explain the task statement for students (Hocking, 2014). A design brief describes a set of requirements related to the design task that needs to be followed. Any changes in design brief can influence design experiences and constraints in a design task could change participants' design behavior (Williams et al., 2013). Biskjaer, et al., (2019) showed that different levels of constraint have different effects. In their research, in each condition participants could choose different types of visual images as their source of inspiration. It was observed that low and high levels of constraints decreased the quality of design solutions. While the results suggested that each type of constraint can prompt participants to choose specific type of visual images, the effect of using a visual constraint on design cognition was not considered. In the next section the effect of different visual representations and their effects on design behavior are outlined.

1.2 Visual constraints and students' design behavior

There is design education research about the effect of visual constraints on students' design behavior. In some of these studies, participants could freely use different visual representations during their design process (Heylighen & Verstijnen, 2003; Ozkan & Dogan, 2013). The results show that provoking students to use visual constraints can influence their design behavior and improve the quality of their design solutions. In some studies, participants can choose from different types of visuals without any limitations, the visuals can have superficial or structural similarity to design problem. Participants prefer to use those examples with superficial similarity

(Heylighen & Verstijnen, 2003; Ozkan & Dogan, 2013); this means their design experiences would be limited by using limited types of visual representations.

Different types of visual representations can have different impacts on design behaviors, so the effect of each type has been explored (Linsey et al., 2008). In one research each group of participants was given different visual representations of a specific type (ambiguous and unambiguous) (Goldschmidt & Smolkov, 2006). Using a visual constraint in this situation could affect students' design performance, however they might not be inspired by visual representations when they are instructed to use images with structural similarities to their developing design.

Research has shown that instruction for using images caused more positive effects on design performance than using those images without any aids (Casakin, 2010; Casakin & Goldschmidt, 2000). In these experiments, participants could freely choose from different types of images and the instruction of using those visual representations led them to consider structural relationship between the given images and design solutions. However, it was not possible to observe the effect of each specific type of visual representation on their design behaviors.

There are studies which involve a constraint of a specific type of visual representation in the design process. In a research related to the effect of visual constraints (Fu et al., 2010), each of the two groups experienced one type of visual constraint. Results suggest that a visual constraint could improve the quality of design solutions or led participants to imitate some features of the given visuals for design solutions which had a negative effect on their design behavior. However, the focus of that research was on team convergence and quality of solutions, and the design behavior of individuals was not mentioned. A summary of related visual constraint research is shown in Table 1.

Table 1. A summary of recent research on visual constraint

| Study | Methods of visual constraint | Results |
|--|---|---|
| Heylighen & Verstijnen, 2003 | Participants could choose visual representations with superficial or structural similarity | Students preferred to choose visual representation with superficial similarity |
| Ozkan & Dogan, 2013 | | |
| Goldschmidt & Smolkov, 2006 | Each group of participants with specific type of visual representations | |
| Casakin, 2010 Casakin & Goldschmidt, 2000 | One group with instruction about using visual representations another group without instruction about using visual representations | Instruction about using visual representations lead participants to have a similar design behavior as experts |
| Fu et al., 2010 | Each group with one specific type of visual representation | Visual constraint could have negative or positive effect on students design behavior |

Since using a visual constraint could have a negative impact on participants' design behavior, the characteristics of visual representations that might prevent designers from this effect were investigated. It was suggested to use examples with remote association to any design solution (Purcell & Gero, 1992). In this condition, participants might be led to produce new knowledge which then would be used in design ideation, and prevent the example from be applied directly as a solution of the proposed problem (Goldschmidt, 2011). By using remote examples designers do not focus just on an existing set of behaviors and they may create new interpretations (Gero & Kannengiesser, 2012). Some concepts like ambiguity can facilitate new interpretations of a visual representation (Goel, 1995). An ambiguous image may affect the designers' reinterpretation (Ball, Ormerod, & Morley, 2004) and generate more novel ideas in comparison to a condition using a rich representation (Cardoso & Badke-Schub, 2011). It is not important that the ambiguous image lead to a specific design solution but to provide the insight to that representation, which would extend the range of possible designs of participants (Muth et al., 2015). Since architecture students are the participants an ambiguous image of an architectural layout was used (section 4.2).

The role of a visual constraint can be the same as an anchor which leads participants to search using the visual constraint as a starting point. Although multiple examples may motivate participants to think about different concepts and produce more innovative solutions, one example may direct them to a deep investigation of the visual representation which decreases the variety but increases the quality of the ideas (Sio et al., 2015).

There are other factors which might have an impact on a visual constraint experiment. If the participants of the control and experiment groups are the same, the order of experiencing the two conditions might affect their design behaviors. It means that participants use the knowledge of the first design task for the second design session. Bilda & Gero (2008) examined the order of carrying out two design sessions on the design behavior of participants. The time between the two design sessions was about one month. The order had no effect on their behavior (Bilda & Gero, 2008). Since visual constraints can be used in design education and the time between different design practices might be less than one month, the knowledge of the first designing activity might have an influence on the next design session. In other research in order to avoid the unintended effect due to temporal order, two different but relevant design problems were used (Camba et al., 2018; Chu et al., 2017). However, the time between the two design sessions was less than one month, which could affect design behaviors. So in this research, the effect of order on design behavior is investigated.

Gender is another factor which might affect design behavior, which can be measured through the distribution of cognitive effort. Gender can affect some types of spatial abilities (Newcombe et al., 1983). These abilities also can be used in problem solving. Different studies have produced inconsistent results on the effect of gender on the design behavior of students (Alelyani et al., 2017; Lu, 2015; Suits & Lagowski, 1994). Female and male students had different focuses on some types

of cognitive activities related to problem solving (Suits & Lagowski, 1994). They also had different tendencies toward solution-driven design cognition (Lu, 2015). However, in a more recent study the role of gender as an important factor which can change the design behavior was rejected (Alelyani et al., 2017). It should be considered that the tool which is used to measure the effect of gender is also important and could change the result (Newcombe et al., 1983), so there is a continuing need to study the effect of gender on design behavior.

In order to examine the effect of a visual constraint on students' design processes, the design behaviors of students are studied using protocol analysis. The verbalized data that indicate the participant's thoughts during the experiment is gathered and analyzed. Two types of reports can be used depending on when participants verbalize their thoughts. Participants can report their thoughts during the design session which is called "concurrent" or "think-aloud" protocol analysis or after finishing the design session which is called "retrospective" protocol analysis (Ericsson & Simon, 1993). While the think-aloud method is widely used there is still some debate about whether it might interfere the participants thinking activity (Chu et al., 2017). Retrospective reporting was used in this research.

2 Aims and Research Questions

The primary goal of the research reported in this paper is to explore further the effect of a visual constraint on the design cognition behaviors of students. The primary research question that motivates this work is:

- How does the design behavior of students vary when designing with and without a visual constraint?

The other questions which are investigated are:

- How does the order of design sessions, one with a visual constraint and the other without, affect students' design behavior when they experience two design sessions?

- Are there gender differences in design behaviors with and without a visual constraint?

In this research the three questioned are explored using statistical tests of the distributions of measured cognitive effort.

3 Method

3.1 Experiment Design

To examine the three research questions a two 2 x 2 within-participant experiment was set up. For each component of the experiment the first variable consisted of the two conditions: no visual constraint and visual constraint. The second variable consisted of the two conditions: the order of the two design sessions. The first experiment participants were all females and the second all males. Each group produced designs under each of the conditions. The experiment data collected through a protocol analysis consisted of videoed retrospective verbal reports and design sketches. The verbal data was coded and this coded data formed the basis of statistical testing for differences to determine support for the three hypotheses. Only 24 volunteers were available, which while satisfactory for an exploratory study, limits the generalizability of the results.

3.2 Protocol Analysis

Protocol analysis consists of the following sequential tasks:

Videoing of design session: participants sketching activities are videoed. After the experiment each participant has a 5-minute rest. Then each participant is asked to report on their thoughts while viewing the video of themselves designing along with their sketches. Each participant is asked to indicate on the video or the sketch what they are talking about. The process of reporting is videoed.

Transcription of utterances to text: Transcription of retrospective report consists of two steps: first, all the verbalizations of participants are transcribed (by the first author); second, since participants might not report design behaviors chronologically, each transcription is reviewed and modified to match the time sequence of the video.

Segmentation/coding the protocol: Segmentation consists of dividing the verbalization into smaller units, called segments, and assigning a code to each segment. Each segment should contain only one design issue (Kan & Gero, 2017). In this way the protocol is transformed into a sequential set of codes for later analysis. The processes of segmentation and coding are done simultaneously so that each segment contains only one code.

Arbitration of segmentation/coding: The process of segmentation and coding was carried out multiple times by a single coder (the first author). In order to increase the robustness of coding there was a ten day separation between the first and second segmentation and coding and other sessions were coded during those ten days to reduce the priming of the first coding (Kan & Gero, 2009). Then the two codings for each session were arbitrated. The arbitrated coding was used in all later analyses.

3.3 Coding Scheme

To test the three questions, the FBS ontology-based coding scheme was used in the protocol analysis (Kan and Gero, 2017). This coding scheme was chosen as it has been found to have been used by multiple other design cognition studies (Hamraz, Caldwell, Ridgman, & Clarkson, 2015) and has been used to code over 10,000 hours of designing in industry (Bott & Mesmer, 2019). The foundational papers for the FBS ontology (Gero, 1990; Gero and Kannengiesser, 2004) have been cited over 3,000 times (Google Scholar, June 15, 2019).

The coding scheme is based on three classes of ontological variables: function (F), behavior (B) and structure (S) (Gero, 1990). Function is the purpose of the artifact. Behavior can be expected to be exhibited by the structure or can be derived from structure, thus splitting behavior into two codes (Be and Bs). All external requirements are coded as R and the description is coded as D, Figure 1. Both R and D are expressible in F, B or S and do not require additional ontological classes.

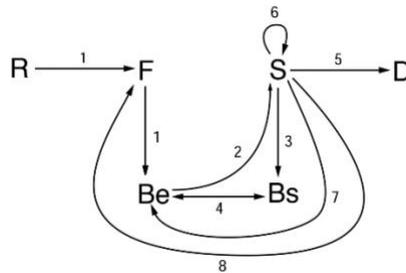


Figure 1. The FBS Ontology showing the six design issues and eight design processes (numbered),
 R=Requirement, F=Function, Be=Expected behavior, Bs=Structure behavior, S=Structure,
 D=Description, 1=Formulation, 2=Synthesis, 3= Analysis, 4=Evaluation, 5=Documentation,
 6=Reformulation 1, 7=Reformulation 2, 8=Reformulation 3 (Gero & Kannengiesser, 2014)

The six issues that map onto the codes are described and presented below:

- *Requirement (R)*: Derived from a brief which is given to designer.
- *Function (F)*: Purposes and goals of design.
- *Behaviors (Be, Bs)*: The attributes which can be expected from structure (Be) or derived from structure (Bs). In architecture light levels or circulation are examples of behavior.
- *Structure (S)*: The structure refers to object components and their relationships (Gero & Kannengiesser, 2004). In architecture the structures are spaces or the elements which construct the spaces.
- *Description (D)*: Any depiction of the design.

In each protocol there might be utterances that are not related to any of the six issues and they coded as “other” (O). The general statements about the method of design or architecture, participant’s intentions about their own future actions are coded as O).

It is assumed that different thinking activities during designing are related to each other, these activities in FBS ontology are associated with the six design issues, the transformation between two design issues is recognized as a design process. There could be different processes between various issues but eight of them are identified and measured. The eight processes, numbered in Figure 1, include (Gero & Kannengiesser, 1990):

- *Formulation*: To transform design requirements into functions and functions into expected behaviors (process 1, Figure 1)
- *Synthesis*: To produce a structure based on expected behavior (process 2)
- *Analysis*: To derive behavior from structure (process 3)
- *Evaluation*: To compare the behavior derived from structure to the expected behavior (process 4)
- *Documentation*: To describe the design externally (process 5)
- *Reformulation 1*: To reframe the structure state space (process 6)
- *Reformulation 2*: To reframe the behavior state space (process 7)
- *Reformulation 3*: To reframe the function state space (process 8)

Examples of design issues and processes are presented in Table 2. The distribution of cognitive effort is measured by the distribution of the coding variables derived from the FBS ontology (Gero & Kannengiesser, 2014; Kan & Gero, 2017).

Table 2. Examples of design issues and the processes of Evaluation (segment 105>106), Reformulation 3 (segment 127>128), Reformulation 2 (segment 174>175), Synthesis (segment 175>176), Reformulation 1 (segment 176>177), Documentation (segment 178>179), and Analysis (segment 182>183)

| Segment number | Code | Utterance |
|----------------|------|--------------------------------------|
| 27 | R | I am reading the required spaces |
| 105 | Bs | It is noisy |
| 106 | Be | But they need silence |
| 127 | S | I am designing audio visual space |
| 128 | F | I think it should have legibility |
| 174 | S | Here is the corridor |
| 175 | Be | Now some one wants to wash his hands |
| 176 | S | And this is a rest room |
| 177 | S | Here is the door |
| 178 | S | Also the class rooms |
| 179 | D | [drawing class rooms] |
| 182 | S | the door is not here |
| 183 | Bs | and has its own personality |

4 Experiment

4.1 Participants and Context

Twenty-four undergraduate architecture students from Shahid Bahonar University of Kerman volunteered. They were more experienced than first year students which could provide them the design skill and knowledge to use a visual constraint. They also had not have the experience of advanced students which might intervene in the process of using visual constraint. They were in second Semester and had passed all introductory design studio courses and started their first design experience in architecture design studio I. The subject of design studio I is related to designing an education building. The experiment was in the last month of the semester because participants had to have fundamental knowledge about the design brief (e.g., functions and behaviors) which was related to designing an education building. In order to choose participants, the experiment had been explained to teachers of that course and asked them to invite students, who were experienced in sketching, to volunteer.

Participants were instructed on the purpose of the research and their role. They also signed the written consent form. Half of them were male and half were female. Each participant received a gift of a book after completing the two design sessions.

Each participant executed two design tasks, one without any visual constraint (control) and the other with a visual constraint (experiment). Since participants of the two design sessions were the same, they were divided into two groups. One group did the constraint design session first and the other group did it second. The time between each design session was about seven days. First the process of the experiment was explained to each of the participants. Then they did a 5-minute pre-test for warm up. For the experiment group a simple pre-test was done by each participant in order to become familiar with designing with a visual constraint. The design brief was provided as a written document. Each participant had to read it and ask any questions before commencing designing. The time for each of design sessions was one hour. Each design task was conducted individually in the same closed room. An example of one of participant's resulting drawings is shown in Figure 2.

Site: Site dimension is 80*80m². Entrances to the building can be from the north and the south sides of the site.

List of spaces:

- 3 Office rooms (registration room, head of institute and one room for teachers), each room is about 20-30 m².
- 4 Studios (for computer, handicrafts, painting and maker space), each room is about 40-50 m².
- 2 Class rooms, each room is about 30-40 m².
- 2 WCs, each one about 10-15m².
- Staff WC and pantry about 10m².
- Storage about 15-20m².
- Gallery about 40-50 m².
- Multipurpose hall about 100-150m² (an extra entry is needed from outside).
- Entrance hall 40-50m².

Figure 3. Design brief of without visual constraint group (Control)

In the second design brief (experiment group) a task was added which was to use an ambiguous image of an architectural layout (Figure 4). The image related to the plan of “After-School Child Care Gistel” in Belgium which was designed by Xavier Nolf. The building had a similar function to the design task. An ambiguous image was produced based on the ground floor plan of that building and then a part of it was used in the experiment. Each participant had to interpret the image, add some of required spaces in it, and add structures for the remaining spaces.

You will be required to design an *institute for the intellectual development of children* according to a layout of an architectural plan which is presented below (Figure 1). Some parts can be added under the section line of the image.

Site: There is no limitation in dimensions of the site. So the building can be design in one or more levels. Entrances to the building can be from the north and the east sides of the site.

List of spaces:

- 4 Office rooms (registration room, head of institute and two others for staff), each room is about 20-30 m².

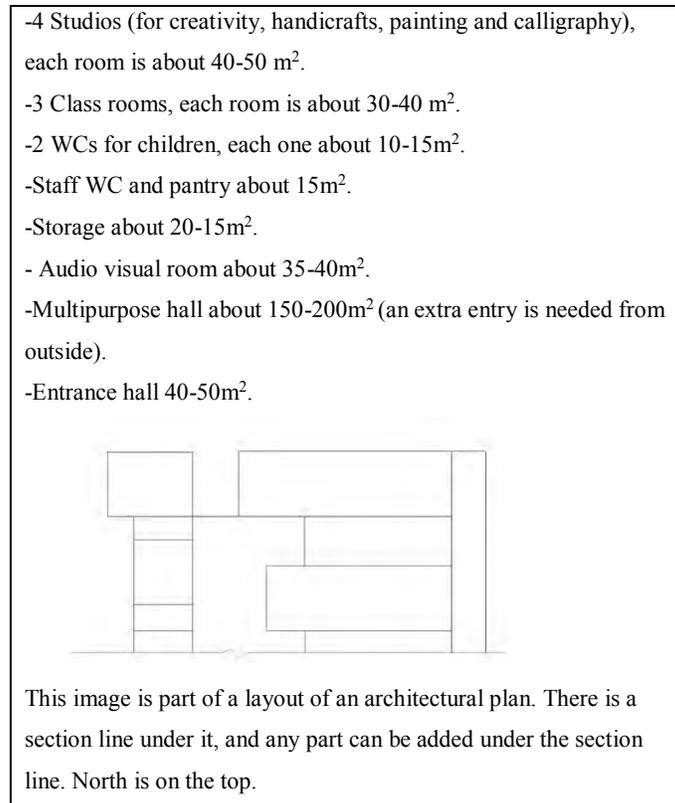


Figure 4. Design brief of visual constraint group (experiment)

5 Results and Analysis

All design sessions were coded twice and then arbitrated. To measure inter-rater agreement, Cohen's kappa coefficient was used (Cohen, 1960). There may be some issue about using Cohen's kappa with the arbitrated coding as these were not produced by an individual rater. However, that result is presented here. The agreement for codings 1 and 2, coding 1 and arbitrated result and coding 2 and arbitrated result were calculated. The average for each pair is presented in Table 3. The final protocols ranged from for 14 to 28 minutes of retrospective reporting and produced between 178 and 358 segments. The average for number of segments is 270.19 (SD=48.50) and the average report duration is 21.4 minutes (SD=3.95).

Table 3. Results of coding agreement Cohen's kappa coefficient

| | <i>Codings 1 & 2</i> | <i>Coding 2 & Arbitrated Result</i> | <i>Coding 1 & Arbitrated Result</i> |
|------|--------------------------|---|---|
| Mean | 0.87* | 0.91** | 0.84* |
| SD | 0.02 | 0.04 | 0.06 |

** Excellent agreement, * Strong agreement

LINKODER is protocol analysis software designed to perform a variety of quantitative analyses based on the FBS coding scheme (Pourmohamadi & Gero, 2011). The percentage occurrence for design issues and processes produced for all protocols and t-test was used to measure the differences (Kan & Gero, 2017). Two sample t-test provides robust results specifically for small sample size even if those are not normally distributed (Lumley et al., 2002). The effect of the visual constraint can be analyzed by measuring statistical distributions related to the different design issues and processes. In this paper three measurements based on the FBS coding distributions were applied. First each design issue and process was analyzed individually. Then at the meta level, the Problem-Solution (P-S) issue index was used to measure when participants focus on the problem or the solution (Section 5.3). A further index was proposed to measure the effect of the given layout in the visual constraint by comparing the behaviors related to pre- and post-structure (Section 5.3). Finally, a correspondence analysis was carried out to investigate the qualitative relationships of the variable categories.

5.1 Syntactic Design Issues

The percentage occurrence of design issues for the control (without visual constraint) and experiment group (with visual constraint) are presented in Figure 5. The means of issues for each group are presented in Table 4. The results indicate that there is a significant difference in the distribution of cognitive effort spent on expected behavior only. This result implies that when participants design with a visual constraint they focus less on expected behavior. From the results

shown in Table 4, it can be seen that there are no significant differences between the distributions of structure and structure behavior related to visual and non-visual conditions which means the visual constraint did not affect the cognitive focus on these issues.

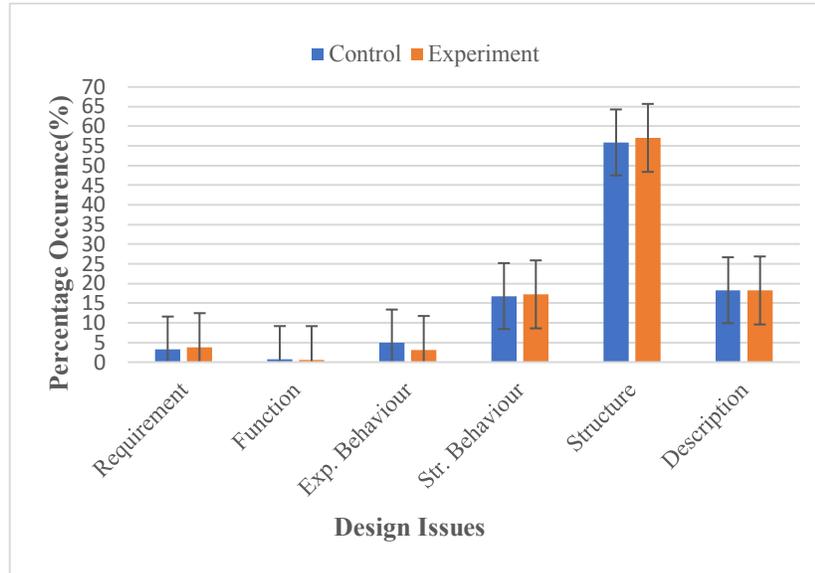


Figure 5. Percentage occurrences of design issues for control and experiment groups

Table 4. Means, standard deviations and results of t-test of design issues for control and experiment groups

| <i>Design Issues</i> | <i>Control Group Mean (SD)</i> | <i>Experiment Group Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|--------------------------------|-----------------------------------|---------------------------|------------------------|----------------|
| R | 3.22(0.169) | 3.83(1.36) | 46 | -1.361 | 0.180 |
| F | 0.80(0.35) | 0.52(0.41) | 46 | - | ¹ |
| Be | 5.00(1.55) | 3.10(1.24) | 46 | 4.678 | <0.001* |
| Bs | 16.82(3.89) | 17.25(4.94) | 46 | -0.334 | 0.740 |
| S | 55.89(4.41) | 57.05(5.41) | 46 | -0.813 | 0.421 |
| D | 18.29(3.70) | 18.24(5.09) | 46 | 0.039 | 0.969 |

¹Insufficient data for analysis, * $p < 0.01$

The effect of order of tasks on distributions of design issues was measured. Group A was exposed to the visual constraint in their second design session and group B was exposed to it in their first session. The means and standard deviations of two design sessions for group A and B are presented

in Tables 5 and 6. It can be observed that there are no significant differences between the groups, which means that the order of design tasks does not affect the distribution of design issues.

Table 5. Means, standard deviations and results of t- test of design issues for without visual constraint group

| <i>Design Issues</i> | <i>Group A Mean (SD)</i> | <i>Group B Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|--------------------------|--------------------------|---------------------------|------------------------|----------------|
| R | 3.64(1.91) | 2.80(1.41) | 22 | -1.230 | 0.232 |
| F | 0.77(0.38) | 0.83(0.32) | 22 | - | ¹ |
| Be | 5.11(1.53) | 4.89(1.62) | 22 | 0.337 | 0.740 |
| Bs | 17.82(3.60) | 15.82(4.06) | 22 | 1.276 | 0.215 |
| S | 55.82(4.74) | 55.96(4.24) | 22 | -0.077 | 0.939 |
| D | 16.88(2.28) | 19.70(4.38) | 16.55 | -1.976 | 0.065 |

¹*Insufficient data for analysis*

Table 6. Means, standard deviations and results of t- test of design issues for visual constraint group

| <i>Design Issues</i> | <i>Group A Mean (SD)</i> | <i>Group B Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|--------------------------|--------------------------|---------------------------|------------------------|----------------|
| R | 3.95(1.52) | 3.70(1.24) | 22 | 0.441 | 0.664 |
| F | 0.46(0.43) | 0.58(0.40) | 22 | - | ¹ |
| Be | 3.03(0.45) | 3.18(0.88) | 22 | -0.305 | 0.763 |
| Bs | 16.39(5.49) | 18.10(4.39) | 22 | -0.849 | 0.409 |
| S | 58.86(6.17) | 55.23(4.00) | 22 | 1.707 | 0.102 |
| D | 17.31(5.75) | 19.18(4.39) | 22 | -0.894 | 0.381 |

¹*Insufficient data for analysis*

The effect of gender on the distribution of design issues was measured. The results of 12 male participants were compared to those of the 12 female participants for each of design sessions. The means and their standard deviations are presented in Tables 7 and 8. The results show that gender does not alter the distribution of design issues. Comparison between the results of design issues

indicates that the order of design sessions and gender have no effect on the distributions of design issues.

Table 7. Means, standard deviations and results of t- test of design issues for without visual constraint group

| <i>Design Issues</i> | <i>Female students Mean (SD)</i> | <i>Male students Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|----------------------------------|--------------------------------|---------------------------|------------------------|----------------|
| R | 2.95(1.68) | 3.49(1.74) | 22 | -0.776 | 0.446 |
| F | 0.67(0.28) | 0.93(0.37) | 22 | - | ¹ |
| Be | 4.91(1.84) | 5.09(1.52) | 22 | -0.285 | 0.779 |
| Bs | 17.07(1.24) | 16.57(1.05) | 22 | 0.309 | 0.761 |
| S | 57.01(4.16) | 54.77(4.54) | 22 | 1.261 | 0.221 |
| D | 17.42(3.21) | 19.17(1.18) | 22 | -1.166 | 0.256 |

¹*Insufficient data for analysis*

Table 8. Means, standard deviations and results of t-test of design issues for visual constraint group

| <i>Design Issues</i> | <i>Female students Mean (SD)</i> | <i>Male students Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|----------------------------------|--------------------------------|---------------------------|------------------------|----------------|
| R | 3.29(1.16) | 4.36(1.39) | 22 | -2.043 | 0.053 |
| F | 0.47(0.36) | 0.58(0.47) | 22 | - | ¹ |
| Be | 2.73(0.83) | 3.48(1.50) | 22 | -1.498 | 0.148 |
| Bs | 17.23(5.34) | 17.26(4.74) | 22 | -0.012 | 0.990 |
| S | 57.33(4.23) | 56.77(6.58) | 18.75 | 0.247 | 0.807 |
| D | 18.93(6.11) | 17.56(3.99) | 22 | 0.649 | 0.523 |

¹*Insufficient data for analysis*

5.2 Syntactic Design Processes

In this analysis, it is assumed that each segment is related to the one preceding it. This relation is a transformation from one issue to another which identifies a design process. The percentage occurrences of design processes for control and experiment groups are presented in Figure 6.

Means and standard deviations of design processes are presented in Table 9. Significantly less cognitive effort was focused by the experiment group than the control group on synthesis and on reformulation 2 And a near significant effect was found related to evaluation.

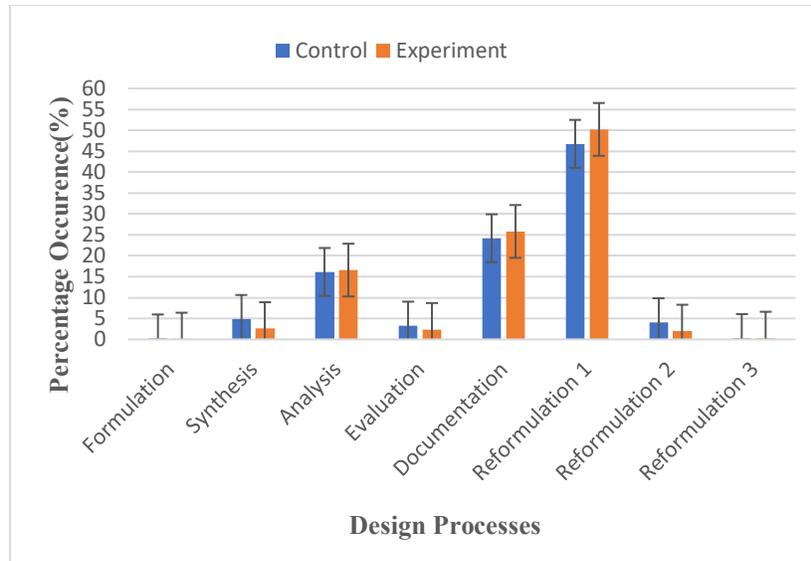


Figure 6. Percentage occurrences of design processes for control and experiment groups

Table 9. Means, standard deviations and results of t- test of design processes for control and experiment Groups

| <i>Design processes</i> | <i>Control Group Mean(SD)</i> | <i>Experiment Group Mean(SD)</i> | <i>Degree of freedom</i> | <i>t(z) statistic</i> | <i>p-value</i> |
|-------------------------|-------------------------------|----------------------------------|--------------------------|-----------------------|----------------|
| Formulation | 0.25(0.38) | 0.08(0.21) | 35.63 | - | ¹ |
| Synthesis | 4.90(1.75) | 2.58(1.18) | 46 | 5.405 | <0.001* |
| Analysis | 16.13(4.02) | 16.58(5.41) | 46 | -0.321 | 0.750 |
| Evaluation | 3.31(1.93) | 2.39(1.68) | 46 | -1.916 | 0.055 |
| Documentation | 24.19(6.81) | 25.81(8.17) | 46 | -0.747 | 0.459 |
| Reformulation 1 | 46.75(7.18) | 50.20(8.37) | 46 | -1.533 | 0.132 |
| Reformulation 2 | 4.12(1.80) | 1.98(1.11) | 38.25 | 4.940 | <0.001* |
| Reformulation 3 | 0.33(0.44) | 0.30(0.39) | 46 | - | ¹ |

¹Insufficient data for analysis, * $p < 0.01$

The distribution of design processes for with and without visual constraint groups were studied by comparing the averages of Groups A and B. The significance for each design processes was calculated, Tables 10 and 11. Since amongst all the processes there is only one that is significantly different, reformulation 2 in Table 11, the order of design sessions have a very small effect on the distribution of design processes between these two groups.

Table 10. Means, standard deviations and results of t- test of design processes for without visual constraint group

| <i>Design processes</i> | <i>Group A Mean (SD)</i> | <i>Group B Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|-------------------------|--------------------------|--------------------------|---------------------------|------------------------|----------------|
| Formulation | 0.15(0.28) | 0.34(0.46) | 18 | - | ⁻¹ |
| Synthesis | 5.20(2.19) | 4.61(1.19) | 16.95 | 0.823 | 0.422 |
| Analysis | 15.96(3.61) | 16.30(4.55) | 22 | 0.209 | 0.836 |
| Evaluation | 3.52(2.15) | 2.68(1.42) | 22 | -0.235 | 0.814 |
| Documentation | 22.12(3.65) | 26.27(8.61) | 14.81 | -1.537 | 0.145 |
| Reformulation 1 | 48.83(7.75) | 44.68(6.18) | 22 | 1.454 | 0.160 |
| Reformulation 2 | 4.03(1.71) | 4.21(1.96) | 22 | -0.244 | 0.809 |
| Reformulation 3 | 0.23(0.34) | 0.44(0.51) | 22 | - | ⁻¹ |

¹*Insufficient data for analysis*

Table 11. Means, standard deviations and results of t- test of design processes for visual constraint group

| <i>Design Issues</i> | <i>Group A Mean (SD)</i> | <i>Group B Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|--------------------------|--------------------------|---------------------------|------------------------|----------------|
| Formulation | 0.11(0.26) | 0.04(0.14) | 22 | - | ⁻¹ |
| Synthesis | 2.43(1.40) | 2.73(0.94) | 22 | -0.598 | 0.556 |
| Analysis | 16.28(6.46) | 16.87(4.39) | 22 | -0.259 | 0.798 |
| Evaluation | 2.59(1.63) | 2.18(1.77) | 22 | 0.589 | 0.562 |
| Documentation | 23.75(8.68) | 27.88(7.40) | 22 | -1.252 | 0.224 |
| Reformulation 1 | 52.84(9.55) | 47.57(6.33) | 19.06 | 1.594 | 0.127 |
| Reformulation 2 | 1.53(1.20) | 2.43(0.84) | 22 | -2.135 | 0.044* |
| Reformulation 3 | 0.30(0.41) | 0.30(0.39) | 22 | - | ⁻¹ |

¹*Insufficient data for analysis, *p < 0.05*

To determine further any effect of order, the results of two design sessions were studied for Groups A and B. The results, Tables 12 and 13, show that synthesis and reformulation 2 are significantly different for both groups. This result is similar to the result of Table 9, implying that the order of experiment has an influence on the distributions of cognitive effort on design processes between control and experiment groups.

Table 12. Means, standard deviations and results of significance tests of design processes for control and experiment groups (Group A)

| <i>Design processes</i> | <i>Control Group Mean (SD)</i> | <i>Experiment Group Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|-------------------------|--------------------------------|-----------------------------------|---------------------------|------------------------|----------------|
| Formulation | 0.15(0.28) | 0.11(0.26) | 22 | - | - ¹ |
| Synthesis | 5.20(2.19) | 2.43(1.40) | 18.72 | 3.688 | 0.002* |
| Analysis | 15.96(3.61) | 16.28(6.47) | 22 | -0.152 | 0.881 |
| Evaluation | 3.52(2.15) | 2.59(1.63) | 22 | 1.187 | 0.248 |
| Documentation | 22.12(3.65) | 23.75(8.68) | 14.76 | -0.601 | 0.557 |
| Reformulation | 48.83(7.75) | 52.84(9.55) | 22 | -1.129 | 0.271 |
| 1 | | | | | |
| Reformulation | 4.03(1.71) | 1.53(1.20) | 22 | 4.142 | <0.001* |
| 2 | | | | | |
| Reformulation | 0.23(0.34) | 0.30(0.41) | 22 | - | - ¹ |
| 3 | | | | | |

¹Insufficient data for analysis, * $p < 0.01$

Table 13. Means, standard deviations and results of significance tests of design processes for control and experiment groups (Group B)

| <i>Design processes</i> | <i>Control Group Mean(SD)</i> | <i>Experiment Group Mean(SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|-------------------------|-------------------------------|----------------------------------|---------------------------|------------------------|----------------|
| Formulation | 0.34(0.46) | 0.04(0.14) | 13.16 | - | - ¹ |
| Synthesis | 4.61(1.19) | 2.73(0.94) | 22 | 4.308 | <0.001* |
| Analysis | 16.31(4.55) | 16.87(4.39) | 22 | -0.306 | 0.762 |
| Evaluation | 3.10(1.76) | 2.18(1.77) | 22 | 1.274 | 0.216 |
| Documentation | 26.27(8.61) | 27.88(7.40) | 22 | -0.491 | 0.629 |
| Reformulation | 44.68(6.18) | 47.57(6.33) | 22 | -1.132 | 0.270 |
| 1 | | | | | |
| Reformulation | 4.21(1.96) | 2.43(0.84) | 22 | -2.881 | 0.009** |
| 2 | | | | | |
| Reformulation | 0.44(0.52) | 0.30(0.39) | 22 | - | - ¹ |
| 3 | | | | | |

¹Insufficient data for analysis, * $p < 0.01$, ** $p < 0.05$

To measure the effect of gender on students' design behavior, the design processes of 12 males and 12 females were analyzed for the two design sessions, Tables 14 and 15. Of all the design processes the only significant difference was found in the visual constraint group, for synthesis, Table 15. So gender has a small effect on the distribution of cognitive effort between females and males, given that the effect is on synthesis, which is a small percentage of all the design processes.

Table 14. Means, standard deviations and results of significance test of design processes for without visual constraint group (Female & Male participants)

| <i>Design Issues</i> | <i>Female students Mean (SD)</i> | <i>Male students Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|--------------------------------------|------------------------------------|---------------------------|------------------------|----------------|
| Formulation | 0.27(0.44) | 0.23(0.34) | 22 | - | ⁻¹ |
| Synthesis | 4.72(1.58) | 5.09(0.37) | 22 | -0.517 | 0.610 |
| Analysis | 16.58(4.99) | 15.69(2.91) | 22 | 0.530 | 0.601 |
| Evaluation | 3.51(2.04) | 3.11(1.89) | 22 | -0.498 | 0.623 |
| Documentation | 22.42(5.47) | 25.97(7.75) | 22 | -1.296 | 0.208 |
| Reformulation 1 | 48.51(6.41) | 45.00(7.73) | 22 | 1.210 | 0.239 |
| Reformulation 2 | 4.14(1.88) | 4.09(1.81) | 22 | 0.067 | 0.948 |
| Reformulation 3 | 0.24(0.37) | 0.43(0.50) | 22 | - | ⁻¹ |

¹*Insufficient data for analysis*

Table 15. Means, standard deviations and results of significance test of design processes for visual constraint group (Female & Male participants)

| <i>Design Issues</i> | <i>Female students Mean (SD)</i> | <i>Male students Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistic</i> | <i>p-value</i> |
|----------------------|--------------------------------------|------------------------------------|---------------------------|-----------------------|----------------|
| Formulation | 0.00(0.00) | 0.15(0.28) | 11 | - | ⁻¹ |
| Synthesis | 2.07(0.81) | 3.10(1.29) | 22 | -2.330 | 0.029* |
| Analysis | 17.13(7.10) | 16.03(4.83) | 22 | 0.490 | 0.629 |
| Evaluation | 1.97(1.08) | 2.81 (2.07) | 16.60 | -1.246 | 0.230 |
| Documentation | 27.31(9.30) | 24.32(6.93) | 22 | 0.893 | 0.381 |
| Reformulation 1 | 49.28(8.07) | 51.13(8.92) | 22 | -0.530 | 0.601 |
| Reformulation 2 | 1.83(1.02) | 2.14(1.22) | 22 | -0.691 | 0.497 |
| Reformulation 3 | 0.38(0.44) | 0.22(0.33) | 22 | - | ⁻¹ |

¹*Insufficient data for analysis, *p < 0.05*

The effect of gender on distribution of design processes was further studied by separately comparing the result of the two design sessions for the female and male participants. Tables 16 and 17 show the differences between control and experiment groups based on gender of participants. The result indicates that for both male and female students the significant differences are for synthesis and reformulation 2 and follows the result of with and without visual constraint experiment shown in Table 9. Therefore, gender has a small effect on control and experiment groups.

Table 16. Means, standard deviations and results of significance test of design processes for control and experiment groups (Female participants)

| <i>Design Issues</i> | <i>Control Group Mean (SD)</i> | <i>Experiment Group Mean (SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|------------------------------------|---------------------------------------|-----------------------------------|----------------------------|----------------|
| Formulation | 0.26(0.44) | 0.00(0.00) | 11 | - | ⁻¹ |
| Synthesis | 4.72(1.58) | 2.07(0.81) | 16.43 | 5.165 | <0.001* |
| Analysis | 16.58(4.99) | 17.13(6.10) | 22 | -0.242 | 0.881 |
| Evaluation | 3.11(1.89) | 1.97(1.08) | 22 | 1.818 | 0.087 |
| Documentation | 22.42(5.47) | 27.31(9.30) | 22 | -1.570 | 0.134 |
| Reformulation 1 | 45.00(7.73) | 49.28(8.07) | 22 | -1.327 | 0.198 |
| Reformulation 2 | 4.14(1.88) | 1.83(1.02) | 22 | 3.757 | 0.001* |
| Reformulation 3 | 0.24(0.37) | 0.38(0.44) | 22 | - | ⁻¹ |

¹Insufficient data for analysis, * $p < 0.01$

Table 17. Means, standard deviation and results of significance test of design processes for control and experiment groups (Male participants)

| <i>Design Issues</i> | <i>Control Group Mean(SD)</i> | <i>Experiment Group Mean(SD)</i> | <i>Degrees of freedom</i> | <i>t(z) statistics</i> | <i>p-value</i> |
|----------------------|-----------------------------------|--------------------------------------|-----------------------------------|----------------------------|----------------|
| Formulation | 0.23(0.34) | 0.15(0.28) | 22 | - | ⁻¹ |
| Synthesis | 5.09(1.95) | 3.09(1.29) | 22 | 2.961 | 0.007* |
| Analysis | 15.69(2.91) | 16.03(4.83) | 22 | -0.205 | 0.840 |
| Evaluation | 3.51(2.04) | 2.81(2.07) | 22 | 0.834 | 0.413 |
| Documentation | 25.97(7.75) | 24.32(6.93) | 22 | 0.550 | 0.588 |
| Reformulation 1 | 45.00(7.73) | 51.13(8.92) | 22 | -1.798 | 0.086 |
| Reformulation 2 | 4.09(1.81) | 2.14(1.22) | 22 | 3.103 | 0.005* |
| Reformulation 3 | 0.43(0.50) | 0.22(0.33) | 22 | - | ⁻¹ |

¹Insufficient data for analysis, * $p < 0.01$

5.3 Meta-level analysis

P-S Index

The distribution of cognitive effort can be compared using a different scale. In this method the results of FBS coding are divided into two categories and then compared. The first category measures the ratio of cognitive effort expended on the problem to that on the solution, which is called the Problem-Solution Index (Jiang et al., 2014). Based on the FBS model, Figure 1, requirement, function and expected behavior are related to the problem space. Structure and the

behavior which is derived from a structure are related to the solution space. The problem to solution issues index measure is the ratio of cognitive effort of problem to cognitive effort of solution. The equation is:

$$\begin{aligned}
 &P - S \text{ Issue Index} && (1) \\
 &= \frac{\text{Requirement} + \text{Function} + \text{Expected Behavior}}{\text{Structure} + \text{Structure Behavior}}
 \end{aligned}$$

Design processes also can be classified into those which focus on problem framing or problem solving. formulation, reformulation 2 and reformulation 3 are transformations belong to problem space. Analysis, evaluation, synthesis and reformulation 1 are design processes that belong to the solution space. To measure the P-S index for FBS design processes the following equation is used, Equation (2):

$$\begin{aligned}
 &P - S \text{ process Index} && (2) \\
 &= \frac{\text{Formulation} + \text{Reformulation 2} + \text{Reformulation 3}}{\text{Analysis} + \text{Evaluation} + \text{Synthesis} + \text{Reformulation 1}}
 \end{aligned}$$

Designing is a dynamic process so the P-S index is explored temporally. Each protocol is divided into time quintiles. For each quintile an independent calculation for P-S issue index and P-S process index is carried out, then the results of each group are averaged. The sequence of the five averages can provide knowledge about the dynamic behavior of each group. By plotting the results of each group, the changes in P-S indices during designing are presented. The graphs produce knowledge for a qualitative comparison of two cohorts based on the problem-solution index.

The P-S issue index graph for control and experiment groups is shown in Figure 7. It can be observed that the control group spent more time on the problem in the first and last quintiles of the design session than the experiment group.

The P-S process index was calculated and plotted in Figure 8. The graph for the experiment group is nearly horizontal with only a small change in slope across time. For the control group, there are

large changes across the design session and they have a different temporal behavior from the experiment group. During design sessions for all quintiles except the third, the control group has higher P-S process index values, which means that participants spent more time framing the problem than the experiment group. The two groups have different distributions of cognitive effort related to problem framing and solving. While in the control group the focus on problem and solution is changed during designing, in the experiment group the ratio of focus on problem and solution is near invariant during the design session.

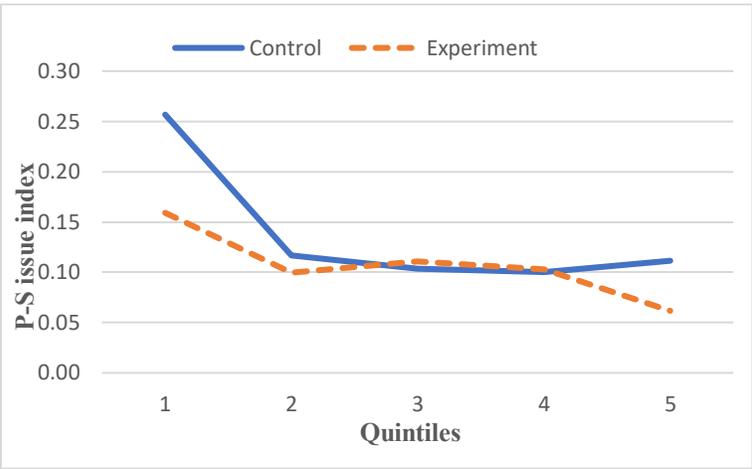


Figure 7. P-S issue index for control and experiment groups in quintiles

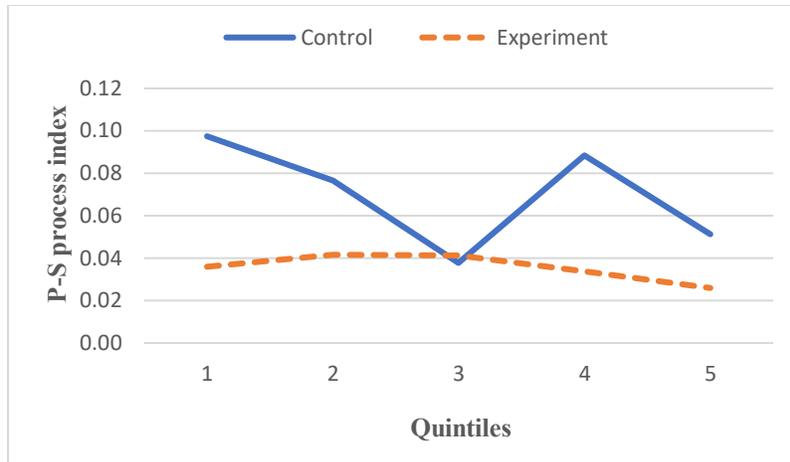


Figure 8. P-S Process Index for control and experiment groups in quintiles

P-P Index

In the FBS coding scheme the processes which can be derived from an existing structure are: analysis (S>Bs), reformulation 1 (S>S), reformulation 2 (S>Be), and reformulation 3 (S>F), Figure 1. Another process which might be linked to an existing structure but does not directly relate to it is evaluation. This process would only be used after a structure behavior is generated by analysis. Formulation and synthesis are processes which are not used for reasoning about an existing structure but to generate a new structure. By formulation, a function can be produced, and a function can also be transformed to an expected behavior in a formulation process. In synthesis, a structure is produced through an expected behavior. In order to measure the impact of a visual constraint on students' design behavior, the FBS-based design processes can be categorized into those which are used before a structure is generated, and those which occur after a structure is produced. Each of the two groups of processes are iteratively repeated during design ideations. The processes relating to an existing structure can be connected to problem or solution space. While reformulations 2 and 3 can be used for problem framing, problem solving is related to analysis, reformulation 1 and evaluation.

To study the effect of visual constraint on the distribution of cognitive effort, the two categories can be measured for the control and experiment groups. A dynamic process which measures the changes of design behaviors is used to understand how and when the visual constraint affects the distribution of cognitive effort related to structure. A simple measurement is proposed: a ratio that computes the total occurrences of the cognitive effort concerned with pre-structure to those which are post-structure. The Pre-structure–Post-structure (P-P) Index, equation (3) is:

$$P - P \text{ Index} = \frac{\text{Formulation} + \text{Synthesis}}{\text{Analysis} + \text{Evaluation} + \text{Reformulation1} + \text{Reformulation2} + \text{Reformulation3}} \quad (3)$$

P-P index averages for the two groups across quintiles is shown in Figure 9. The control group has an average negative slope through the session which shows that the processes associated with generating structure are high in the beginning but decrease during the design session. The slope for the experiment group shows very small changes during design session which suggests that both types of processes are unchanged during the design session. Comparing the values of P-P index of the two groups shows that participants in the control group spent more time on producing structure than the experiment group. The difference between the two groups narrows over time.

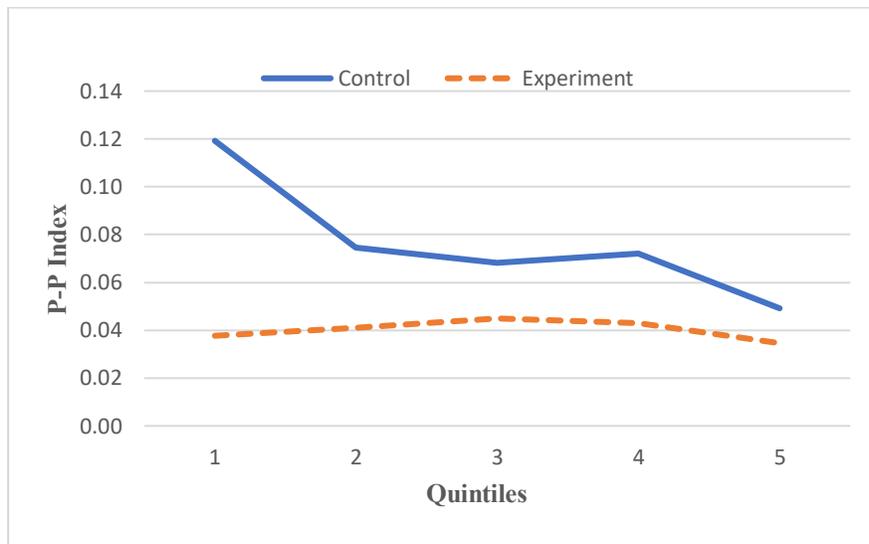


Figure 9. P-P Index for control and experiment groups

5.4 Correspondence Analysis

Multiple correspondence analysis is used to determine qualitative relationships between the five categories of: males with and without the visual constraint, females with and without the visual constraint and all participants. In this method the variables are illustrated by points in a two-dimensional graph where their locations are used to determine the relationships between the categories. The results are shown in Figure 10, where the two axes refer to dimensions in hyperspace rather than dimensions in terms of variables in the experiment. The percentages on the axes refer to the amount of data variance covered. Here the coverage at 87.59% is high. The locations of the categories males in both control and experiment groups as a single category and all females in both control and experiment groups as a single category are on opposite sides in Dimension 2 implying that these two categories are qualitatively different. This categorical difference, which is related to the gender of the participants, was not fully picked up by the statistical testing. However, both females and males without the visual constraints lie on the same positive side of Dimension 1, while both males and females with the visual constraint lie on the same negative side of Dimension 1. This implies that there is no categorical gender difference between the control group and the experiment group with a visual constraint and also no categorical gender difference between the control group and the experiment group without a visual constraint, even though in another dimension there are differences. This implies that the effect of gender is multifaceted and requires further investigation to untangle.

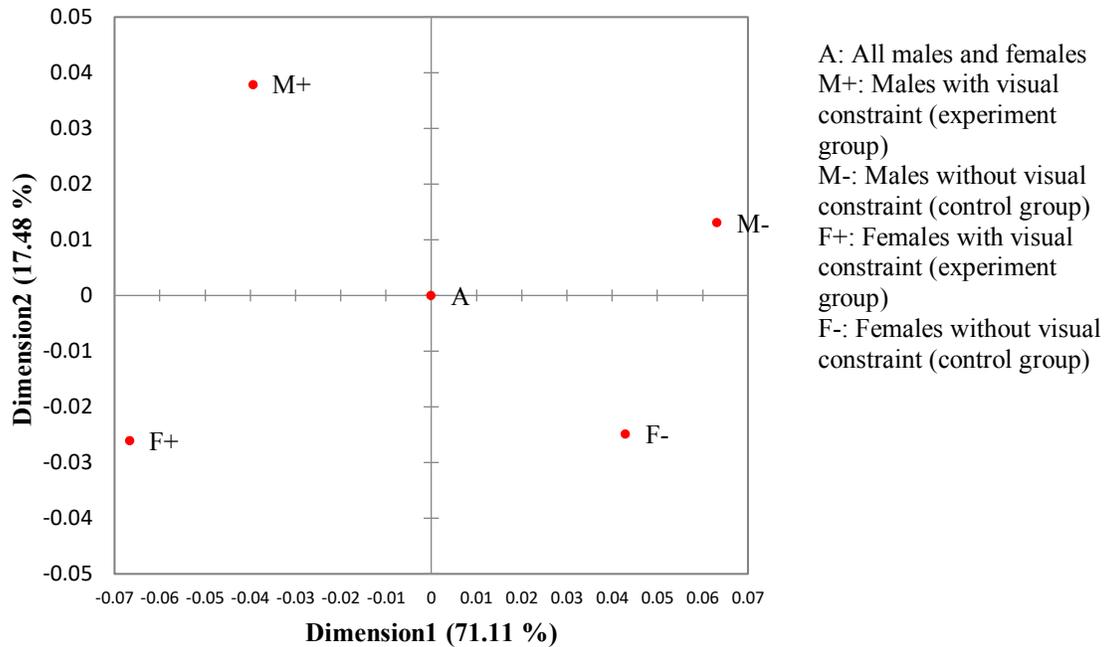


Figure 10. Joint plot of the 5 categories after a multiple correspondence analysis

In order to determine whether there is a temporal dimension to the cognitive behavior, each design session was divided into two halves, resulting in doubling the number of categories to 10. A multiple correspondence analysis was carried out for these 10 categories, Figure 11. Between the two dimensions 95.85% of the variance in the data is covered. This is a high level of coverage. Note that the dimensions in Figure 11 bear no relation to those in Figure 10 as correspondence analysis recalculates the optimal dimensions for each data set. The first halves for all categories are located on the positive side of Dimension 1, while the second halves are all located on the negative side. This implies that for both groups the distributions of cognitive effort related to design issues changed during the design session. For the first half, the difference can be observed between control and experiment groups in Dimension 2. In the first half the locations related to female and male students who experienced the visual constraint are near each other. This

corresponds to their categories being similar in design behavior. The same relation can be observed for control group. In the second half, based on Dimension 2, the locations of male and female students of the control group are on opposite sides. It can be observed that the female participants of the control group have the same focus on cognitive effort as all participants of experiment groups. Both the control and the experiment groups' positions are in the fourth quadrant implying that as a category they have something in common. The relations between different points in the first and second halves show a more nuanced behavior than the statistical analysis and imply that gender has an influence on the cognitive behavior of students.

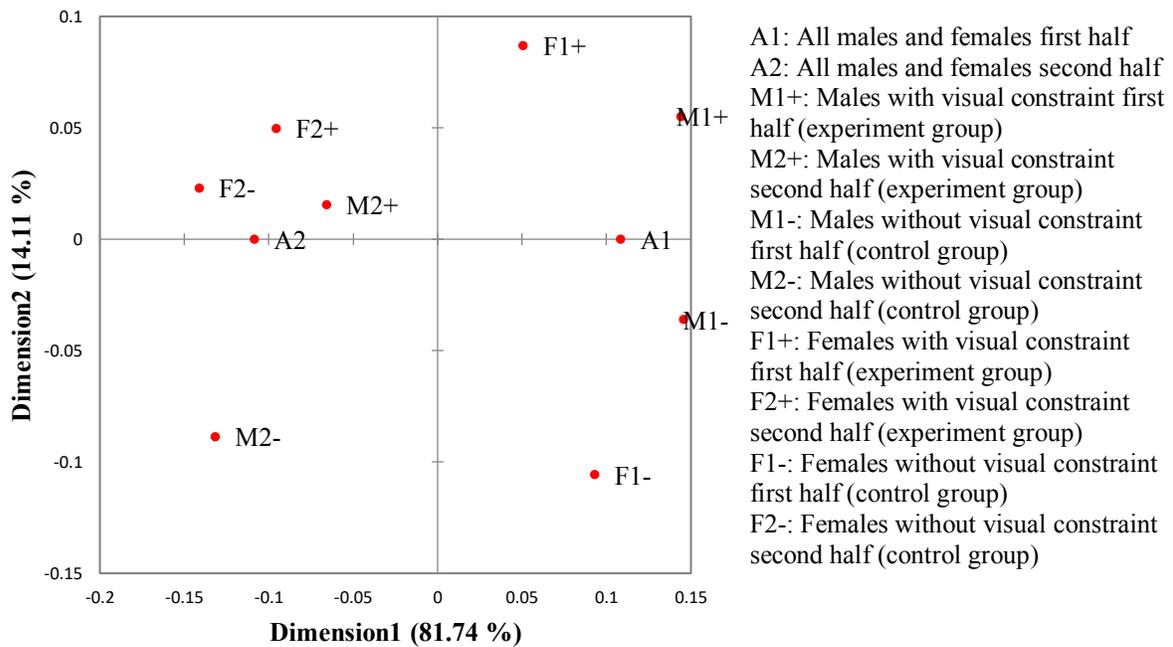


Figure 11. Joint plot of the 10 categories after a multiple correspondence analysis

6 Discussion

In this paper, the effect of a visual constraint on design behavior of architecture students was studied using protocol analysis. In order to observe the changes of design activities, the FBS ontology was used to code the protocols of the two groups: one designing without a visual constraint and the other designing with a visual constraint. The results of statistical analyses showed that in the visual constraint condition, the distributions of cognitive effort were affected compared to the no visual constraint condition. Participants expended less cognitive effort on behavior which was used before the structure. Also, the cognitive effort expended on synthesis and reformulation 2 as two design processes related to expected behavior decreased. These results showed that a visual constraint changed the design behavior of participants. Investigation of temporal changes of design processes showed that in the no visual constraint condition participants changed their attention to problem framing and problem solving several times during the design session. In the visual constraint condition, the focus on problem framing and problem solving did not change during design session. In other words, in a visual constraint condition participants increased their focus on solutions from the beginning of design process. This result can be compared to another study which showed that a design brief with fewer constraints provides for more possible options so it becomes harder to generate solutions (Pauwels et al., 2015). A new index was introduced in this paper to demonstrate the sequential change of design behavior based on structure. In this index the ratio of pre- structure to post-structure design processes (P-P index) is measured during design sessions. It was expected that the distribution of cognitive effort related to the processes before and after structure might be affected when participants used an example during designing. The P-P index was calculated for the two groups. It was observed that in the

visual constraint condition, participants did not alter their focus on pre- and post-structure design processes which was different from other group that spent more time on producing a design.

The results of the statistical analyses related to the first research question (*how does the design behavior of students vary when designing with and without a visual constraint?*) suggested that design behavior was changed by a visual constraint. In previous research Sio et al, (2015) showed that using one example led participants to deep investigation of design ideations, so our findings also contribute to that result by describing how distributions of cognitive effort changed.

In a previous study the time between the two design sessions was about one month (Bilda & Gero, 2008) and based on that result the order did not affect design behaviors of participants. In other studies (Camba et al., 2018; Chu et al., 2017) the time between design sessions was less than one month, however the effect of order was not considered. In our research, participants experienced two design sessions with an interval of one week. The two groups of participants did visual and non-visual design sessions in a different order. The result of statistical analysis showed no changes in their design behavior, thus answering the second research question (*how does the order of design sessions, one with a visual constraint and the other without, affect students' design behavior when they experience two design sessions?*).

The results of the statistical analyses related to the third research question (*are there gender differences in design behaviors with and without a visual constraint?*) implied that the design behavior of male and female participants were not the same, i. e., in the no visual constraint condition, female students did not exhibit the same behavior as the male students, specifically in the second half of design session. In contrast, Goldschmidt & Sever, (2011) showed that there was no difference between male and female students when designing with and without examples. Our findings contradict that but extended other studies that showed the effect of gender on design

behavior (Alelyani et al., 2017; Lu, 2015; Newcombe et al., 1983; Suits & Lagowski, 1994). An important aspect in our study was the method of measuring the effect of gender. The importance of the method of analysis on measuring the effect of gender was previously demonstrated (Newcombe et al., 1983). So in our research different tests were carried out. As such, the result of this study might be due to the more nuanced analyses undertaken.

The design processes which are the result of FBS ontology coding, are transition processes between two design issues. Classifying them into pre- and post-structure can provide a different insight when studying the design behaviors. The proposed P-P index can describe the distribution of cognitive effort during design session based on structure.

Using an ambiguous image as a visual constraint for second year architecture students could be a limitation of this research. The participants experienced two design sessions during the second semester. While they finished the introductory design solutions they were still novice designers, which means that possibly they had insufficient experience to use a visual constraint (Casakin, 2010; Casakin & Goldschmidt, 2000). However, the source of images was an ambiguous architectural layout. So all students had some knowledge of such an image. An ambiguous image leads to multiple interpretations and potentially evokes insights (Muth et al., 2015). However, the research that investigated the effect of visual constraints on design students, showed that only advanced students could benefit from the representations that were not superficially similar to design solutions and had expert-like design behaviors (Casakin, 2010; Casakin & Goldschmidt, 2000). In other studies, students in different academic years levels showed differences in using representations with superficial similarities (Heylighen & Verstijnen, 2003; Ozkan & Dogan, 2013). A visual constraint can be used as an educational tool because it has the potential to change the design behavior of students. However, in order to extend the role of visual constraint in

education, different types of visual images and their effects on different level of students need to be investigated in further studies.

The results of this study are limited by the relatively small number of participants in the experiment. A larger study is needed to be confident that the findings can be generalized. In similar research the number of protocols in each group was 12 or less (Chu et al., 2017; Gonçalves et al., 2016; Yilmaz et al., 2015), so this experiment fits within the standard set by that research. Similar research with three or four variables has been conducted with a fewer number of design protocols (Gonçalves et al., 2016; Strimel et al., 2018; Yilmaz et al., 2015). This may be because verbal protocol analysis is a very time consuming technique(Atman & Bursic, 1998).

7 Conclusion

In this exploratory research about the effect of a visual constraint on design cognition, three variables were studied by analyzing verbal protocols. The main question of the research was how the design behavior of architecture students was affected by visual constraints, the other two questions were about the role of order of experiencing two design sessions and gender of participants. This study provides the results for the three questions by applying statistical and other methods that can be used in further research.

A visual constraint changed the distribution of cognitive effort. A visual constraint serves as a pedagogical strategy that leads students to focus more on the solution. It appears that in a visual constraint condition participants do not spend more time on generating forms and shapes but in interpreting them as parts of a design solution. The order in which the constraint was presented had no effect on students' design behavior but gender did. The methods of analysis have an important role in exploring the effect of gender on students' design behavior. A study with a larger number of participants is required to be confident about generalizing these results.

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