Extended linkography and distance graph in design evaluation: an empirical study of the dual effects of inspiration sources in creative design

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All design is influenced by previous exposure to ideas in different formats and in different levels of abstraction. This paper introduces refined methods to represent and analyze the creativity and fixation effects of inspiration sources on designs. Based on a critical review of existing design research methods, we develop an extension of linkography and a distance graph to investigate design patterns among designers of different expertise levels and exposure to different inspiration sources prior to design. In our explorative experiment, novices and experts were given five types of external stimuli—keyword, diagram, plan, sketch rendering, and precedent photo—as inspiration sources for the same design task. Our extended linkography represents and measures the creativity and fixation propensities of different inspiration sources at the micro-level of design processes.

Keywords: creativity, conceptual design, extended linkography, design knowledge, design education

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Architects draw various sources of inspiration from daily life. The term 'inspiration sources' refers to all conscious uses of previous designs and other resources, as the references for the solution to the current problem (Eckert, Stacey, & Clarkson, 2000). Inspiration sources may take the form of the basic geometrical shapes, works of art, objects and phenomena from nature and everyday life, as well as abstract texts, architectural precedents, design sketches, diagrams, and technical drawings such as plans and sections. On the one hand, inspiration sources can facilitate design thinking and function as 'triggers for idea generation, and as anchors for structuring designers' mental representations of designs' (Eckert et al., 2000). On the other hand, exposure to inspiration sources can sometime lead to design fixation, 'a blind adherence' to certain set of ideas or concepts (Jansson & Smith, 1991; Tseng, Moss, Cagan, & Kotovsky, 2008).

www.elsevier.com/locate/destud
0142-694X $ - see front matter *Design Studies* **31** (2010) 146–168
doi:10.1016/j.destud.2009.12.003

Previous studies have found that specific sources such as word graphs (Segers, De Vries, & Achten, 2005), or visual stimuli (Goldschmidt & Smolkov, 2006) have different impacts. In this paper we explore how the modalities and representations of external stimuli—keyword, diagram, plan, sketch rendering, and precedent photos—impact designers' subsequent designs and particularly on their design fixation. We designed an explorative experiment to seek answers to several questions: To what extent, can sources of inspiration enhance or constrain creativity? How would different inspiration sources, presented as external stimuli, affect design performance? Do novices and experienced designers respond to external stimuli differently?

To explore these questions we have employed both qualitative and quantitative methods and are particularly interested in developing a method that allows analysis of links between the sources of inspiration and the target. Below, after a brief survey of the literature on creativity and design fixation, we describe the experiments and the analysis using an extension of linkography and a distance graph. The patterns of 'extended linkography' and 'distance graph' are developed to represent how exposure to various stimuli may enhance or inhibit design performance for designers of different levels of expertise. In the last section, we report the contribution and limitation of the current study and discuss directions for future development.

1 Stimuli as sources of inspiration in design

Several studies from different theoretical backgrounds have investigated the role of stimuli as sources of inspiration (Goldschmidt, 2001; Mednick, 1962). Associative theory claims that the creation of new ideas is the result of association, which can be facilitated by providing unique stimuli (Mednick, 1962). When external stimuli are applied as sources of inspiration, the stimuli form search cues in short term memory and then can be used to probe long-term memory to ease knowledge acquisition and enhance idea production (Nijstad, Stroebe, & Lodewijkx, 2002; Nijstad & Stroebe, 2006; Perttula & Sipilä, 2007). Once an idea is activated, it may further spread activation to other ideas with related attributes (Perttula & Liikkanen, 2006). Some computer-aided design tools are developed based on associative theory, aiming to stimulate design performance. For instance, Segers et al. (2005) proposed the Idea Space System to provide word graph as feedback to help architects generate more associations and increase novelty of design concepts. The use of word graphs is found to be useful in a divergent, explorative thinking process, rather than as a convergent and focused development.

Analogical reasoning is another important strategy that accounts for knowledge transfer from source to target (Casakin & Goldschmidt, 1999; Goel, 1997; Goldschmidt, 2001). Analogy is defined as a process of mapping and transfer from one situation to another based on 'similarities between relationships' (Goldschmidt, 2001: p 201). The process of analogical mapping and

transfer is a two-way operation: from a known example to abstraction, and from abstraction to a new candidate-example to solve the problem in hand (Goldschmidt, 1995). The transfer is made possible through the activation of the cognitive mechanism of mental visual imagery. Visual analogy has been shown to be an important strategy in solving ill-defined problems for both novices and experienced designers (Casakin & Goldschmidt, 1999). The presence or absence of visual stimuli is closely related to the originality of the resulting design idea (Goldschmidt & Smolkov, 2006).

1.1 Inspiration sources as design aids

Several researchers have examined the effects of external stimuli as design aids. They found that the impact on design performance was related to the modality of stimuli. For instance, Malaga (2000) designed an experiment for the participants to generate ideas in response to a specific task, by showing them words, pictures, and combined word and picture stimuli. He reported that pictures could induce more creative ideas than words and combined stimuli. Yet the impact of modality of stimuli may depend on the person who perceives them. For instance, Mednick (1962) has categorized people as 'visualizers' and 'verbalizers' based on their different tendencies of making associations. 'Visualizers' are adept at generating and manipulating mental images; whereas 'verbalizers' tend to produce creative solutions when there is a high verbal stimulus. Due to the nature of design education and practice, most designers are trained to be 'visualizers'. As a result, we expect that novices and experienced designers may respond differently to different stimuli modalities.

In addition, studies have shown that response to visual stimuli was related to the level of abstraction of the representations. Christensen and Schunn (2007) performed an experiment comparing the impact of external support systems in the form of sketches and prototypes generated by the designers themselves on design performance. They argued that physical prototypes contained more high-resolution and superficial details than sketching. Therefore exposure to prototypes would lead to more within-domain and surface analogies, whereas sketching would lead to more distant and structural analogies. Linsey, Wood, and Markman (2008) found that the level of abstraction for the representation of prior knowledge and the current problem both affect design performance. More general description and representation can facilitate mapping and knowledge transfer. Kokotovich and Purcell (2000) examined the different impacts on creativity of two-dimensional shapes and three-dimensional forms on different professions. Their subjects included graphic designers, industrial designers, and law students. They found that the subjects were more sensitive to the stimuli that were more typically used in their domains. For example, graphic design students performed better with two-dimensional shapes and industrial design students performed better responding to three-dimensional forms.

Expertise can affect how inferences are made from 'inspiration sources'. When source and target are at different abstract levels, it takes specific design experiences to 'instantiate' high-level abstractions (Bhatta, Goel, & Prabhakar, 1994). Suwa and Tversky (1997) claimed that professional architects were more adept at seeing functional and abstract properties in sketches than students. Novick (1988) found that experts drew analogies based on structural similarities while novices tended to retrieve surface features from inspiration sources. Similarly, Ball, Ormerod, and Morley (2004) reported in an experimental comparison of analogy use by experts and novices that, expert designers would demonstrate more schema-driven than case-driven analogizing, while novices tended to show the reverse pattern. Schema-driven analogy referred to the application of abstract knowledge or principle from the source to the target solution. Case-driven analogy referred to the mapping and transfer of elements from a prior example to current problem.

In summary, these studies support the notion that different modalities and representations of inspiration sources have different impacts on design performance. The responses also vary according to designers' level of expertise.

1.2 Inspiration sources as design fixation causes

While it can be beneficial, exposure to inspiration sources may actually impede creativity. It may produce cognitive interference or constraints for new design, thus leading to the occurrence of the premature commitment to a particular problem, referred as 'design fixation' (Jansson & Smith, 1991). For example, once an interpretation has been reached, it may be difficult for designers to see alternatives (Suwa, Tversky, Gero, & Purcell, 2001).

Evidence has shown that design fixation may be associated with seeing pictorial representations of possible design solutions. A pictorial representation can take the form of a photograph of a design precedent or a functional diagram. Jansson and Smith (1991) discovered that by showing students a diagram or a related concept associated with part of a diagram would make it hard for students to free their imagination. Purcell and Gero (1996) applied the modified Jansson and Smith's experiment on mechanical engineers and industrial designers. They found that mechanical engineers became fixated when they were forced to rely on everyday knowledge or being shown the principle involved in an innovative design. Similarly, Perttula and Sipilä (2007) indicated that common examples might cause more fixation than novel ones through a series of experiments on engineering students. The effect of design fixation may depend on the designers' level of expertise (Bonnardel, 2000). Experienced designers tend to be more influenced by the examples and design principles in their domain.

To sum up, these research findings illustrate that modality, degree of abstraction of the inspiration source and designers' level of expertise interact to impact design fixation.

2 The experiment

We conducted a pilot experiment to investigate to what extent the use of various inspiration sources affect the performance of novices and expert designers. The design task was to generate design schemes for a single-family house at around 1500 square feet (around 135 square meters), with 'sources of inspiration' given prior to design process. The program of the house included one master bedroom and one guest bedroom, each with its own bathroom. The total design time was 30 min with five sub-sessions. For each sub-session, the subjects were asked to generate as many schemes as they could within 5 min, based on one specific stimulus provided to them: 1) abstract textual description; 2) diagram; 3) plan; 4) sketch rendering; and, 5) precedent photo. All of the above stimuli were derived from the Frank Lloyd Wright's Robie House. They ranged from lexicon to pictorial stimuli. The first stimulus was a textual description of physical characters of the Robie House, stated as 'parallel, three rectangles, symmetric & asymmetric' (Figure 1). The second stimulus was a diagram composed of five rectangles, depicting the geometry of the Robie House (Figure 1). The third was the plan of the first floor (Figure 1). The fourth was an exterior sketch rendering of the Robie House (Figure 1). The last one was the black and white exterior photo of the Robie House (Figure 1e). The stimuli were similar in content, but different in modality and representation types. The sequence of showing text–diagram–plan–sketch rendering–photo was based on the level of abstraction.

2.1 Participants

Three subjects participated in this experiment. Subject-A is a PhD student in Industry System & Engineering. She has no prior architectural design experience. Subject-B has 7 years of architecture education and 3 years of professional design practice. Subject-C has 10 years of architecture education and 8 years of professional practice.

2.2 Experimental setting

We asked the three subjects to perform the experiment in their daily work settings to minimize the impact of physical environment on creativity (McCoy & Evans, 2002). Subjects were tested individually. The experimenter presented the design problem and explained the procedure to the participating designer and did not intervene during the design process. Participants were asked to draw and 'talk-out-loud'. They could either sketch or make hard line drawings. The design activities were videotaped. We interviewed the participants after they finished their design tasks. They were asked to report the subjective evaluation on their design performance and how the uses of different inspiration sources affect their design.

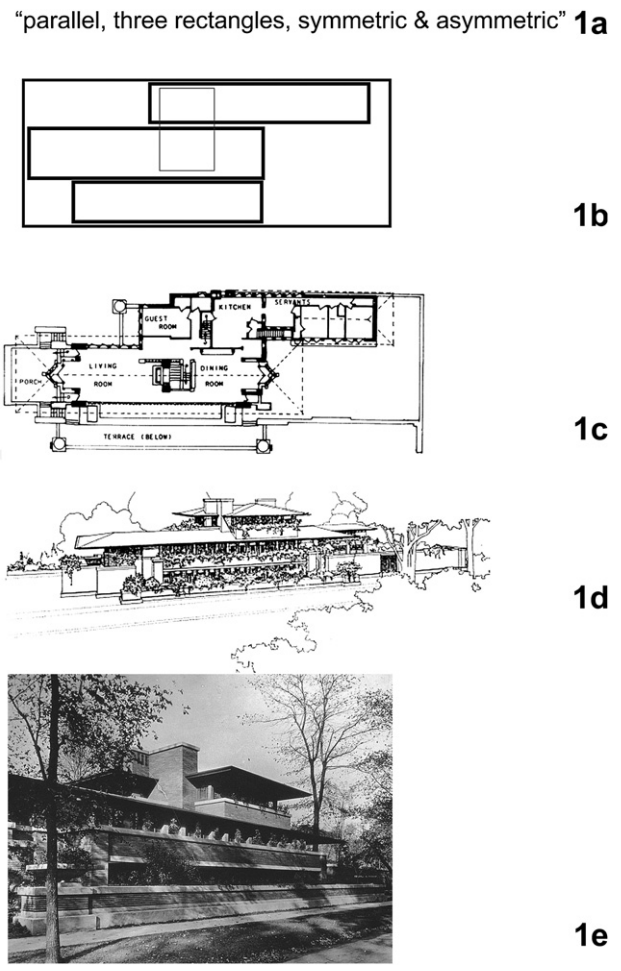


Figure 1 (a) Inspiration sources No. 1: textural description. (b) Inspiration sources No. 2: diagram. (c) Inspiration sources No. 3: floor plan (Source: http://www.delmars.com/wright/flw8-5.htm, Copyright: Frank Lloyd Wright Foundation). (d) Inspiration sources No. 4: exterior sketch rendering (Source: http://www.delmars.com/wright/flw8-5.htm, Copyright: Frank Lloyd Wright Foundation). (e) Inspiration sources No. 5: exterior photo (Source: Great Buildings Collection)

2.3 Coding scheme

All graphic output was collected and indexed according to the coding scheme developed from a previous study (Neiman, Gross, & Do, 1999). In this study, we indexed the drawings according to the subject, the experiment sub-session, the sequential number of solution type and process sketch. For instance, 'Sc-T-N2-4' referred the fourth sketch of the second solution generated by Subject-C in the 'Text as inspiration' sub-session. To differentiate 'plan' and 'photo', we used 'PL' as abbreviate of 'plan' and 'PH' as abbreviation of 'photo'. For each drawing, the information we coded including the drawing type, design transformation as compared to inspiration source, design transformation as compared to previous sketch, related 'distance from inspiration source' and the 'distance from previous sketch' (Table 1). The 'distance from inspiration source' was based on the degree of design transformation that took place between the source image and the current sketch; the 'distance from previous sketch' was based on the degree of transformation from the previous sketch.

Table 1 Coding scheme for the drawings generated during the experiment

ID#	*Drawing type*	*Design transformation compared to inspiration*	*Distance from inspiration source*	*Design transformation compared to previous sketch*	*Distance from previous sketch*
Sa-T-N1	D1: plan	F1: direct reference	1	F1: direct reference	1
	D2: section	F2: formal variations	2	F2: formal variations	2
	D3: elevation	F3: functions variations	3	F3: functions variations	3
	D4: isometric	F4: spatial variations	4	F4: spatial variations	4
	D5: perspective	F5: context consideration	5	F5: context consideration	5
	D6: other	F6: other further modification	6	F6: other further modification	6

Similar approaches have been used earlier (Perttula & Sipilä, 2007; Van der Lugt, 2000). The value varied from 1 to 6. We defined 'direct reference' as 1; 'formal variation' as 2; 'functional variation' as 3; 'spatial variation' as 4; 'surroundings and context consideration' as 5; 'other further consideration and modification' as 6.

Here the 'distance value' is one of the key indexes we propose to measure design development and creativity. We believe that creativity is associated with knowledge transfer. Specifically, the greater transfer of abstraction level and greater distance between the 'source' and the 'target' the higher the creativity. According to the content of the knowledge transferred, researchers have categorized inspiration sources based on 'surface similarity' and 'deep (structural) similarity' (Gentner, 1983). Adaptation based on 'structural similarity' is believed to relate to transference of higher hierarchy of knowledge. Therefore, it may lead to more creative design (Casakin, 2004). Similarly, Goel (1997) stated that the degree of creativity depends on the extent of problem and solution reformulation and the transfer of knowledge from different knowledge sources to the current problem. Likewise, associative theory claimed that the greater the distance between associative elements the greater the possibility of a creative response (Mednick, 1962).

2.3 Qualitative comparison of three subjects' design performance

The experimental results showed different reactions to various stimuli across three subjects. In this section we will first present an overview and qualitative analysis of the experiment results and then apply our 'extended linkograph' and 'distance graph' to represent and analyze the results in detail.

Overall, Subject-B generated the largest amount of alternatives during all subsessions. Subject-A and Subject-C produced similar number of alternatives. But Subject-C produced more sketches when developing design alternatives. The results are presented in Table 2.

Table 2 The number of design alternatives and process images created by each subject in each sub-session

		Text	*Diagram*	*Plan*	*Sketch*	*Photo*
Sa	Design alternatives	3	2	2	1	0
	Process sketches	3	2	2	1	0
Sb	Design alternatives	5	5	4	2	3
	Process sketches	5	5	4	4	4
Sc	Design alternatives	2	2	3	1	1
	Process sketches	4	3	6	5	2

Subject-A showed low productivity in creating design alternatives. In 'diagram' and 'plan' sessions, she exhausted design alternatives before she reached the time limit. She considered the diagram stimulus inhibited her design the most. During the 'photo' session, she failed to create any design based on the inspiration source. She expressed her difficulty in understanding and using the photo, as she cannot 'imagine the interior space'. High similarity was found among her design alternatives. Most of them were 'surface analogy' from the inspiration source (Figure 2a, b).

> 00:21:25, 'I think all of them look similar, not too many differences. I really feel frustrated.'

Subject-B showed a higher productivity in his designs than Subject-A. In the 'sketch rendering' and 'photo' sessions he explored both spatial transformations and the context of the surrounding environment. His sketches expanded from plan view to both plan and elevation views. The landscape elements such as plants were included in his drawings (Figure 3a–d). For Subject-B, sketch renderings and photos were most helpful to his design. He claimed that these two stimuli provided more design details for him to develop the design in-depth (vertical transformation) instead of developing variations of design alternatives (lateral transformation). At that stage, he was 'not going for more alternatives', but concentrating on developing the ideas derived from the given stimuli. They gave him more information and more constraints at the same time.

> 00:30:05, 'You could see the whole context of the surrounding.'

Subject-B also identified text as an important source of inspiration in the experiment. He said those keywords were open-ended and allowed more

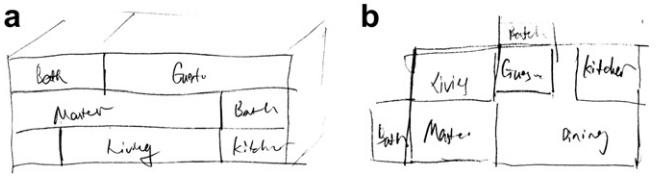
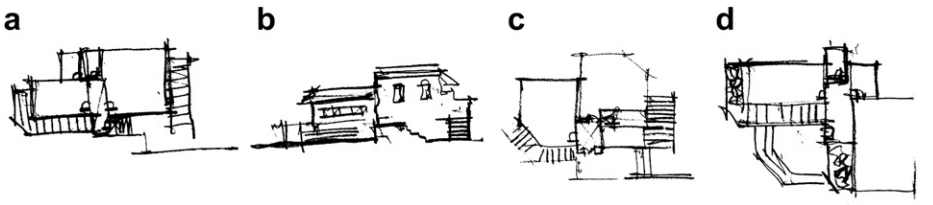


Figure 2 (a) (Left) sketch by Subject-A in 'plan' session (Sa-PL-N2). (b) (Right) sketch by Subject-A in 'diagram' session (Sa-D-N1)



Figures 3 (a–d) Sketch by Subject-B in 'photo' session (Sb-PH-N1-1, Sb-PH-N1-2, Sb-PH-N2, Sb-PH-N3)

possibilities. He described having difficulties in distilling the geometry from the diagram to use in his designs because it was too abstract to digest in a short period of time.

Subject-C produced fewer alternatives but demonstrated more depth in design exploration. He made a distinction between 'inspiration tool' and 'development tool'. For him, words 'opened a lot of doors' as inspiration, whereas sketch rendering changed the way he viewed things and fostered the design development (Figure 4a–d). Once he recognized that the case was Wright's Robie House in the third sub-session ('plan as inspiration'), he started to relate his design to the precedent case. The content and the design principles of the precedent became the dominant idea in his new design. He found himself fixated since then.

> 00:36:21, 'You will go for that and imitate the idea. At the moment you recognize it (being Wright's Robie House), you got stuck with his idea.'

2.4 *Qualitative interpretation of experiment results*

The sample size is too small to draw any generalizable conclusion. Yet some interesting patterns start to emerge. During the interview, all three subjects claimed textual description and sketch rendering were helpful inspirational stimuli for design. Participants created similar numbers of alternatives in

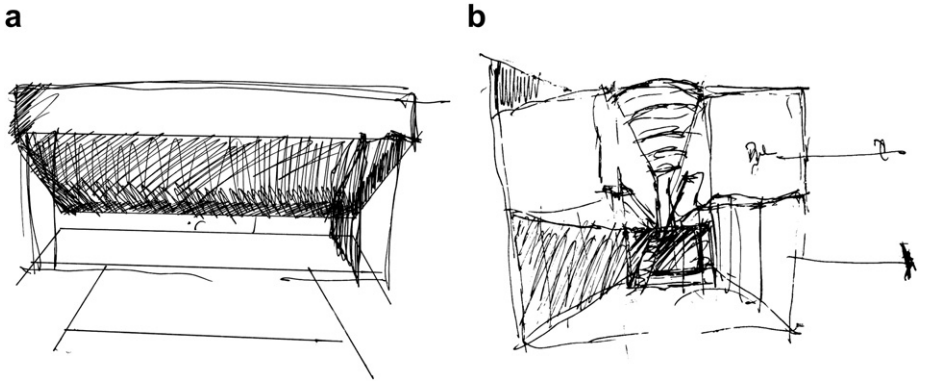


Figure 4 (a) (Left): sketch by Subject-C in 'photo' session (Sc-PH-N2). (b) (Right): sketch by Subject-C in 'plan' session (Sc-PL-N2)

the 'text' and 'sketch' sessions and showed no obvious fixation effect for either of them. This may be related to the abstraction level of the stimuli. Textual description is the most abstract external stimuli. Designers tend to rely on everyday experience to establish the mapping and transfer from this source. Therefore, novices can use text as inspiring source almost the same way as experienced designers. The result is consistent with Segers et al.'s (2005) finding that verbal stimuli can facilitate divergent, explorative thinking process. Sketch renderings are beneficial to novices and experienced designers for different reasons. For novices, sketch renderings contain visual information that is closely related to real-life experience, helping them evoke sources that they are familiar with. For experienced designers, sketches contain some contextual information, which allow them to shift design focus and retrieve the domain knowledge. Diagrams impact on creativity differently depending on the person's design experience. Diagrams constrain creativity for novices and less experienced designers. The fixation effect does not seem to impact experienced designers so seriously. We argue that because the diagram is such an abstract visual stimulus, it requires domain knowledge to establish the mapping and transfer. Less experienced designers or novices may fail to evoke connections due to the lack of domain knowledge and time limitations.

3 *Evaluation of creativity and degree of fixation*

The number of designs and the interview data help us understand the general pattern of design productivity. However, the differences in the resulting design quality between novices and experts across various sub-sessions cannot be fully revealed by the qualitative analysis. For instance, in the sketch session, Subject-A created more design alternatives than Subject-C. However, the higher number of design alternatives generated does not necessarily lead to higher creativity. Therefore, we need to find a method to reveal the impact of inspiration sources on design performance at a 'microscopic' level. Several researchers have proposed ways to evaluate creativity and design fixation. Goldschmidt and Smolkov (2006) used judges to give subjective scores for originality, practicality and the general quality of design. The design solution was considered creative if both the sum of its originality scores and practicality scores were at least 11 out of 15 (maximum). However, this approach depends on subjective judgment, and lacks consistency and reliability.

Jansson and Smith (1991) used 'the number of designs', 'the number of replication of errors appeared in example', and 'the number of designers which were highly similar to the example design' to evaluate the level of design fixation. Yet the criterion of 'highly similar' is vague. They did not specify how they differentiated whether the adaptation of inspiration source is based on the replication of design features or the design principles. Purcell and Gero (1996) proposed 'the frequency of occurrence of design feature details', 'the frequency of occurrence of design principles', 'the number of designs', and 'the range of design solution types' as indices of fixation effect. They believed

that if there were more feature details and principles associated with the example appeared in the design product, less number of designs and smaller range of design solution types would be generated, as the design process would tend to be more fixated. The quantitative description method does provide a macroscopic understanding of the design fixation. But the inter-relationships between different measures are not defined. It is not clear if 'the frequency of occurrence of design features', 'the range of design solution types' and 'the number of designs' are equally important for detecting fixation effects. In one of their experiments, Purcell and Gero (1996) asked advanced students in mechanical engineering and industrial design to design a device for assisting the elderly into and out of a bath in a domestic setting. They were presented with a pictorial representation of an Autolift device, which embodied typical mechanical engineering principles. The fixation effect was found in mechanical engineers' group. However it was only related to the measure of 'the frequency of occurrence of design features', but not significant for the other two measures, 'the number of designs produced' and 'the number of solution types'.

3.1 Linkography

Goldschmidt's (1990) linkography provides a more fine-grained assessment of design performance and linkage between the source and design product. In the linkograph, the sequence of moves is represented as hollow dots aligned in a horizontal line and the links are the nodes at the intersections of diagonal network lines connecting two related moves (Figure 5). Goldschmidt (1992) found that the distribution of links among design moves could represent the general pattern of design process. In her definition, the link index is the ratio between the number of links and the number of moves generated in a design cycle. A chunk refers to 'the block of links among successive moves that link exclusively among themselves and barely interconnected with other moves'. A web refers to a relatively small number of moves with a large number of links. The linkograph of more creative design would display higher link indexes, more chunks and more webs.

3.2 Extension of linkography by other scholars

As Goldschmidt and Tatsa (2005) have identified, the links are determined by common sense, which have certain ambiguity. Some researchers have further

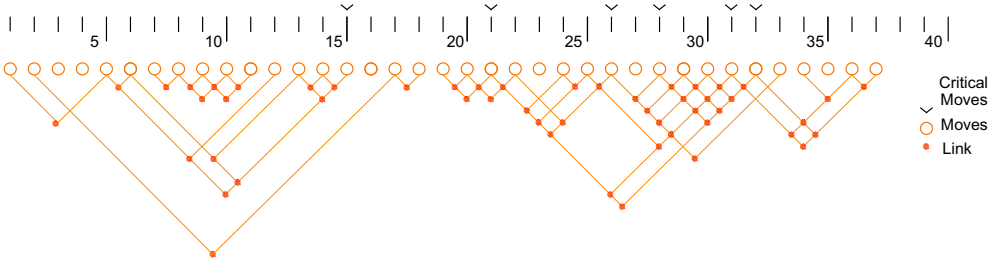


Figure 5 Linkograph of design cycle (Goldschmidt, 1990)

extended linkography based on the definition of link. For example, Van der Lugt (2000) has extended links into three types such as 'supplementary' (S), 'modification' (M) and 'tangential' (T) links. The 'supplementary' link indicates small and auxiliary change on the same general idea; the 'modification' link refers to structural changes in the idea, while maintaining the existing line of thought; the 'tangential' link represents a radical change from the previous idea based on free association. Van der Lugt (2000) proposed the link type indexes (LTI) as the measurement of creativity in design process. A higher LTIT indicated rich novelty of design ideas while a higher LTIS and LTIM signified thorough idea development. A well-integrated creative process should have a large network of links and a balance of link types. Similarly, Perttula and Sipilä (2007) developed a metric named 'weighted link density' by assigning different weights for three links, parts sharing (PS), same principle (SP) and modification (MD), respectively. The higher 'link density index' would lead to a higher genealogical linkage between examples and solutions, which was a symbol of design fixation.

Another development is focused on the interpretation of linkographs. Kan and Gero (2005, 2008) considered the linkographs from the statistical viewpoint. They removed the linking lines in the linkographs and considered only the nodes (links). They analyzed the scattering distribution of links by calculating the means and standard deviations of *X*- and *Y*-axes. They adopted entropy from information theory for measuring creativity in linkographs. They claimed that the higher entropy of forelink and backlink implied a richer idea generation process as they reveal higher degree of uncertainty. Another important index they introduced was 'horizonlink entropy', which measured the time separation between linked moves. The higher value indicated a mixture of long and short links, which led to cohesiveness an incubation of ideas without early fixation.

3.3 'Extended linkography'

The methods above are objective and effective. Van der Lugt (2000) provided us the insights about the complexity of the links. However he focused on the quantitative calculation of link types without incorporating them into representation of linkograph. Kan and Gero's (2005) statistical approach measured creativity in a global manner. Nevertheless the transfer of inspiration source to design moves and the inter-relationships among each design move cannot be fully represented by the entropy. In order to describe microscopic level information about the design process, we propose an approach called 'extended linkography' that combines the concept of 'lateral transformation' (LT) and 'vertical transformation' (VT) with the current linkography. In a 'lateral transformation' the movement is from one idea to a slightly different idea, or an alternative idea. In a 'vertical transformation' the move is from one idea to a more detailed or elaborated version of the same idea (Goel, 1995). In other words, an LT is a process that broadens the problem space while a VT deepens

the problem space. Here we use LT and VT to represent the linkages between each 'move' in design. The consideration of L_{LT} is similar to the 'tangential link', and the L_{VT} is similar to the 'supplementary link' and 'modification link' defined by Van der Lugt (2000).

Goldschmidt (1995) defined a design move as 'a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move'. In the 'extended linkograph', we identified each design sketch as the primary unit or move in the protocol. The definition of move in this study allows investigation of a long design process, where contains a large number of design sketches. We defined the given stimulus as the first move. The following moves referred to the process sketches that were generated in the subsequent design sub-session. The moves were aligned with the previous move either horizontally or vertically, depending on the direction of the linkage between them (LT and VT). L_{VT} was expressed in vertical axis and L_{LT} was expressed in horizontal axis. Let's use an example from the experiment to illustrate the generation and reading of the extended linkography (Figure 6). In the text sub-session of Subject-C, he generated 4 process sketches and 2 design alternatives, one process sketch for the first design alternative and three process sketches for the second design alternative. We coded the design alternatives as Sc-T-N1 and Sc-T-N2. Since there was only one process sketch for the first

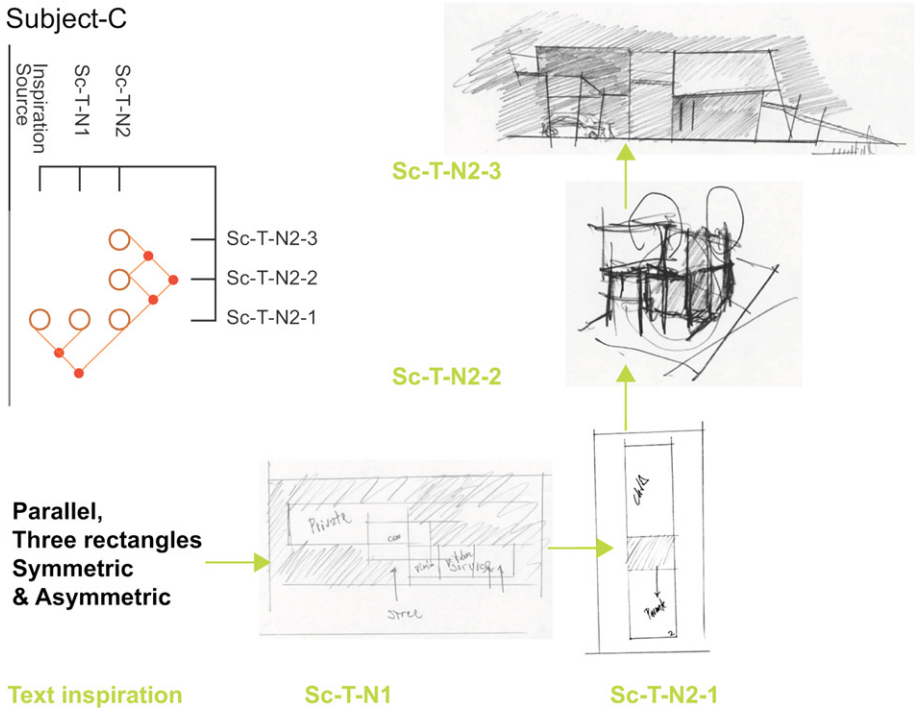


Figure 6 Example of extended linkograph analysis on Subject-C's design in the 'text as inspiration' sub-session

design alternative, we coded the process sketch as Sc-T-N1 as well. The process sketches that he produced for the second design alternative were coded as Sc-T-N2-1, Sc-T-N2-2, and Sc-T-N2-3, respectively. All process sketches were represented as hollow circles and all links between design moves were represented as solid dots. In addition, we designated the textual inspiration source as the first hollow circle. Since the first design alternative (Sc-T-N1) was based on lateral transformation (LT) of inspiration source, it was aligned with the first hollow circle in horizontal direction. The second process drawing Sc-T-N2-1 was a different design idea comparing to the first process drawing Sc-T-N1. So we aligned Sc-T-N2-1 next to Sc-T-N1 horizontally. Process sketches Sc-T-N2-2 and Sc-T-N2-3 were aligned to Sc-T-N2-1 in vertical axis, because they were further explorations of Sc-T-N2-1 based on vertical transformation (VT). The textual notations on the horizontal axis denoted the names of design alternatives; the textual notation on the vertical axis denoted the names of process drawings. According to the development of design process, the reading of 'extended linkography' would follow the sequence from left to right, from bottom to up.

The distribution pattern of 'extended linkograph' can represent creativity and fixation in a design cycle. The more creative the design is, the higher number of alternatives and more chucks and webs are displayed in the 'extended linkograph'. In addition, the more linkages are connected to the adjacent previous moves, the more features associated with the previous move appeared in the latter moves. The frequent repetition of elements of the previous move is a sign of fixation. Another virtue of 'extended linkograph' is that it differentiates the links between moves as L_{LT} and L_{VT}. It helps to reveal productivity in both the lateral and vertical dimension. Let's use the 'extended linkograph' in Figure 7 as an example. Although Subject-C generated less design alternatives than Subject-A (2 solutions versus 3), Subject-C was more creative in another sense, as he presented more in-depth exploration in one design option other than seeking for unrelated alternatives. Therefore, we extended the link density index (LDI) to L_{VT} index (LDI_{VT}) and L_{LT} index (LDI_{LT}). LDI_{VT} is the ratio between the number of vertical transformation link and the number of total design moves. LDI_{LT} represents the ratio between the number of lateral transformation link and the number of total design moves. The distribution pattern of linkograph together with the extended measures of link density indexes

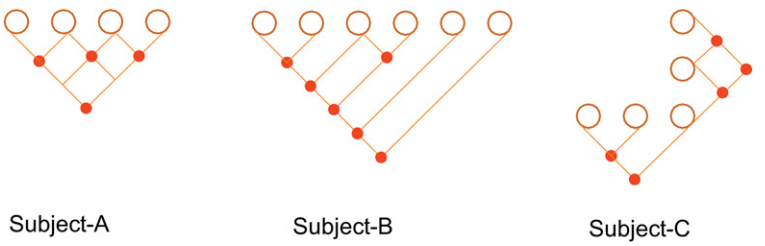


Figure 7 Example of extended linkograph for comparing design performance

(LDI, LDI_{VT}, LDI_{LT}) can provide more insight about the impact of inspiration sources on design performance.

3.4 Distance graph

In order to quantify the development of design process, we developed another method called a 'distance graph', which was based on the distance value we have assigned for each process drawing (see Section 2.3). In the 'distance graph', we mapped the 'distance from previous sketch' in the *X*-axis and 'distance from inspiration source' in the *Y*-axis. The inspiration source was designated as the origin of the coordinate system (0, 0). For example, Subject-A produced 3 design alternatives in the textual stimulus sub-session. The textual stimulus was represented as the origin. Her first drawing in text session Sa-T-N1 was a 'direct reference' of the 'textural stimulus'. Therefore, its distance from the 'inspiration source' was 1. We plotted the value of 1 in both *X*- and *Y*-axis to define the coordinates of Sa-T-N1. Sa-T-N2 was a 'functional variation' of Sa-T-N1. So the distance between Sa-T-N2 and Sa-T-N1 in *X*-axis was 3 units. Comparing to the textual stimulus, Sa-T-N2 was based on 'functional variation' of the source. As a result, the value of Sa-T-N2 in *Y*-axis was 3. The resulted coordinated for Sa-T-N2 was (4, 3). Similarly, Sa-T-N3 was a 'formal variation' of Sa-T-N2, hence it was 2 units away from Sa-T-N2 in *X*-axis. The transfer from the textural stimulus to Sa-T-N3 was based on a 'functional variation'. Hence we assigned 3 as the value of Sa-T-N3 in *Y*-axis. The resulted coordinates for Sa-T-N3 was (6, 3) (Figure 8).

By defining the 'distance from previous sketch' in *X*-axis and 'distance from inspiration source' in *Y*-axis, we can derive the coordinates of each design move in the distance graph. It can visualize how each design move is transferred from the inspiration source, and signifies the level of abstraction of

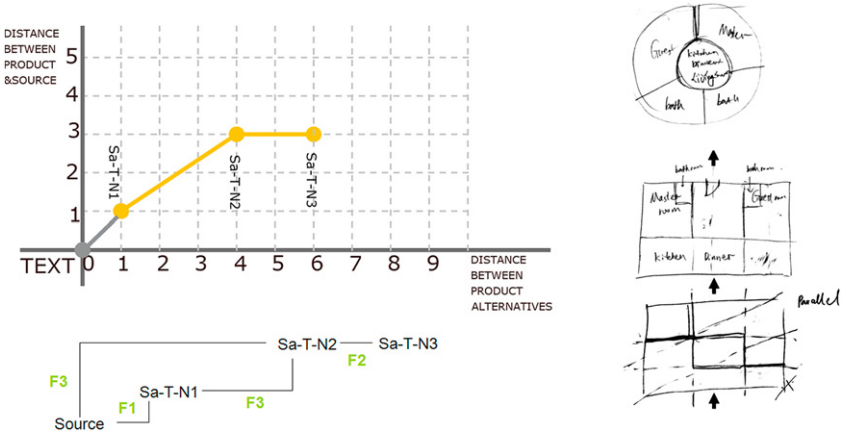


Figure 8 Example of 'distance graph' on design experiment of Subject-A in 'text' sub-session

knowledge transfer. It also portrays the shift of design focus across different design moves, which can help us to capture the creativity and fixation effect.

4 *'Extended linkography' and 'distance graph' analysis*

In order to cross-compare the design performance related to different modalities of inspiration source and designers' experience level, we arranged all

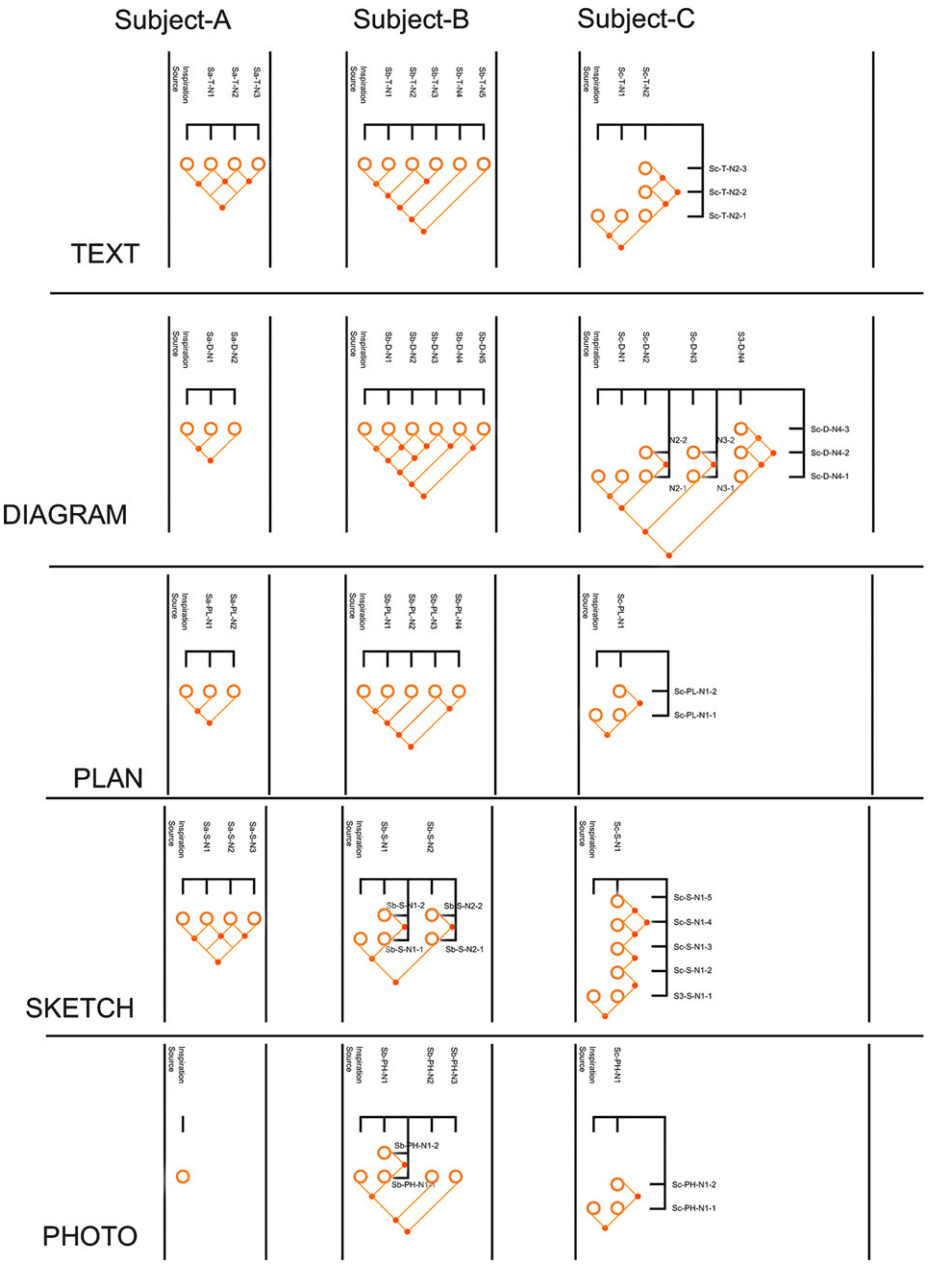


Figure 9 Aligned 'extended linkograph'

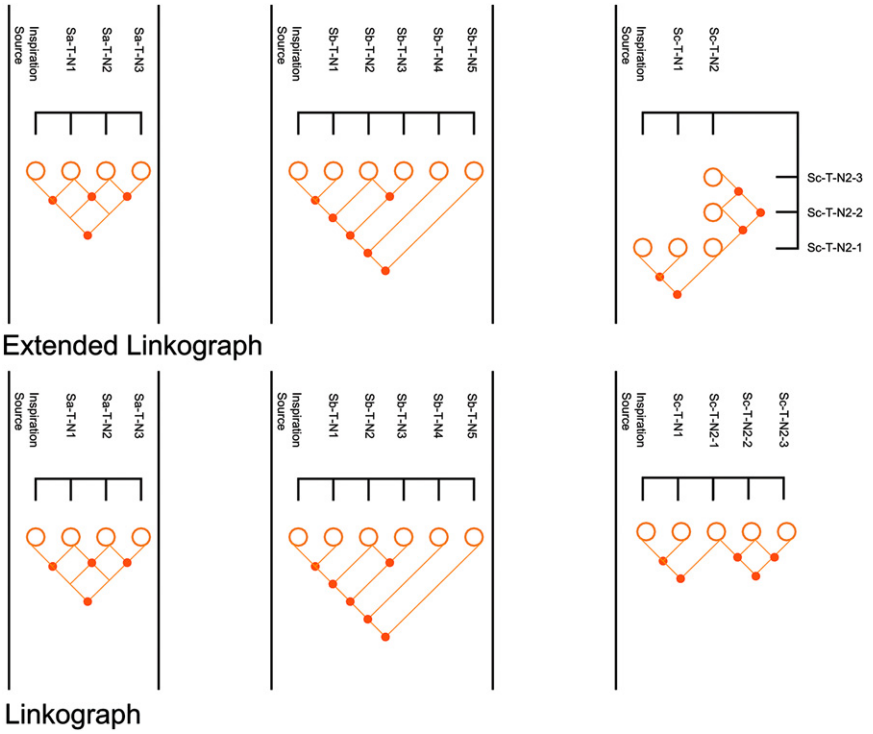


Figure 10 Comparison of 'extended linkograph' and traditional linkograph

individual graphs together into a 5-by-3 matrix. Each column represents one subject. Each row represents one specific modality of external stimuli. Figure 9 shows the resulted aligned extended linkography.

4.1 'Extended linkography' analysis

From the aligned 'extended linkograph', we can tell that Subject-B and Subject-C were more productive and creative than Subject-A, since there were more chunks and webs in the graph. Subject-C had more L_{VT} and showed an obvious earlier fixation comparing to Subject-B. In terms of different stimuli, we found some subtle differences, which were not shown in our qualitative study. Although all the subjects had identified text to be helpful

Table 3 LDI, LDI_{LT} and LDI_{VT} of different subjects in each sub-session

	Subject-A			*Subject-B*			*Subject-C*		
	LDI	LDI_{LT}	LDI_{VT}	*LDI*	LDI_{LT}	LDI_{VT}	*LDI*	LDI_{LT}	LDI_{VT}
Text sub-session	1.00	1.00	0.00	1.00	1.00	0.00	1.33	0.25	0.75
Diagram sub-session	0.67	1.00	0.00	1.67	1.00	0.00	1.00	0.44	0.56
Plan sub-session	0.67	1.00	0.00	1.00	1.00	0.00	0.67	0.50	0.50
Sketch rendering sub-session	1.00	1.00	0.00	0.67	0.50	0.50	1.00	0.17	0.83
Photo sub-session	0.00	0.00	0.00	0.80	0.75	0.25	0.67	0.50	0.50

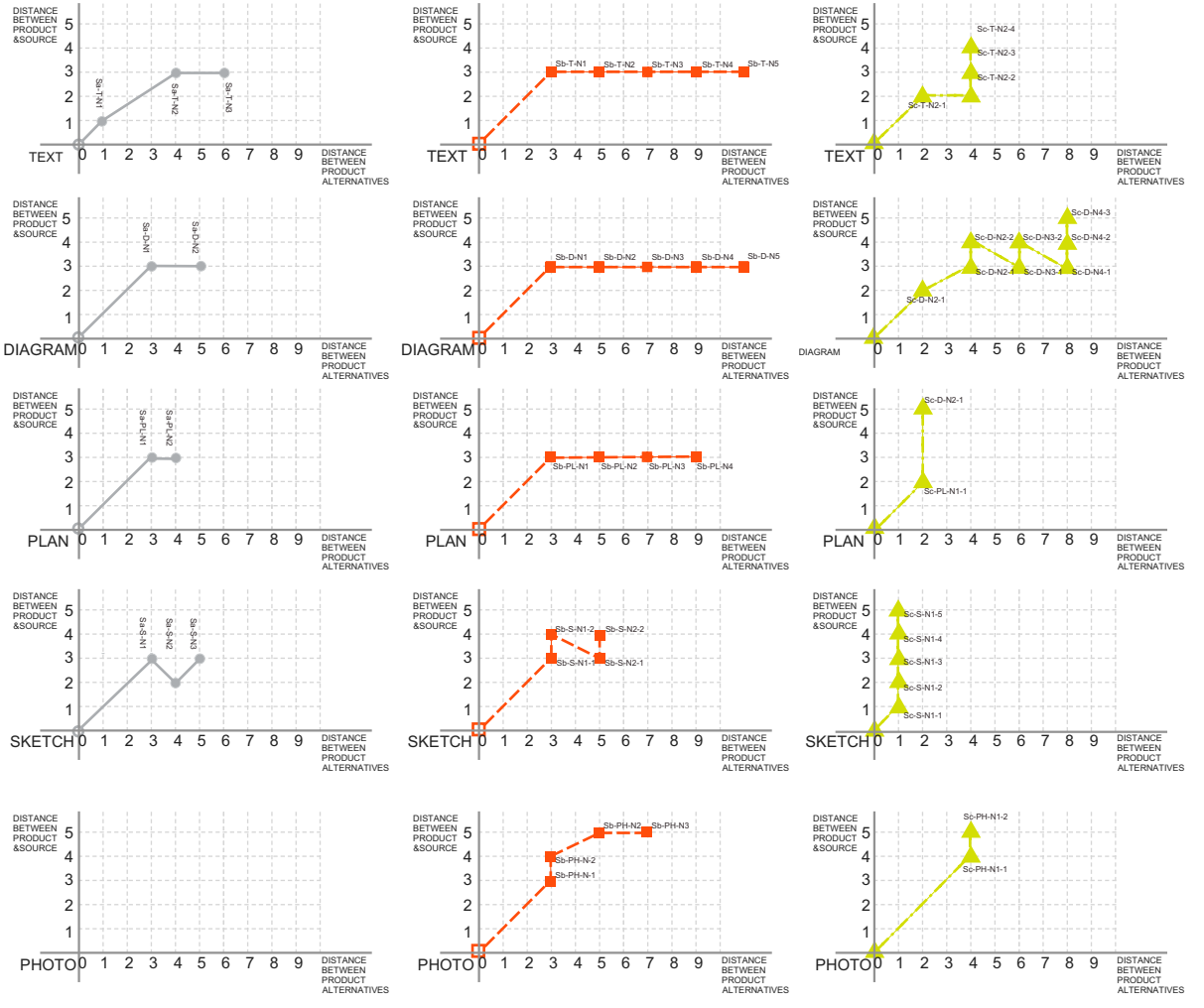


Figure 11 Aligned 'distance graph'

stimulus for them, they reacted to it in different ways. Subject-A and Subject-B generated more alternatives with text stimulus whereas Subject-C developed an in-depth design instead of alternatives. In the diagram sub-session, the three subjects had different responses. Compared to

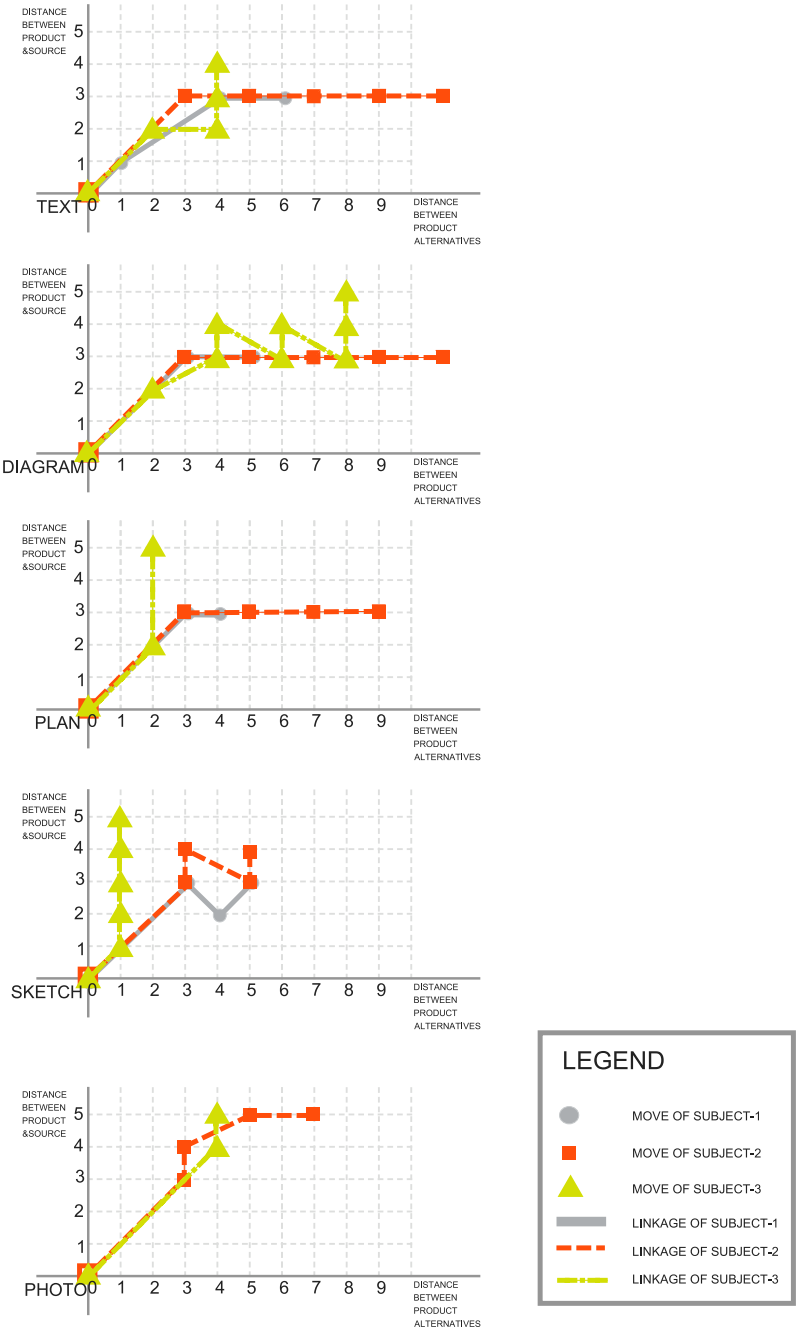


Figure 12 Overlay of three subjects' design performance in each sub-session in 'distance graph'

Subject-A, Subject-B and Subject-C had better performances. But Subject-B displayed stronger fixation than Subject-C, as there were more recurrences of elements from previous moves in Subject-B's linkograph. It was consistent with Subject-B's claiming of 'lack of time to decide what to capture from the diagram'. Plan and photo didn't work well as inspiration sources for any of them. Especially for Subject-C, the breadth and depth of design exploration decreased dramatically in the plan and photo sub-sessions. The result was in agreement with Subject-C's self-reflection that recognizing the Robie House had constrained his exploration. Our finding seemed to support Perttula and Sipilä's (2007) statement. They claimed that familiar examples related to domain knowledge might constrain the designers' perception of the problem space, and cause the search process to focus only on a few categories or principles. Sketch rendering demonstrated as being helpful in enhancing all subjects' productivity. However, Subject-A showed lower design performance than other subjects. We believe that the idea generation is composed of a two-stage cognitive process, 'knowledge acquisition' followed by 'idea production' (Nijstad & Stroebe, 2006). Although sketch rendering formed an active search cue, Subject-A did not have enough domain knowledge to support the design generation. Whereas for Subject-B and Subject-C, the sketch rendering provided them rich cues to activate the domain knowledge and led to more in-depth design. These results matched with our qualitative analysis of each sub-session. However, it also disclosed more fine-grained information for us to interpret the subtle differences across the subjects and sub-sessions.

If we compare the 'extended linkography' to traditional linkography, we can find that the new method is capable of capturing the microscopic characters of design process. The fixation of Subject-C is better represented in 'extended linkography' (Figure 10). We also discover that the link density index (LDI) alone cannot precisely reflect the creativity of design. For example, in textual description sub-session, Subject-C had higher LDI than Subject-B (1.33:1), which seemed to be an indicator of higher creativity. But as we included L_{VT} index (LDI_{VT}) and L_{LT} index (LDI_{LT}), we found Subject-C had a much higher ratio of LDI_{VT} than LDI_{LT}, which demonstrated a tendency of early fixation (Table 3).

4.2 'Distance graph' analysis

Similar to 'aligned extended linkograph', the 'distance graph' was arranged horizontally according to different subjects and vertically according to various stimuli (Figure 11). By overlaying the three subjects' distance graphs together, we found the differences between novices and experts in transferring knowledge from source to design products (Figure 12). Subject-A's analogy was the lower level 'surface analogy' since distance value between her design and the original source was low. Subject-B and Subject-C were apt to draw 'structural analogy' as they had overall higher distance values in the *Y*-axis. In

addition, Subject-B expanded the breadth of problem space during his design, and his pattern exhibited the largest *X*-axis value among the three. By contrast, Subject-C went in depth into the problem space. His design pattern had the largest *Y*-axis value but relative small *X*-axis value.

5 *Conclusion and future work*

In sum, we designed a small-scale experiment to empirically examine the impact of various stimuli as inspiration sources on design performance. We proposed 'extended linkography' and 'distance graph' as methods to represent and analyze dual effects of inspiration sources on creative design process. The definition of links based on 'lateral transformation' and 'vertical transformation' allows us to represent both the breadth and the depth of the problem space explored in design. The 'distance graph' can reveal the degree of developments both from stimuli source to design moves and among design moves themselves. We tested the methods with the data from our pilot experiment. The results were promising, as they were in line with our qualitative analysis. We found textual descriptions and sketch renderings helpful in facilitating innovation and not causing early fixation. Furthermore, we found that subjects' ability to make valid and higher level analogies is contingent on their design experience and domain knowledge. Novices tend to make surface analogy, while experienced designers tend to make structural analogy. Novices prefer stimuli that can help them establish the mapping and link to their everyday knowledge. At the same time, recognizing a familiar domain example (e.g., Wright's Robie House) can cause experienced designers to focus only on a few categories or principles (as exhibited in the design precedent) and lead to fixation.

Although the findings cannot be generalized due to the small sample size, the new methods are useful for future research as they help us discover the subtle difference of design performance with respect to creativity and fixation, which cannot be described by the qualitative study or the traditional linkography alone. In our study we didn't consider the impact of the order of stimuli exposure. All the stimuli in this study were based on the same precedent case. We presented these stimuli to the subjects in the same order. However, for experienced designer, the recognition of the precedent in an earlier sub-session may create bias for the latter sub-sessions. In our future study, we will include more diverse population of participants, separate subjects into groups, and randomly assign each group to a different sequence of stimuli exposure.

Acknowledgements

This manuscript is based on an earlier study supervised by the second author. Part of the study was presented at the IASDR07 conference (International Association of Societies of Design Research) on November 2007. Revision of this paper has been supported by both the second and the third author. We are

very grateful to the insightful advices from Professors Gabriela Goldschmidt and Nancy Yen-wen Cheng and the anonymous reviewers for the journal of Design Studies.

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