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Pen-and-paper versus digital sketching in architectural design education

Parvin Heidari and Çiğdem Polatoğlu

Abstract

This study aimed to compare and evaluate the digital-based sketching versus conventional pen-and-paper sketching through conducting an experiment via protocol study in educational field. To this aim, the linkography analysis technique was used to obatin the related data from the protocol study. Linkography technique allows analyzing design as a system and is capable of tracing the design ideas and their connections; therefore, it facilitated the purposes of the current study. The results demonstrated that designers had a richer design process and more opportunities for generating ideas in the pen-and-paper sketching versus digital sketching. Furthermore, the designers' performance in the digital media with two-dimensional sketching software was more satisfactory than the digital session with three-dimensional sketching software. However, digital media encouraged designers to make more integration among the ideas.

Keywords

Conceptual design, pen-and-paper sketching, digital sketching, linkography

Introduction

In the architectural design, a designer focuses on the conceptual stage. In this stage, the designer generates and explores new ideas based on analyzing the problem. Traditionally, the early stage of design begins with sketching and making model to explore the ideas and solutions. Sketching is regarded as one of the most explored activities in design cognition studies. The results of sketch studies indicated that ambiguity is one of the sketching aspects, which gives some specific characteristics. All of the researchers who explored and defined the act of sketching believe that the ambiguity of the sketch is related to the reinterpretation, which enables unexpected discoveries to explore new design ideas.[1–5] Since the lines drawn by freehand sketches are ambiguous, they can be interpreted differently. The designer may get new insights, see new relations as well as make new inferences and meanings by reinterpreting these lines, leading to the discovery of new ideas.[4,5] In addition, it may prevent the early fixations of ideas.[1,3] Thus, designers use sketches by both expressing their ideas and generating new ones.

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As digital technology progresses, there are attempts to integrate digital tools with the early phases of design in order to make a digital design media in the architectural education. Furthermore, the recent developments in computer-aided architectural design (CAAD) software indicated a shift to focus toward conceptual design interface or computer-aided conceptual design (CACD).[6] CACD systems are based on "a digital sketching environment which mimics freehand sketching behaviors"[6] such as graphics tablets or pen-based systems and associated sketching software. However, according to Tang and Gero,[6] a dense and ambiguous representation for CACD is still difficult. Therefore, the application of digital sketching tools has raised discussions among design instructors and researchers. They emphasized that computer software may impede the creative behaviors, which can encourage poor and unproductive design by the students.

Literature review

A large number of studies have been conducted to compare and evaluate traditional and digital mediums during the sketching process of design and highlight how they influence the designer' behaviors.[1,6–8]

Goel[1] compared the protocols related to design sessions where expert graphic designers solved a problem via sketching or using a computer-based drawing system. He studied the ambiguity in terms of reinterpretation, which occurred during the design protocol. In addition, Tang and Gero[6] examined the design process in a traditional and digital sketching environment, which had been devised to emulate freehand sketching. In another study, Won[7] aimed at understanding the differences between designers' cognitive visual thinking while generating concepts using computer or conventional media. Furthermore, Bilda and Demirkan[8] focused on gaining an insight on the designers' cognitive processes while sketching in digital versus traditional media.

In addition, some researchers emphasized on reviewing and exploring the role which computers can play in the conceptual design stage and attempted to provide empirical evidence on the potential links between CAAD and creativity.[9–14] Since the mouse-based computer software is unable to support the actions of sketching during the preliminary designing stage, a large number of studies developed a pen-based system.[15–17] In these systems, the designer sketches with a pen on a touch screen instead of sketching with a pencil on a paper.

Previous studies have focused more on the cognitive thinking process of sketches. However, this study aimed to evaluate the conceptual design in terms of productivity as a sign of creativity. In addition, this study emphasized more on pen-based systems and software developed to support the sketching action.

Method

Due to the significance of the design thinking process in architectural education, this study focused on the early stage of architectural design and attempted to evaluate the digital sketching versus pen-and-paper design thinking tools via a protocol study.

Researchers commonly use the protocol analysis method for "studying design thinking from the cognitive viewpoint."[18] It is a method, which is limited to short stretches of time.[18] Thus, it has been applied in evaluating the sketching process during conceptual design in different studies. Researchers addressed two types of protocol analysis method, which has been classified into process-oriented and content-oriented approaches by Dorst and Dijkhuis. In addition, two types of protocols are classified as concurrent protocols (think-aloud), which are obtained from "verbalization of a subject's thinking while he/she is working on a given task" and retrospective protocols are obtained from "verbalization of a subject's recall of thinking after he or she has finished works" (Dorst & Dijkhuis, 1995 cited in Tang and Gero[6]).

Since this study aimed to evaluate the sketching process, the process-oriented design study was selected tending to use "concurrent" (think-aloud) protocols. In this study, the linkography analysis technique was used to obtain the information from the protocol study.

Based on the above objectives, two questions were raised:

1. Can using digital-based sketching enhance the students' thinking process in the early stages of architectural design?
2. How is the linkography analysis technique used in assessing the sketching process?

Linkography

According to Kan and Gero,[19] "Linkography is a technique used in analyzing design protocols and was first introduced to protocol analysis by Goldschmidt to assess design productivity." In the linkography system, the design protocol is segmented into smaller units called a "move" (or design idea or decision), and the related moves are joined by a "link."[18] Thus, linkography is related to the links among design moves, as it is believed to be the best way to capture the essence of design cognition and behavior.[18]

In addition, Goldschmidt[18] identified two types of links including "backlinks" and "forelinks." Backlinks are regarded as the links among the moves, which are connected to the previous moves.[20] The symbol "<" denotes backlinking. However, forelinks are considered as the links between the moves, which are connected to the subsequent moves.[20] Forelinking is represented by the ">" symbol. Thus, forelinks are virtual and cannot be determined by judgment while they can be established only after the fact.[18,21,22] Kan and Gero[23] introduced another link type, called "horizonlink," which refers to the notion of cohesiveness between the linked moves.

Linkography and the design process

Some researchers used protocol and linkography for evaluating the design process. Goldschmidt[18] in different studies introduced the "link index" value to evaluate the design sessions in protocol analysis to compare design productivity, which is considered as "an indication of creativity." In addition, the "critical moves" were used in linkography to interpret the divergent thinking—forelinking of design moves, and convergent thinking—backlinking of moves.[18,21] Furthermore, the shifts between divergent and convergent thinking should be considered as the yardstick instead of or alongside measurements of divergent thinking in evaluating the design creativity.[21] In other studies, Kan and Gero and their associates used the "entropy" of Shannon's information theory for evaluating the design process by linkography. Furthermore, they[19] proposed some methods to acquire information from linkography in the protocol study based on the mean values of X and Y. Similarly, a quantitative tool was implemented to interpret the linkography using entropy.[20] Kan and Gero[24] also evaluated the entropy of Shannon's information theory as a tool for measuring the creativity of design in a protocol analysis method. In addition, a method was developed for measuring the design process and correlating through assessing the design outcome using a linkography analysis technique in a protocol study.[23]

Therefore, by considering the previous studies, the *Link index, Critical Moves* (both developed by Goldschmidt), and *Entropy* (developed by Kan and Gero) were used in this study to evaluate the sketching process by "linkography." Furthermore, the *mean values of X and Y* of all sessions were compared as an indicator of design structure to explain the main values. These four scales were separately identified in different studies, which are implemented to evaluate the productivity of design. However, these values were used together to evaluate the conceptual design process for the first time in this study.

Link index. The link index (LI) value was developed by Goldschmidt[18] to evaluate the design sessions in the protocol analysis to compare design productivity, which is considered as a sign of creativity. She emphasized that a productive process has a higher LI value indicating a higher density of links in a linkograph. An LI is "the number of links divided by the number of ideas."[22]

If the density of links is considered as an indication for the quality of ideas, Goldschmidt and Tatsa[22] claimed that the most productive processes having the highest LI values and the densest links are regarded as the most creative ones. However, according to Goldschmidt,[18] the LI is a value which should be used cautiously and only where appropriate, because a high LI is not necessarily a hallmark of good design due to many repetitions or attempts to discover alternative ideas with little continuity among these ideas.[18]

Critical moves. Goldschmidt[18] in her book raised a specific proposition for the first time that "there is a correspondence between forward and backward linking and *divergent* and *convergent* thinking".* Goldschmidt[18] claimed that linking moves forward and backward reflect shifts between divergent and convergent thinking. According to her, the forelink reflects the divergent thinking and the backlink stands for convergent thinking. In addition, she distinguished between critical moves (CMs) due to a large number of backlinks (<CMs) and forelinks (CMs>), as well as a large number of links in both directions in a few cases (<CM>).[21] Furthermore, she argued that inventive ideas are developed more on the previous work.[18] Thus, both divergent and convergent thinking, as two modes of thinking, should be balanced in a creative design which represent *shifts* between them. Goldschmidt[18,21] interpreted this shifting as the equal proportion of the two types of CMs (<CMs and CMs>), that is, suggesting the balanced cycles for generating ideas. In addition, the high percentage of CMs in this unit represents its highly productive nature.[18] In fact, creative episodes display a high proportion of CMs. CM percentage in linkographs refers to the total number of CM in a design session with respect to the total number of moves.

Accordingly, the percentage of CMs of the total moves as well as the ratio of forelink CMs related to the total CMs and backlink CMs of the total CMs, which demonstrates the balance between two types of CMs, should be used for evaluating the design thinking process by linkography.

Entropy. The traditional study of linkographs uses LI and CMs as the benchmark for the productivity of a design session. Kan and Gero[19] believe that the LI and CM approach may be the result of highly linked and saturated linkographs. Thus, they proposed the methodology to calculate the entropy using Shannon's information theory and Goldschmidt's linkography based on the idea that fully linked and empty linked linkographs demonstrate the processes used for substandard design.[23] Kan and Gero[19,23] and Kan et al.[20] argued that an empty linked linkograph can be considered as a non-converging process with no coherent ideas and a fully linked linkograph represents a fully integrated process with no diversification. In addition, the high values of entropy represent a richer process for generating the ideas.[23] Furthermore, Kan and Gero[24] reported a potential relation between the productivity of design activities and the entropy of linkographs as a measure for design creativity.[23,24]

In order to measure the entropy of linkograph, Kan and Gero[23,24] measured entropy based on the conceptual difference of forelink, backlink, and horizonlink rows separately according to a probability algorithm devised by Shannon as "linked" or "unlinked." They[19] also suggested that forelink entropy can measure the idea generation opportunities based on new creations or initiations. Backlink entropy is able to evaluate the opportunities

*The notions of "convergent" and "divergent" thinking have a long history in creativity research. According to Salama,[25] "Convergent thinking relates to solving well-defined rational problems leading to one correct answer, divergent thinking requires producing several answers to tackle an ill-defined problem.

according to enhancements or responses. Horizonlink entropy evaluates the opportunities related to cohesiveness and incubation.

Mean values of X and Y. Furthermore, Kan and Gero[19] demonstrated a linkography according to the mean values of X and Y. In other words, the centroid or the average position of all the nodes is considered in this regard. The mean value of X is calculated by adding all the X coordinates related to the nodes and dividing them by the total number of nodes, which is the average location of the links in the x-axis.[19] Furthermore, they believe that a higher mean value of X means that more nodes appear at the end of a session and a lower value indicates that more nodes appear in the beginning of the session. Similarly, in order to calculate the mean value of Y, the Y coordinates of the nodes are added and divided by the total number of nodes, which is regarded as the average location of the nodes in the y-axis.[19] Finally, the mean value of Y represents the depth of the ideas, and accordingly it indicates the lengths of the nodes.

Empirical study

Since this study was conducted in the educational field, the participants were selected from among students in order to get closer to the more realistic outcomes. They were selected based on different educational stages since the performance of each subject was compared and evaluated in design sessions with herself or himself without making any comparison among them. In addition, due to the large amount of information and data in the protocol study method, and also due to the non-comparison of subjects, this experiment was conducted with two designers. However, a sample size of 1–3 is acceptable in most of the protocol studies conducted so far. Thus, in this study, two students, who had enough backgrounds in sketching with pen and paper and using CAAD and digital media, were selected from the Faculty of Architecture, Islamic Azad University in Iran. One of the subjects was a graduate student (SUB1) and another was a sophomore student (SUB2).

Design sessions

As each subject participated in three design sessions, totally six design sessions were conducted. During the experiment, they took advantage of three different media to examine. These sessions were held in the same place under the same conditions. During the three sessions, the subjects' sketching activities, as well as their verbalization, were videotaped and recorded by two video cameras at two different points. The first camera was mounted near the subjects to record their sketching and designing behavior, and the second camera to capture a general picture as illustrated in Figures 1 and 2. In each design session, the subjects had 60 min for the test.

The order of the tests was highlighted in this study. Pen-and-paper sketching was done first, due to more experience and familiarity of the subjects. Then, the digital session was conducted with a two-dimensional (2D) software. Finally, the designer participated in the three-dimensional (3D) digital session. In the first session, the subjects were asked to work on the design task while sketching only on the sheets of tracing paper in A4 size in order to equalize the screen to tablet size of digital sessions. In the second and third design sessions, the subjects were asked to sketch and design only on a tablet PC using a 2D interface sketching software, named "Sketchbook Pro" in the second session, and designing and drawing with a 3D interface sketching software named "uMake" in the third session. During the two digital experiments, the designers were not allowed to sketch using paper and pencil. The digital sessions of the experiment consisted of a 2-week training program aiming to provide both subjects with the same proficiency in using the software.

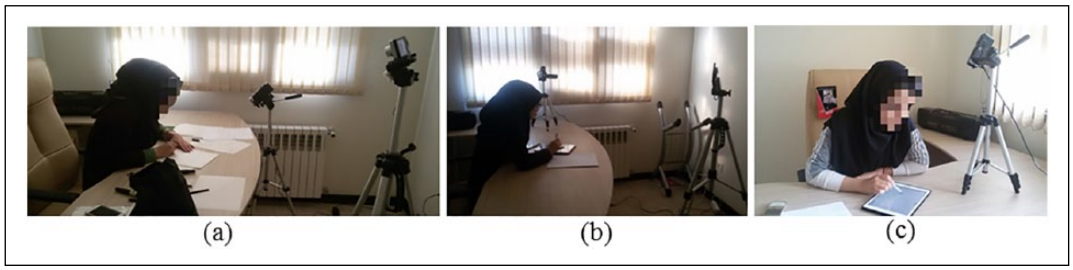

Figure 1. Design sessions in (a) pen and paper, (b) sketchbook, and (c) uMake related to SUB1.



Figure 2. Design sessions in (a) pen and paper, (b) sketchbook, and (c) uMake related to SUB2.

Most of the applications used in previous studies were modeling tools, 2D or programming based, and were implemented on the computer. However, this study aimed to use the software to support the sketching action on the tablet. *Sketchbook Pro* is one of the most used 2D sketching software, which emulated the pen-and-paper environment. It was used in the studies by Tang and Gero.[6] *uMake* is a mobile app for the iPad device which is different from 3D modeling software such as 3D Max and allows the users to sketch out their ideas in the 3D space using natural sketching gestures. uMake combines a freehand sketching experience with a powerful 3D workspace (https://www.umake.xyz/).

Design tasks

This study aimed to evaluate the thinking process. Thus, attempts were made to select different design problems for each session. The subjects were first asked for a pen-and-paper sketching session for designing an art gallery at the Faculty of Architecture with an approach of green architecture and respect for nature in a garden pit with the dimensions of 40×30 and a depth of 2 m. They were requested to design a part of the gallery inside the garden pit. Second, a digital pen-based session was conducted with Sketchbook Pro software to design a memorial for Iranian poets in an area of approximately 150 m^2 that is suggestive of Persian poets and poetry. Finally, the digital pen-based session was performed with "uMake" software in order to design an entry gate for an amusement park reflective of an exciting, happy, and amusing environment. Due to the complexity of design media in terms of application and use, we tried to select the design tasks such that they are more complex for the pen-and-paper session, which is of less complexity and simpler for uMake application that may be slightly more complex due to being 3D.

Results

The design sessions of two subjects were recorded and the utterance from each design session was segmented and labeled as a design move. Then, the links between moves were explored to create linkographs and analyze the design protocol. Therefore, three linkographs were produced for each designer using LINKODER (LINKOgrapher) software[26] and totally six linkographs were obtained from six design sessions (some sketches of the sessions and linkographs are shown in Figures 3 and 4).

First, the "Link Index" and "Critical Moves" percentage values, as the traditional benchmarks for the productive design session, were calculated for each linkograph. These values provide a context to discuss related to the productivity of the design comparatively. Based on the literature review, it is considered as a sign of creativity. Then, the "Entropy" values as the recent hallmark for productivity were evaluated. In addition, the mean values of X and Y of the sessions were compared.

The LINKODER software was implemented to calculate the total segments, total links, link ratio per segment, and the mean values of X and Y, along with forelinks, backlinks, and horizonlinks' entropies in its General Statistics window. Figures 5 and 6 display the related values for six sessions including pen and paper, Sketchbook Pro, and uMake software for the two subjects (SUB1 and SUB2).

Link index (LI) of subjects' sketching sessions

Based on the general statistics of LINKODER software, the link ratio is equal to the LI value introduced by Goldschmidt. In addition, it is calculated through dividing the total links into the total segments. Tables 1 and 2 indicate the total segments, total links, and the LI values for the six sessions.

In this experiment, the performance of each subject was compared with herself or himself in the three sessions. Thus, regarding SUB1, the value of LI in the pen-and-paper session (4.21) is higher than that of the digital sessions, and the Sketchbook session value (3.66), which mimics the freehand environment, is close to the pen and paper, although it is higher, compared to the uMake session (2.52). Similarly, regarding SUB2, the value of LI in the pen-and-paper session (4.56) is higher than that of the digital sessions, and the Sketchbook session value (3.26) is higher than the value in the uMake software session (2.88) with a slight difference (Figure 7).

Critical moves (CMs) of subjects' sketching sessions

Tables 3 and 4 present the total CMs over the total number of moves and their percentages, forelink and backlink CMs and their percentages over the total CMs related to the SUB1 and SUB2 sessions, respectively. As shown, the thresholds with 7 moves were considered for determining whether a move is recorded as a forelink or backlink CM.

As indicated in Table 3, SUB1 in the pen-and-paper session had 40% of the CMs, which is higher than those of the digital sessions (Sketchbook with 35.7% and uMake with 14.3%). In addition, the CMs' percentages of the pen-and-paper and Sketchbook sessions are close together. Furthermore, the Sketchbook session has higher CMs than the uMake session.

Similarly, regarding SUB2, the pen-and-paper session had 43% of the CMs which is higher than those of the other two digital sessions (Sketchbook with 29% and uMake with 14.2%; Table 4). Furthermore, the Sketchbook session has higher CMs than those in the uMake session (Figure 8).

In addition, Tables 3 and 4 indicate the percentages of forelink CMs and backlink CMs of total CMs at the level of CM[7]. These values were counted to interpret the shift between divergent and convergent thinking or to find out the balance between the forelink and backlink CMs. These values are important regarding the literature about the cyclical shift between convergent and divergent thinking as a sign of a creative thought.

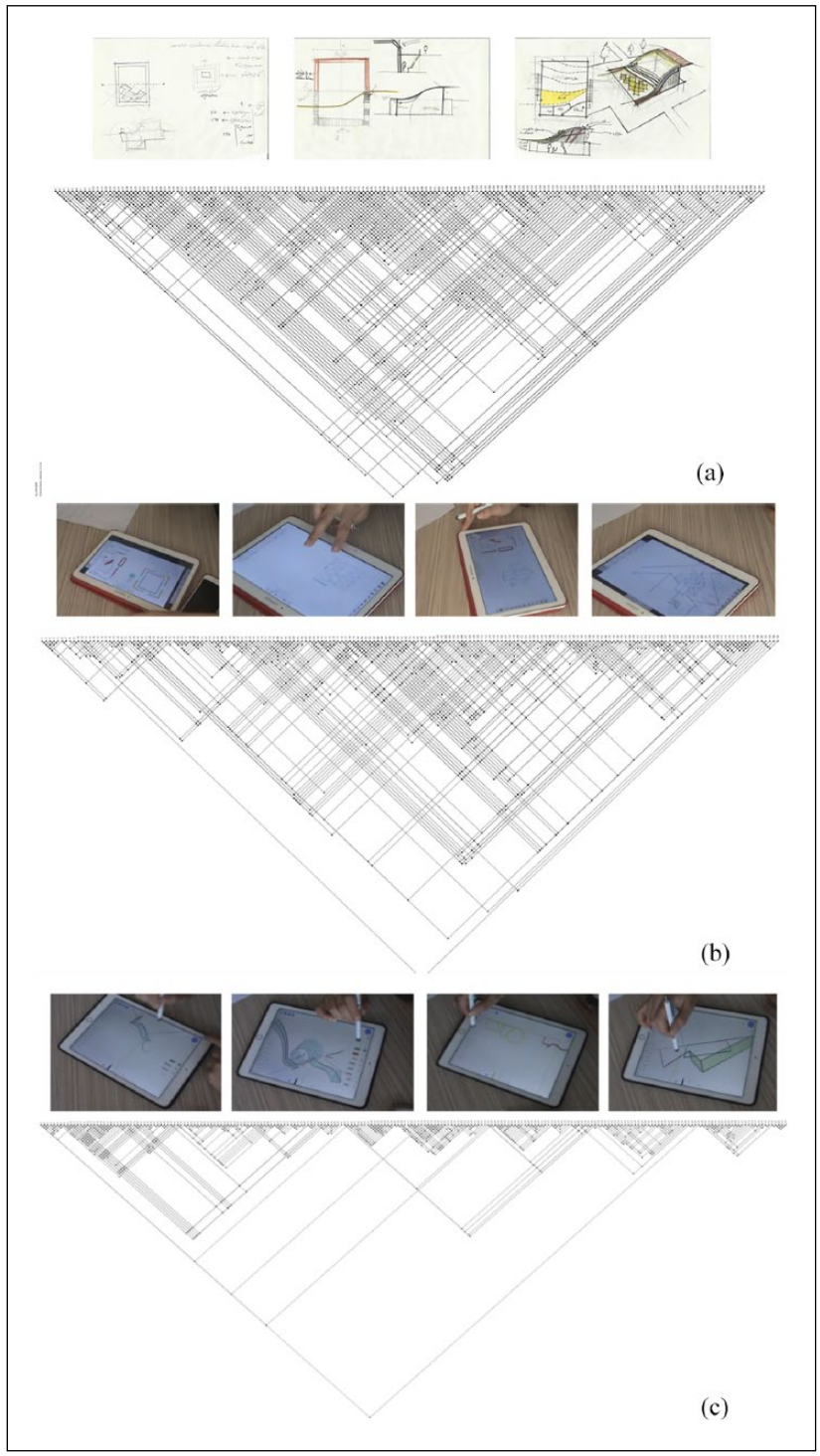

Figure 3. Designs and linkographs related to SUB1 in (a) pen and paper, (b) Sketchbook, and (c) uMake sessions.

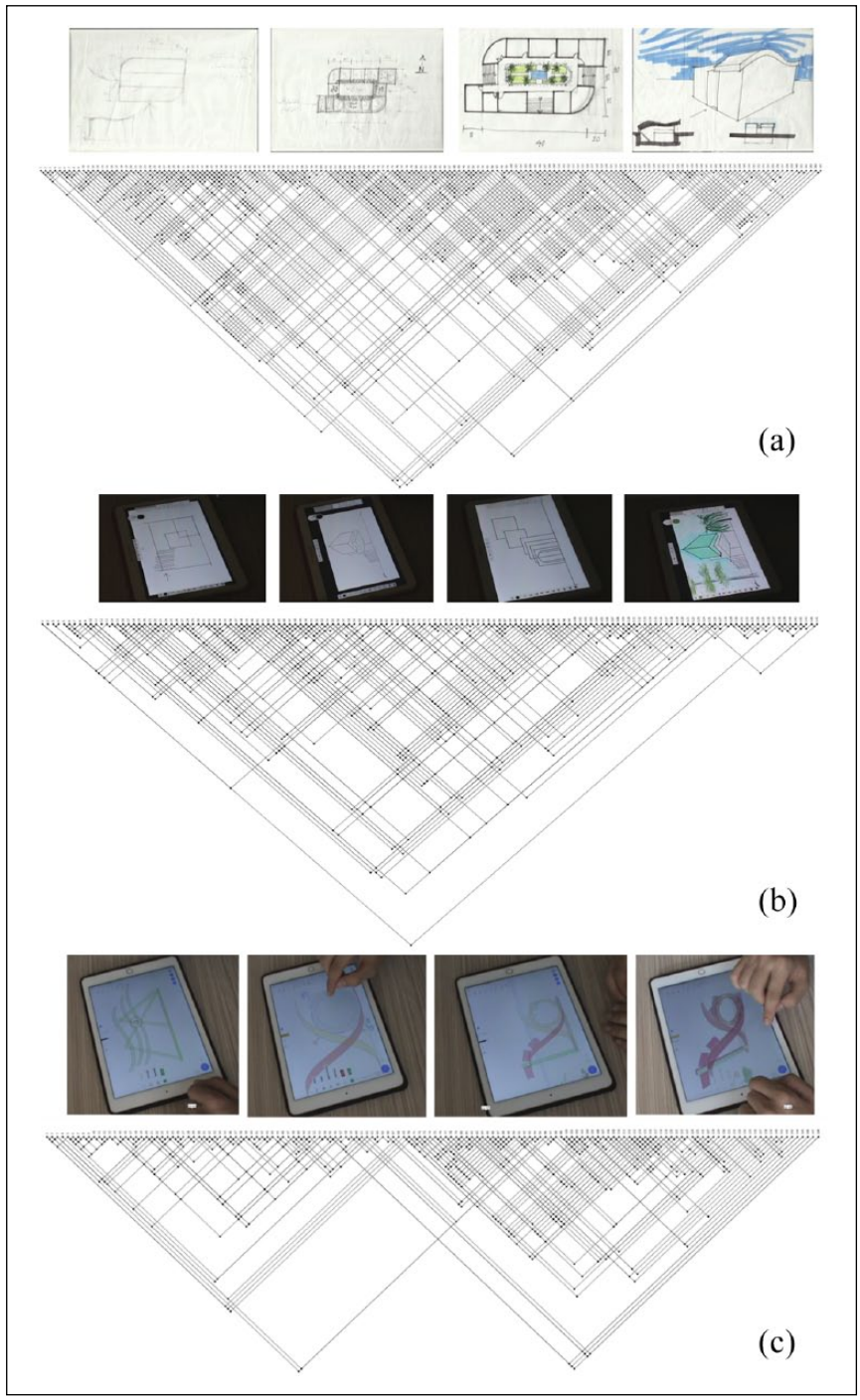

Figure 4. Designs and linkographs related to SUB2 in (a) pen and paper, (b) Sketchbook, and (c) uMake sessions.

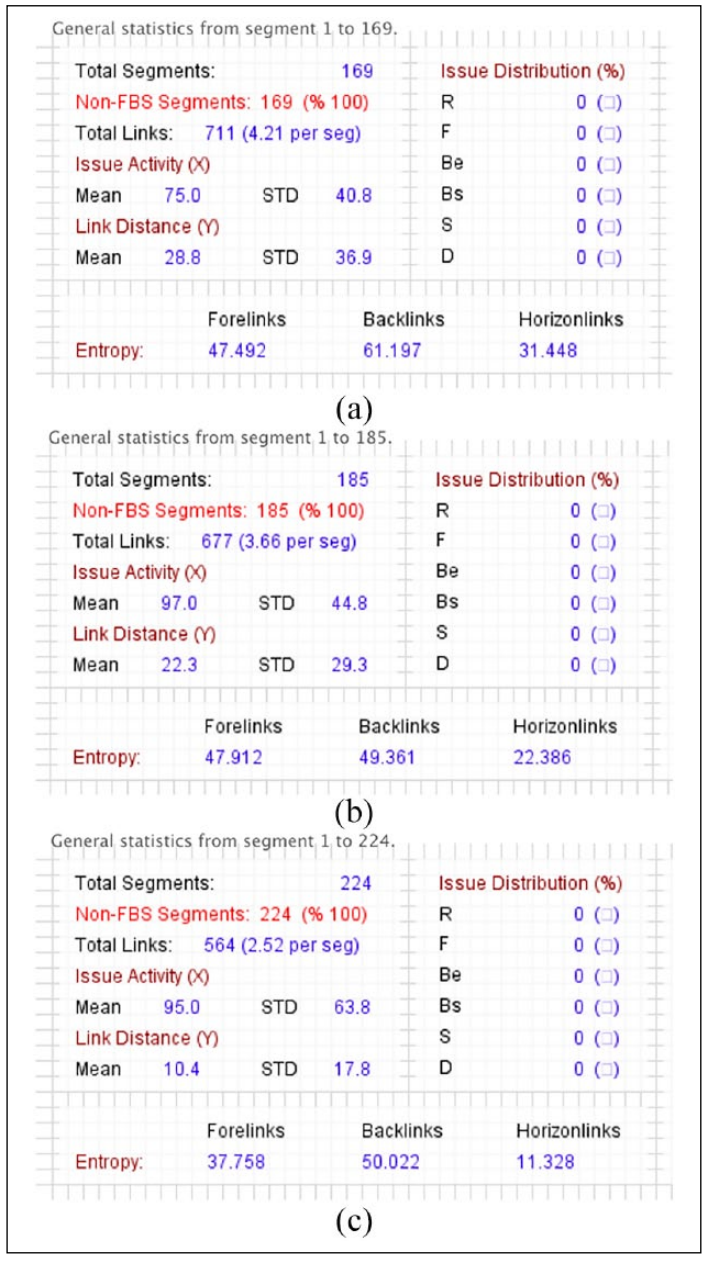

Figure 5. General statistics from (a) pen and paper, (b) Sketchbook, and (c) uMake sessions related to SUB1.

As shown in Table 3, the percentages of forelink CMs for all three sessions are higher than those in backlink CMs for SBU1. However, they indicate that the proportion of CMs> to <CMs is almost equal in the three sessions with a slight difference (close to 55:45). Regarding SUB2, as shown in Table 4, the percentages of forelink CMs related to all the three sessions are higher than those in backlink CMs. Based on the

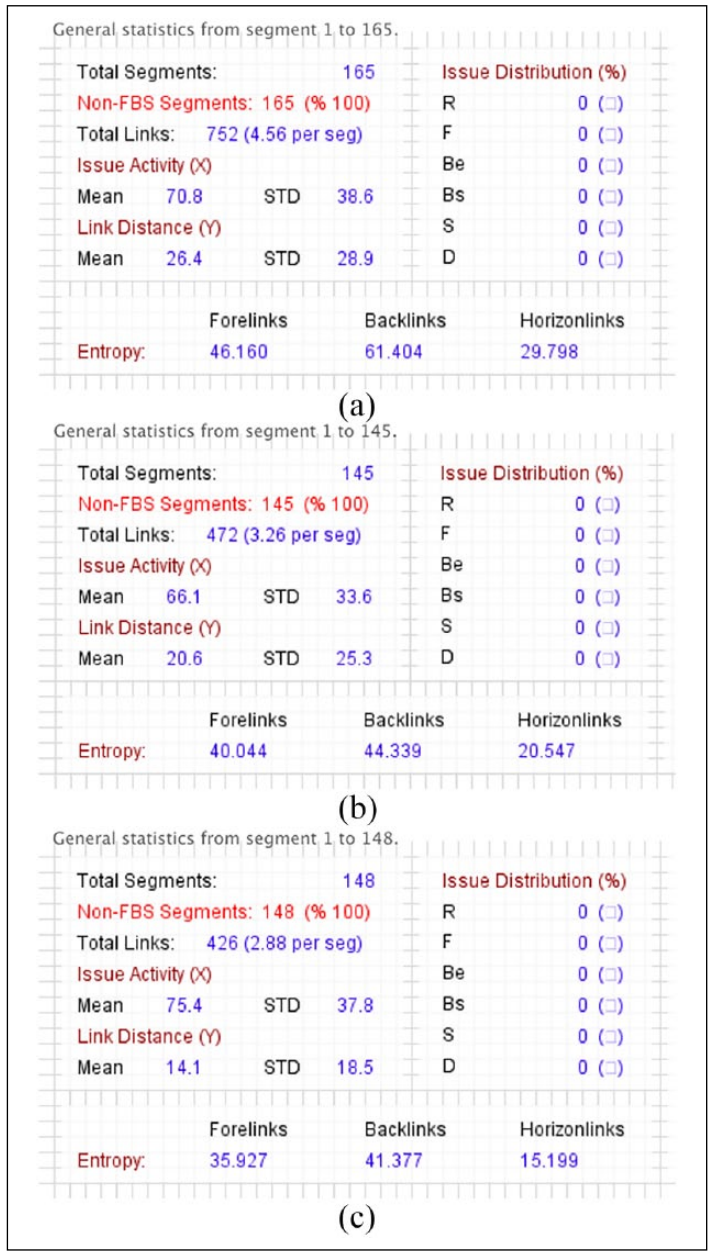

Figure 6. General statistics from (a) pen and paper, (b) Sketchbook, and (c) uMake sessions related to SUB2.

results, the proportion of CMs> to <CMs is almost equal in the pen-and-paper and Sketchbook sessions (close to 55:45) and is close to 76:24 in the uMake session (highlighted in bold in Table 4). In other words, the forelink and backlink CMs related to the three sessions in SUB1, and the pen-and-paper and Sketchbook sessions of SUB2 tend to be rather balanced, with more forelink CMs compared to backlink CMs.

Table 1. Link indexes related to SUB1 in the three sessions.

	Pen and paper S.	Sketchbook S.	uMake S.
Total segments	169	185	224
Total links	711	677	564
Link index	4.21	3.66	2.52

Table 2. Link indexes related to SUB2 in the three sessions.

	Pen and paper S.	Sketchbook S.	uMake S.
Total segments	165	145	148
Total links	752	472	426
Link index	4.56	3.26	2.88

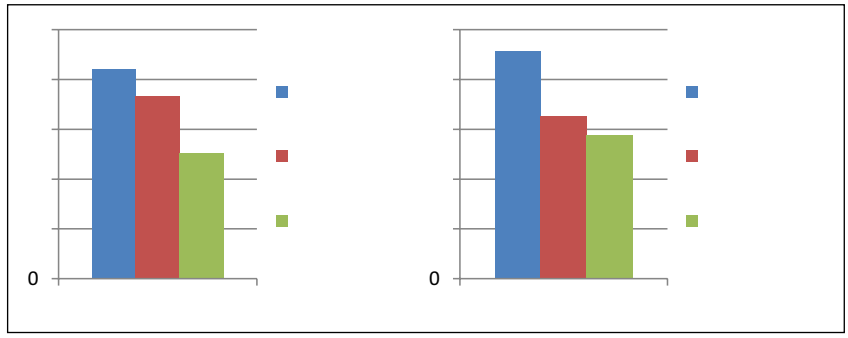

Figure 7. Comparison of link index of the three sessions related to SUB1 (left) and SUB2 (right).

Table 3. Critical moves as percentage with more than 7 links and percentage of critical forelinks and backlinks of total critical moves for SUB1.

	No. of CMs	Total[a] CMs (%)	No. & %CM^{7}> of CM	No. & %<CM^{7} of CM
Pen and paper S.	67	40	(37) 55.2%	(30) 44.8%
Sketchbook S.	66	35.7	(35) 53%	(31) 47%
uMake S.	32	14.3	(17) 53.1%	(15) 46.9%

CM: critical move.
[a]<CMs> were counted twice.

Entropy of subjects' sketching sessions

The values of forelinks, backlinks, and horizonlinks' entropies are shown in the general statistics window of LINKODER software (Figures 5 and 6). Tables 5 and 6 indicate the values for two subjects (SUB1 and SUB2) in the three sessions including pen and paper, Sketchbook, and uMake. Furthermore, comparison of the values is shown in Figures 9 and 10.

As displayed in Table 5 and Figure 9, the entropy values for forelinks in the pen-and-paper and Sketchbook sessions are almost equal (47.49 against 47.91) and are higher than those in the uMake session (37.76).

Table 4. Critical moves as percentage with more than seven links and percentage of critical forelinks and backlinks of total critical moves for SUB2.

	No. of CMs	Total[a] CMs (%)	No. & %CM^{7}> of CM	No. & %<CM^{7} of CM
Pen and paper S.	71	43	(39) 54.9%	(32) 45.1%
Sketchbook S.	42	29	(24) 57.1%	(18) 42.9%
uMake S.	21	14.2	(16) **76.2%**	(5) **23.8%**

CM: critical move.
[a]<CMs> were counted twice.

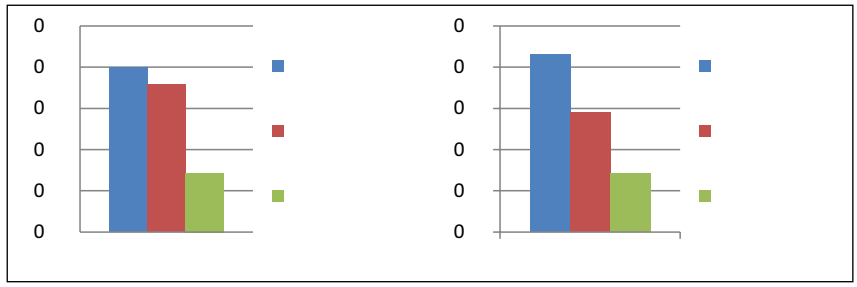

Figure 8. Percentage of CMs in the three sessions related to SUB1 (left) and SUB2 (right).

Table 5. Three types of entropy and their cumulative total entropy for SUB1.

	Pen and paper S.	Sketchbook S.	uMake S.
Forelink entropy	47.49	47.91	37.76
Backlink entropy	61.2	49.36	50.02
Horizonlink entropy	31.45	22.39	11.33
Cumulative total	140.14	119.66	99.11

Table 6. Three types of entropy and their cumulative total entropy for SUB2.

	Pen and paper S.	Sketchbook S.	uMake S.
Forelink entropy	46.16	40.04	35.93
Backlink entropy	61.4	44.34	41.38
Horizonlink entropy	29.8	20.55	15.2
Cumulative total	137.36	104.93	92.51

Similarly, the backlink entropy value in the pen-and-paper session (61.2) is higher than those in the digital sessions, and the uMake and Sketchbook sessions have almost equal backlink entropies (50.02 against 49.36). Regarding horizonlink entropy, the pen-and-paper session has a higher value (31.45) than the digital sessions. In addition, the horizonlink entropy of the Sketchbook session (22.39) is higher than that of the uMake session (11.33). Totally, the value of cumulative entropy indicates that the pen-and-paper session has a higher entropy value (140.14), compared to the two digital sessions, and the entropy of the Sketchbook session (119.66) is higher than that of the uMake session (99.11).

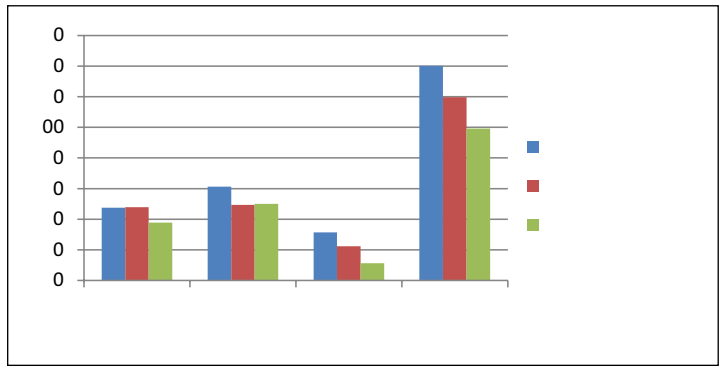

Figure 9. Comparison between the three types of entropy in the three sessions for SUB1.

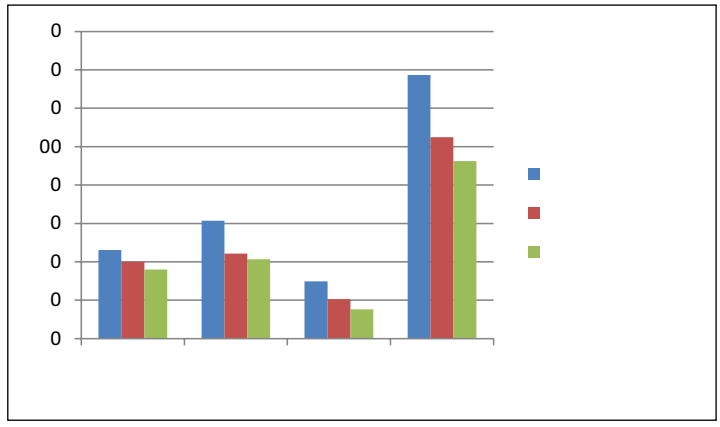

Figure 10. Comparison between the three types of entropy in the three sessions for SUB2.

Given the results of SUB2 in Table 6 and Figure 10, the forelink entropy value in the pen-and-paper session (46.16) is higher than that of the Sketchbook session (40.04). Furthermore, regarding the forelinks for the Sketchbook session, the entropy value is higher than that of the uMake session (35.93). Similarly, the backlink entropy value in the pen-and-paper session (61.4) is higher than those of the digital sessions, while the uMake and Sketchbook sessions have almost equal backlink entropies (44.34 against 41.38). In horizonlink entropy, the pen-and-paper session has a higher value (29.8) than the digital sessions and the horizonlink entropy of the Sketchbook session (20.55) is higher than that of the uMake session (15.2). In general, the cumulative entropy values indicate that the pen-and-paper session has a higher entropy value (137.36) than the two digital sessions and the entropy of the Sketchbook session (104.93) is higher than that of the uMake session (92.51).

Mean values of X and Y of subjects' sketching sessions

Tables 7 and 8 present the mean values of X and Y for two subjects in three sessions, extracted from LINKODER software.

Regarding SUB1, the mean values of X in the Sketchbook and uMake sessions are almost equal (97 and 95, respectively) and are higher than those in the pen-and-paper session (75) (Table 7). As for SUB2, the

Table 7. Mean values of X and Y in the three sessions for SUB1.

	Pen and paper S.	Sketchbook S.	uMake S.
Issue activity (X) mean	75	97	95
Link distance (Y) mean	28.8	22.3	10.4

Table 8. Mean values of X and Y in the three sessions for SUB2.

	Pen and paper S.	Sketchbook S.	uMake S.
Issue activity (X) mean	70.8	66.1	75.4
Link distance (Y) mean	26.4	20.6	14.1

mean value of X in the uMake session (75.4) is higher than those of the other sessions, while the value in the pen-and-paper session (70.8) is higher than that of the sketchbook session (66.1) (Table 8).

Finally, the mean values of Y for both SUB1 and SUB2 in the pen-and-paper session are higher than those in the digital sessions, and these values in the Sketchbook session are higher than those in the uMake session. In other words, the link distance values in the pen-and-paper session for the two subjects are longer than those of the other sessions.

Discussion

In this research, the digital sketching processes were compared with the pen-and-paper sketching using linkography. To this aim, LI, CMs, and entropy were used as the main values. The mftable 5ean values of X and Y were calculated to explain the structure of the sessions. As it was already mentioned, the related values were combined and used together for the first time in this study.

The results demonstrated that both SUB1 and SUB2 have higher values of the LI, percentage of CMs, and entropy in their pen-and-paper sketching sessions, compared to the values in the digital sketching. In addition, among the digital sketching sessions, these values in the Sketchbook sketching processes are higher than those in the uMake sketching processes (Figure 11).

The results indicated that these values match together for both subjects. Comparing the results of the LI and the CMs with those in the entropy indicated that the high values of these factors in the pen-and-paper design processes according to Goldschmidt are not related to a large number of repetitions in ideas. In fact, two subjects created more links in pen-and-paper sketching, and more dense linkographs, compared to their digital sessions. Thus, according to Goldschmidt, and Kan and Gero, they had richer idea generation processes and more opportunities for developing ideas and consequently more productive and creative thinking processes in pen-and-paper sketching. The results of this study were consistent with those in some other studies with their own particular approaches.[1,8] In addition, among the digital design sessions for the two participants, these values were higher in sketching with the 2D program than those in the sketching with the 3D program, because the 2D program on a pen-based device provides an environment similar to sketching with a pen on a paper, which allows the designer to sketch on a tablet with a digital pen or touch a finger. The result supports Tang and Gero's[6] study, which used the 2D digital environment.

The balance between convergent and divergent thinking, which is evident in backlinks (<CMs) and forelinks (CMs>), emphasized the results that the balance between two types of CMs is considered as a more important factor in assessing creativity than the percentage of forelink CMs individually. The result supports Goldschmidt's proposition, as was already mentioned by which a frequent shift between convergent and

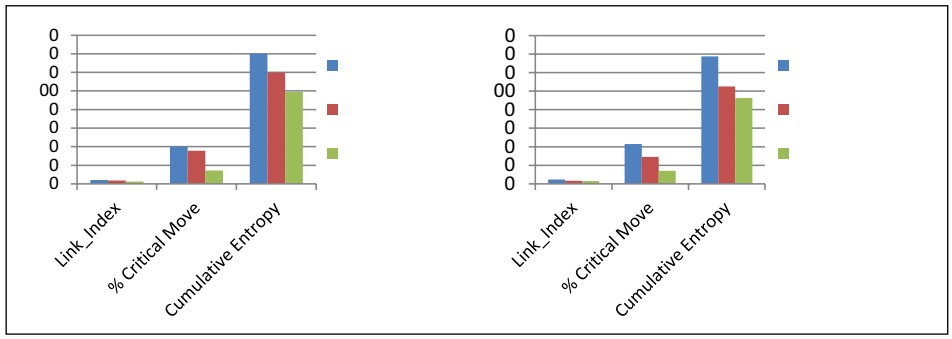

Figure 11. Results of link index, critical moves, and entropy in the three sessions related to SUB1 (left) and SUB2 (right).

divergent thinking can confirm a creative thinking process. She evaluated the shift between divergent and convergent thinking by measuring the percentages of the forelink and backlink CMs within the total CMs.[21]

In addition, the values of the three types of entropy including forelinks, backlinks, and horizonlinks were in line with the study results. The higher values related to the three types of entropy in the pen-and-paper session for both subjects demonstrated that the ideas were backlinked many previous ideas in these sessions, they were reinterpreted to develop the new ones simultaneously, and they had many influences in conversation.[20,23] Furthermore, the uMake session of SUB1 consists of some novel ideas, while the discussion was wholly fixated on the main idea in the uMake session of SUB2, and the three links of entropy tend to be low in both situations. Consequently, in these sessions, linked moves are close together without any farther links, which encourage strong cohesiveness. However, linked moves are far apart in the pen-and-paper sessions, which encourage the occurrence of incubation. The structures of linkographs confirm and reflect the results.

Furthermore, the higher mean values of X in the Sketchbook and uMake sessions of SUB1 and the uMake session of SUB2 suggest that links were distributed more toward the end of the sessions in these sessions (Tables 7 and 8), which represents better integration of moves according to Kan and Gero.[23] However, regarding the pen-and-paper session of SUB1 and the Sketchbook session of SUB2, more nodes have been created among moves in the beginning of the sessions indicating higher opportunities in generating ideas, which generally occur in the beginning of the sessions.

Conclusion

In general, current debates are keened on the sketching process and try to explain the process especially from the point of view of pen-based systems; the comparison of traditional sketching techniques with the digital ones is the main issue of concern. This study aimed to go beyond this situation; instead of looking to the process of sketching, it was focused on the conceptual design stage and how a pen-based system could develop/support the sketching action with proper software. Furthermore, this study aimed not at measuring the creativity but at comparing and discussing the productivity as a sign of creativity during the conceptual stage in three different design environments. In addition, this study emphasized more on pen-based systems developed to support the sketching action. As relevant with the aim, the study concerned the issues (is limited with) in the early design stage in the architectural design process and used protocol analysis to explain the relations in this stage through

design thinking;

conceptual design;

creativity;

sketching—both digital and pen and paper.

The concurrent protocol analysis is chosen for the evaluation of the empirical study. The think-aloud sessions in protocol analysis enable the subjects to explain their thinking in the given design tasks. It is evident that in protocol analysis 2–3 subjects are enough for the study. The measurement technique in this study was linkography analysis. Goldschmidt presented this tool to facilitate her own definition of productivity. Kan and Gero have extended its use to serve the specific purposes of their different studies. This technique allows analyzing design as a system and shows the relation of the smallest move with whole by "links," and this peculiarity is the best way to explain the essence of design movements, cognitions, and behaviors. Linkography is capable of tracing the design ideas and their connections; therefore, it facilitated the purposes of this study and this study was able to provide the base for applying the linkography in evaluating the conceptual design.

The method used in this study can be useful in cognitive comparative studies taking into account its new approach and the simultaneous application of several evaluation criteria (LI, CMs, and entropy) which were used in different studies to evaluate and compare design productivity, which is considered as "an indication of creativity."[18] These values matched together for both subjects which showed that the high values of these factors in the pen-and-paper design processes according to Goldschmidt are not related to a large number of repetitions in ideas. The designer's performance (not thought) was different among the three designing media. But in this research, since the "change" between the designer's actions and decisions was taken as a benchmark in measurement instead of the type of performance during the design, the designer's type of performance in the three media did not have a significant role effect on the quantitative findings. Regarding the 3D environment of uMake sessions, the designers used more physical and modification actions rather than changing design intention. This may be due to their limited cognitive interaction with the 3D digital sketching environment.[8]

In addition, the results demonstrated that, despite the fact that two participants were selected with two different educational stages, the results of the experiment were relatively the same for both. The performance of each subject was compared and evaluated in the design sessions with herself or himself without making any comparison among them. Furthermore, the complexity level of the selected tasks was suitable for designing and the participants did not have any problem with the media in terms of designing and reflection on the design problem. Future recommended research will, therefore, be useful with different software on various design briefs at different educational stages.

The findings of this study formed different views on digital and real presentation techniques from the point of view of design thinking via sketching; it is evident that the digital market is developing rapidly and technological improvements support the software, which enable digital sketching. As the final results indicated that pen-and-paper sketching was preferred, digital sketching had a great demand too. But we must not forget that in very early examples the gap between these two techniques was so large. Because today using digital sketching is more common than using a tool, the eye–mind–hand correlation is working in the same way whether the media is digital or not.

According to the findings, the results cannot be interpreted as the designers have a lower tendency to think, explore, and develop ideas in the digital medium. As discussed by Bilda and Demirkan,[8] digital media lacked supporting the designers' habitual activities such as doodling and sketching, because designers are accustomed to designing with conventional freehand sketching throughout their education, not the digital media. Thus, in this study, students could create a good design process with the 2D software, compared to the 3D sketching software, because of its similarity to the pen-and-paper sketching. This situation is predictable according to the digital background of students in the current architecture schools. Most 3D software used in previous studies were modeling software that work differently compared to sketching. In this study, the 3D sketching software (uMake) was used which could be properly chosen to be compared to the pen-and-paper

sketching. Although there are only a small number of these kinds of software, it is expected that with an increase in the cognitive research in the near future, more sketching tools become available. In addition, the market is developing so rapidly and getting more popular in architectural education. For the coming years, it is evident that more and more students get used to implement their design thoughts on a digital media besides pen and paper. Interdisciplinary studies in architecture, mathematics, and computer sciences with cognitive studies will formulate new approaches to lead new findings to support design thinking.

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Appendix

