COMPARING ENTROPY MEASURES OF IDEA LINKS IN DESIGN PROTOCOLS

Linkography entropy measurement and analysis of differently conditioned design sessions

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Abstract. This paper explores using Shannon's entropy of information to measure linkographs of twelve design sessions which involved six architects in two different experimental conditions. The aim is to find a quantitative tool to interpret the linkographs. This study examines if the differences in the design processes and the design outcomes can be reflected in the entropic interpretations. The results show that the overall entropy of one design condition is slightly higher than the other. Further, there are indications that the change of entropy might reflect design outcomes.

1. Background

The aim of this study is to explore the use of a quantitative tool – entropy measurement of a linkograph – in protocol studies of designers in order to provide insight on design activities, especially at the early stage of idea development. This section presents the necessary background for this study; they are the construction of linkography, the measurement of linkography using Shannon's entropy, and the theory and method of the blindfolded designing experiment.

1.1. LINKOGRAPH

Linkography was first introduced to protocol analysis by Goldschmidt (1990) to assess design productivity of designers. It is a technique used in protocol analysis to study designers. The design protocol is decomposed into small units called "design moves". Goldschmidt defines 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" (Goldschmidt 1995), or "an act of reasoning that presents a coherent proposition pertaining to an entity that is being designed" (Goldschmidt 1992). A linkograph is then constructed by linking related moves. It can be seen as a graphical network of associated moves that represents the design session. Figure 1 is a linkograph with 3 moves.

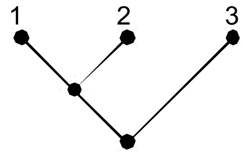


Figure 1. A linkograph with 3 moves, both moves 2 and 3 are related to move 1 but move 2 and move 3 are not related.

The design process can then be looked at in terms of the patterns of moves associations. Goldschmidt identified two types of links: backlinks and forelinks. Backlinks are links of moves that connect to previous moves, in Figure 1 moves 2 and 3 are backlinked to move 1. Forelinks are links of moves that connect to subsequent moves, move 1 is forelinked to moves 2 and 3. Conceptually they are very different: "backlinks record the path that led to a move's generation, while forelinks bear evidence to its contribution to the production of further moves" (Goldschmidt 1995). Link index and critical moves were devised as indicators of design productivity. Link index is the ratio between the number of links and the number of moves, and critical moves are design moves that are rich in links, they can be forelinks, backlinks, or both. In her exposition, design productivity is positively related to the link index and critical moves, that is, a higher value of link index and critical moves indicates a more productive design process.

This link index and critical moves approach is biased towards highly linked linkographs because a saturated linkograph will have a high value of link index and critical moves. Kan and Gero (2005) argue that a fully saturated linkograph indicates no diversification of ideas, hence less opportunity for quality outcomes. Four hypothetical design scenarios with only five moves are used to illustrate our concept, Table 1 (Kan and Gero 2007). Case 1, 2, and 3 might not happen in practice but this demonstrates our theoretical ground. With the link index calculation, case 2 will score the highest (2) followed by case 4 (1) then case 3 (0.8). We propose that case 2 should not be rated as the best designing scenario.

TABLE 1. Four hypothical scenarios,

Case 1		Five moves are totally unrelated, indicating no converging ideas, hence very low opportunity for idea development.
Case 2		All moves are interconnected; this shows that this is a totally integrated process with no diversification, hinting that a pre-mature crystallization or fixation of one idea may have occurred; therefore there is a very low opportunity for novel idea.
Case 3		Moves are related only to directly preceding moves. This indicates the process is progressing but not developing; indicating some opportunities for idea development.
Case 4		Moves are inter-related but not totally connected, indicating that there are lots of opportunities for good ideas with development.

1.2. INFORMATION THEORY

Following the above argument, empty linked and fully linked linkographs are not interesting, we speculate, intuitively, a partially linked linkograph embodies a balanced process that embraces integration and diversification of ideas. Both fully linked and empty linked linkographs are highly compressible in terms of communicating it. Only one ON or OFF signal is sufficient to describe it. A partially, random, linked linkograph is highly incompressible; much more information is needed to communicate where the links are ON or OFF. This directs us to Shannon’s (1948) concept of entropy as a measure of information. In Shannon’s information theory, the amount of information carried by a message or symbol is based on the probability of its outcome. If there is only one possible outcome, then there is no additional information because the outcome is known. Information is transmitted through recognizable symbols predetermined by the source and the receiver. For example a source is sending out ten ON/OFF signals and one of them is OFF but the others are ON. We can say the probability of an OFF symbol, p(OFF), is 0.1 and the probability of an ON symbol, p(ON), is 0.9. Consider the following two cases:

1) If the first signal the receiver get is an OFF symbol (p=0.1) then there is no further transmission needed because the outcome is known. This has the assumptions that the receiver knows the total number of signals (10), and

the probabilities of the symbols (ON/OFF) with the total probability equals 1 (p(ON)+p(OFF)=1).

2) If the first signal being transmitted is an ON symbol (p=0.9) the receiver is still uncertain of the rest of the signals.

So the transmission of case 1 carries more information and we can see the amount of information carry by a symbol (ON or OFF in this case) is related to its probability of its outcome. Based on this Shannon proposed an information-generating function h(p); in mathematical terms this information function needs to have the following properties:

$h(p)$ is continuous for $0 <= p <= 1$, where p is the probability,

$h(p_i)$ = infinity if $p_i = 0$, where p_i is the probability of a given state,

$h(p_i) = 0$ if $p_i = 1$,

$h(p_i) > h(p_j)$ if $p_j > p_i$, where p_i and p_j are the probabilities at two different states,

$h(p_i) + h(p_j) = h(p_i * p_j)$ if the two states are independent.

Shannon proved that the only function that satisfies the above five properties is

$$h(p) = - \log(P) \tag{1}$$

Given a set of N independent states $a_1, \dots a_N$ and corresponding possibilities $p_1, \dots p_N$, (in our example N=2, p_1=p(ON)=0.9, and p_2=p(OFF)=0.1) he derived Entropy (H), the average information per symbol in a set of symbols, to be $p_1*h(p_1) + p_2*h(p_2) + \dots + p_N*h(p_N)$

$$\text{Therefore } H = -\sum_{i=1}^{n} p_i \log(p_i) \quad \text{with} \quad \sum_{i=1}^{n} p_i = 1 \tag{2}$$

In our case there are two symbols (ON/OFF) and entropy is expressed by:

$$H = -p(ON)Log(p(ON)) - p(OFF)Log(p(OFF)) \tag{3}$$

$$H = -(0.9*\log_2(0.9) + 0.1*\log_2(0.1)) = 0.469$$

The “logarithmic base corresponds to the choice of a unit for measuring information” (Shannon 1948). Here we use base 2 to represent the ON and OFF symbols.

Section 2.3 will describe how this can be applied to calculate the entropy of a linkograph.

1.3. SKETCHING AND BLINDFOLDED DESIGNING

Do architects necessarily start designing with external representations in the early stages of design? Anecdotal examples are often quoted of major architects such as Frank Lloyd Wright who could conceive of and develop a design entirely using imagery with an external representation of the design only being produced at the end of the process (Franklin 2003). Then it should be possible for some designers to develop and maintain an internal designing activity for a prolonged time. We refer to this activity as the use of imagery alone in designing.

The earliest published experimental study related to the use of imagery alone in designing is that of Athavankar (1997). He conducted an experiment where an industrial designer was required to design a product in his imagery (with an eye mask on), having no access to sketching and the visual feedback it provides. The study showed that the expert was able to use imagery alone in the conceptual design phase, before externalizing his/her design thoughts. Similar results were obtained in a study with software designers (Petre and Blackwell 1999) where they were required to design using their mental imagery alone. These results inform the possible cognitive processes and mechanisms that might be involved in blindfolded designing.

We can present two views on imagery and sketching activities in design, which also make a distinction between them. In the first view, sketching directly produces images and ideas externalized on paper and then the designer starts to have a dialogue with them via their perceptual mechanisms. In this way, the design problem is explored, and restructured through this dialogue (Schon and Wiggins 1992; Goldschmidt 1991; Suwa Purcell and Gero 1998). As with sketching activity, there is a dialogue with direct perceptual input from drawings to restructure the design problem. In the second view, during the use of imagery alone for designing (designing without sketching), a designer has to accumulate considerable amount of knowledge/meaning before an image is generated, which suggests formulation of concepts without drawings and without seeing.

Bilda et al (2006) studied blindfolded architects with an approach similar to Athavankar's (1997) study. At the end of the blindfolded designing, the participants were asked to quickly sketch the design solution they held in their minds. When the participants were blindfolded, they were able to produce designs by using their cognitive resources to create and hold an internal representation of the design.

In another study, Bilda and Gero (2007) presented the cognitive activity differences of three expert architects when they design under blindfolded and sketching conditions. It was observed that all participants' overall cognitive activity in the blindfolded condition dropped below their activity in the sketching condition approximately after 20 minutes during the timeline of the design sessions. This drop was explained by limitations of visuo-spatial working memory in the blindfolded conditions. The results showed that sketching off-loaded visuo-spatial working memory.

In this paper we use entropy to investigate whether the working memory limitations have an impact on idea development. Evidence in working memory research supports that the cognitive load should be higher in a blindfolded condition since image maintenance and synthesis of images requires more executive control resources (Pearson et al 1999, Baddeley et al 1998). Similar results have been obtained for the phonological loop of the working memory, when verbal tasks were performed using imagery (Baddeley 1986). Other empirical studies on visuo-spatial working memory also show that the capacity of the visuo-spatial working memory is limited when visuo-spatial tasks are done using imagery (Ballard et al 1995, Walker et al 1993, Phillips and Christie 1997). We presume that the design ideas could have a visuo-spatial mode and a verbal conceptual mode in imagery, working in parallel. Since there is a working memory limitation when using imagery, the idea development could slow down after a while during the timeline of the blindfolded designing activity. On the other hand sketching activity could support and improve the idea development activity, since working memory is off-loaded continuously.

2. Method

The question we posed could be paraphrased as: 'can an entropy measurement be used as a quantitative tool to study design protocols?' This section explains how two sets of design protocols from two different conditions were collected, coded, and measured using entropy for comparison.

2.1. DESIGN OF THE EXPERIMENTS

We conducted think-aloud designing experiments with six architects. The six architects who participated (2 female and 4 male) have each been practicing for more than 15 years. Architects A1 and A2 run their own companies and have been awarded prizes for their designs in Australia; Architect A3 is a senior designer in a well-known architectural firm. The three participants were teaching part-time in design studios. A4 works for one the Australia's largest architectural companies and he has been the leader of many residential building projects from small to large scales. A5 is one of the founders and director of an award wining architectural company. A6 is a very famous residential architect in Sydney, and he directs his company known by his name with 50 employees.

The first group of the three architects, A1, A2 and A3 were initially engaged in a design process with design brief 01 where they are not allowed to sketch (blindfolded sessions). One month after the experiment condition the same three architects were engaged in a design process with design brief 02 where they are allowed to sketch (sketching sessions). Design brief 01 requires designing a house for two artists: a painter and a dancer. The house is to have two studios, an observatory, a sculpture garden and living, eating, sleeping areas. Design brief 02 requires designing a house on the same site as design brief 01 but this time for a couple with 5 children aged from 3 to 17, that would accommodate children and parent sleeping areas, family space, study, guest house, eating and outdoor playing spaces.

The second group of the three architects was first engaged in the sketching session (SK), where they received design brief 02. Then after one month they were working on design brief 01 under the blindfolded condition (BF) where they were not allowed to sketch.

The set-up of the study for both BF and SK conditions has a digital video recorder with a lapel microphone, directed at the designer. Under the BF condition, the architects were required to put on a blindfold and start thinking aloud, Figure 2(a). At the end of the blindfolded session they were asked to take off the blindfold and quickly sketch what they held in their minds in the allowed 5 minute period. Under the sketch condition, the architects were required to think aloud and sketch. The details of the experimental procedure can be found in Bilda et al (2006).

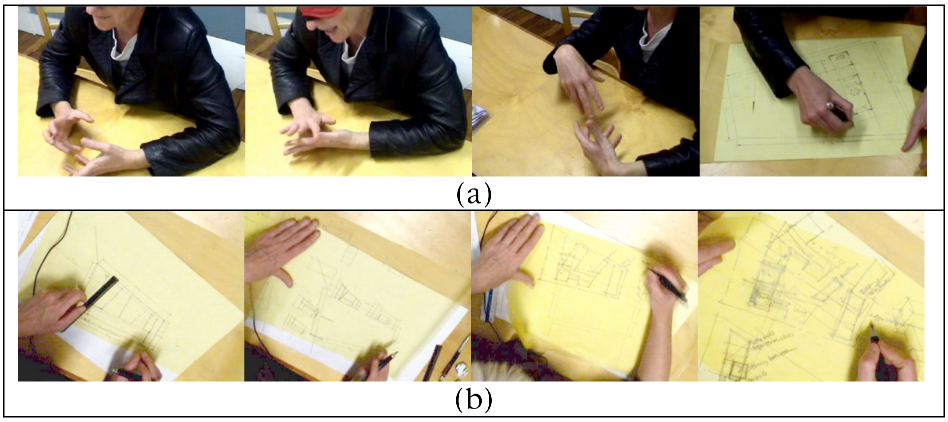


Figure 2. (a) blindfolded (BF) session followed by quick sketching, (b) sketching (SK) session

2.2. ESTABLISHING THE LINKS

The linkography technique involves dividing the protocol into design moves (Goldschmidt 1991) and looking at the design process in terms of relationships created by the links between those moves. In this study we segmented the protocols according to designers' intentions (Suwa et al.

1998). Suwa et al. (1998) discussed that this segmentation technique was similar to the notion of design moves, thus we used the same segmented intervals in the process of establishing links.

The process of establishing the idea links between the segments is carried out in two runs. In the first run, the analyzer starts from the first segment and sequentially establishes the links between the ideas, based on the revisited meanings amongst the segments. The analyzer relies on the verbalization while linking the ideas in the blindfolded designing protocols. During linking the ideas of sketching protocols, video footage for each segment was inspected as well. Linking the ideas in protocols could be a difficult task, if the analyzer loses track of the ideas developed previously along the timeline of the protocol session. In order to prevent missing links and for linking the ideas more reliably, we employed a technique that involves a word search in order to detect the words used more frequently so that the analyzer ends up with a list of frequently repeated words in each segment. The next stage is browsing through the selected segments, to confirm that the words are used in the appropriate context. If the meanings in the segments are related, then these ideas are established. This procedure helps us to establish the links, which are distant from each other and which might have been missed in a sequential analysis.

2.3. ENTROPY MEASUREMENT

In our measure of linkograph entropy we are interested not only in the number of linked segments but also the distribution of those links. Two extremes example are: an empty linked (none of the segments is related) and a fully linked (all the segments are linked) linkograph. An empty linked linkograph can be considered as a non-converging process with no coherent ideas and a fully linked linkograph stands for a total integrated process with no diversification. In both cases the opportunities for idea development are very low. This line of reasoning can be expressed in terms of entropy; if we randomly pick a segment in an empty linked linkograph we can be sure that it has no links. This sounds obvious but if we consider this linkograph as a carrier with zero information content, because the outcome is known, it will have zero entropy. Similarly, a fully linked linkograph will also have zero entropy.

In order for entropy measurement of linkograph to be meaningful, we follow Kan and Gero’s (2007) measurement method, which is based on the conceptual difference of forelink, backlink, and horizontal link (called “horizonlink”). Entropy is measured in rows of forelinks, backlinks, and horizonlinks separately. Consider an abstracted linkograph with four segments in Figures 3. The links between ideas are denoted by black dots and the grey dots denote possible linkages but not actually linked. We are going to calculate forelink entropy for each segment except the last two segments. As seen in Figure 3(a), segment 4 will not have forelinks and segment 3 is either linked or unlinked to segment 4 which will have zero entropy, see below for explanations. Similarly each segment except the first two, will receive a backlink entropy, Figure 3(b). Segments can be linked to a previous segment (n-1) or segments further apart, Figure 3(c). Horizonlink carries the notion of distance/time between the linked segments. Segments that reside in working memory will usually have high interconnections; we refer to these linkages as the cohesiveness of segments. We refer to links that connect segments that are far apart, and those that are not in working memory as incubated linked segments.

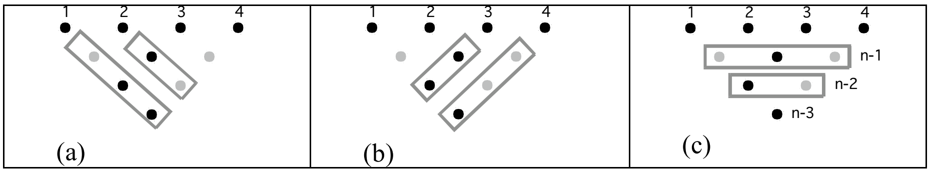


Figure3. Abstracted linkograph for entropy measurement, back dots denote linkage between segments. (a) Measuring entropy of forelinks of each row, (b) measuring entropy of backlinks of each row, and (c) measuring entropy of horizonlinks.

For calculating the forelink entropy of an individual segment in Figure 3(a) we marked them by a rectangle. In segment 1 there are three nodes for links inside the rectangle; segment 1 and segment 2 are unlinked while segment 1 is linked to segment 3 and segment 4. The percentage for linked nodes is 66.6% and the percentage of unlinked node is 33.3%. If we consider linked nodes as ON and unlinked nodes as OFF, the probability will be: p(ON)=0.666 and p(OFF)= 0.333 respectively.

This case is the same as the example in section 1.2 so we can use formula (3) to calculate forelink H for segment 1, which becomes:

$$- 0.666Log_2(0.666)-0.333Log_2(0.33) =0.918$$

Similarly for segment 2 the forelink H is:

$$-0.5Log_2(0.5) - 0.5Log_2(0.5)=1$$

As we can see for segment 3 there is only one possible link, so no matter whether it is ON or OFF the probability is 1 and the entropy is zero because $Log_2(1) = 0$.

Using this method, in Figure 3(b) the backlink entropy for segment 3 and segment 4 are 0 and 0.918 respectively.

For the horizonlink entropy we consider, in this case, the two rows: n-1 and n-2. Using formula 3 we can get the entropy of the n-1 row which is 0.918 and the entropy of the n-2 row is 1. Since people have limited short term memory (Miller 1956), if we follow Miller's "magic number seven plus or minus two" objects, linkographs seldom have segments with more than nine links and the number of links between far apart segments will decrease. Figure 4 shows a typical linkograph which has many cohesive links but very few incubated links. Fully cohesive link, for example all ON in n-1, will have 0 horizonlink entropy; similarly if there is no incubated links that row will score 0 in horizonlink entropy as well.

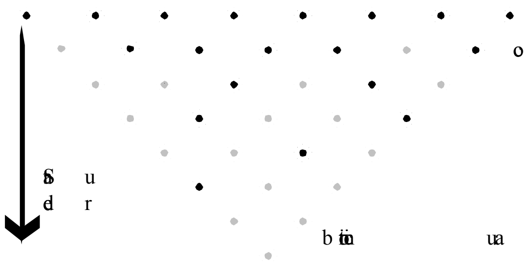


Figure 4. A linkography with typical distribution of links during a design process

If an idea is weak, it will not have many forelinks and this is represented by a low entropy. However, if an idea has too many forelinks, this might indicate fixation; this is also indicated by a low entropy. Backlink entropy measures the opportunities according to enhancements or responses. If an idea is very novel, it will not have backlinks, the resulting entropy is low. On the other end if an idea is backlinked to all previous ideas, it is not novel hence is represented by a low entropy. Horizonlink entropy measures the occurrence of incubated segments and a low horizonlink entropy indicates complete cohesiveness. Horizonlink entropy measures the opportunities relating to cohesiveness and incubation.

In general we agree that intensive linking design moves may yield good designs. However, the intensity should only advance to a certain point. In the early stage of designing, fixation is not desirable. Fixation is indicated by a move with near-saturated forelinks. Kan and Gero (2007) suggested that forelink entropy measures the idea generation opportunities in terms of new creations or initiations. Figure 5 compares the link index measurement with the entropy measurement of a move. A heavily linked and a sparsely linked linkograph will have low entropy values. However, the link index increases as the number of links increases. The slop of the link index in the Figure 5 is not fixed as it is determine by the total number of move of the linkograph. In this particular graph we can observe that the link index agrees with the entropy until the lines intersect at about 75% of saturation. It is very rare to have linkographs over 10 moves to have that kind of saturation. After this point entropy drops and link index score is in a different direction.

In our cumulative entropy measurement we are counting the contribution of each move in three different ways: according to initiations (forelinks), responses (backlinks), and cohesiveness (horizonlinks).

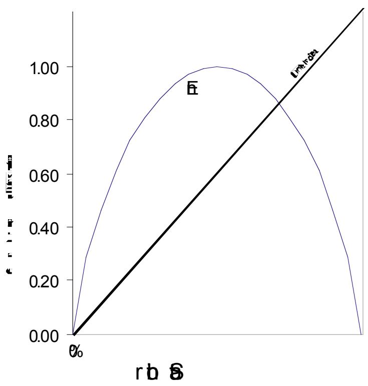


Figure 5. Compare Link Index and Entropy measurement

3. Results

A previous study, showed that the overall cognitive activity in the blindfolded condition dropped below the activity in the sketching condition approximately after 20 minutes (half way) into the design sessions (Bilda and Gero 2007). This drop in performance can be explained by higher cognitive demands and limitations of visuo-spatial working memory in blindfolded conditions. However, with this drop of cognitive activity, in the blindfolded condition the architects can still produce satisfactory designs. Their design outcomes, sketches, were judged by a qualified jury of three designers. Surprisingly, all the blindfolded sessions received a higher score compared to the corresponding sketch sessions. We attempt to explore these phenomena by using entropy measures of the linkographs.

3.1. LINKOGRAPHS OF THE SESSIONS

After coding the links, the 12 linkographs of the sessions had been produced; they exhibit different patterns that reflect different design processes. For example the linkograph in Figure 6(a) reflects a relatively holistic design process (the linkograph is well integrated) while the linkograph in Figure 6(b) represents a process of trying out different options (there are obvious clusters in the linkograph). This observation was confirmed with our qualitative analysis.

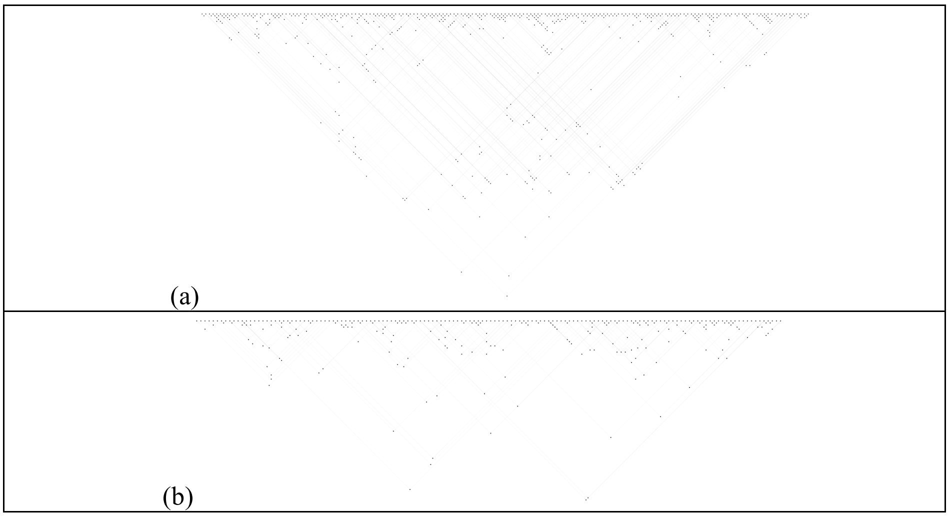


Figure 6. (a) Linkograph of a sketch session, (b) linkograph of a blindfolded session

The detailed qualitative analysis of the 12 linkographs is beyond the scope of this paper. Here we examine whether the drop in cognitive activity in the blindfolded session is reflected in the linkograph.

Looking at the linkograph, some of the blindfolded sessions seem to suggest a more productive process according to Goldschmidt's definition due to the visual density of links. Bilda (2006) showed that for the six architects' design sessions, the frequencies of cognitive activities were correlated to the number of links: more activities will result in more links. However, inspecting the linkographs we cannot track down where the cognitive activity started to drop as reported by the previous study (Bilda and Gero 2007). Each design session was approximately forty five minutes. We count the segments of the first 20 minutes in all the sessions as compared to the rest of the session, Table 2. The blindfolded sessions have slightly more segments in the first half of the session; this is consistent with the previous result (Bilda and Gero 2007). Again assuming cognitive activity can be reflected in the number of segments, will the number of links among segments drop as well? Visually the number of links does not seem to drop in the second half. The average and standard deviation in Table 2 are for reference only; each case should be looked at individually.

TABLE 2. Number of segments in the first 20 minutes and the rest of the session; those sessions with the number of segments drop after 20 minutes are highlighted

	Blindfolded No. of Segments			**Sketch No. of Segments**		
	20 min	Rest	Total (45 mins)	20 min	Rest	Total (45 mins)
Architect 1	89	78	167	68	77	145
Architect 2	63	91	154	77	107	184
Architect 3	87	82	169	65	77	142
Architect 4	92	75	167	74	95	169
Architect 5	73	72	145	91	62	153
Architect 6	69	53	122	71	101	172
Average	*78.83*	*75.17*	*154.00*	*74.33*	*86.50*	*160.83*
Standard Deviation	*12.04*	*12.70*	*18.26*	*9.20*	*17.22*	*16.70*

3.2. ENTROPY OF THE SESSIONS

We use formula (3) to calculate the forelink and backlink entropy of each segment in a linkograph. In order to produce a picture of the whole session, we add the entropy of each segment to obtain the total forelink and backlink entropy of a session. Likewise, we obtain the total horizonlink entropy by adding the entropy of all the horizontal rows. We normalize the results by dividing the entropy by the total number of segments in that session. Table 3 shows the normalized results of entropy of each session together with their link index. Average and standard deviation values are calculated for the two groups of experiments. Overall the blindfolded sessions have higher entropies and link indices in both groups. Only the first architect in the first group does not follow this trend.

Table 3 shows that the first group of three architects' blindfolded and sketch sessions have very similar link indices (average 1.39 and 1.36) and entropy values (average 0.343 and 0.336). For the second group of architects, the average link index and average total entropy are higher in the blindfolded condition compared to their sketch condition (0.511, 0.441 and 2.39, 1.95) with a relatively small standard deviation in the blindfolded condition. We observe that for the second group of architects the link index and the entropy of the blindfolded sessions are the highest. This difference could be due to the experimental condition where the second group received the sketching exercise first and the blindfolded exercise later. The second group had an increased familiarity with the problem, including the site geometry and the environmental factors around the building. This familiarity with the problem could have improved the second group's potential for idea development, hence higher entropy. In general the BF sessions have higher entropy. Could this account for their better design outcome?

TABLE 3. Entropy and link index of each session

		BH/ segments	**FH/ segments**	**HH/ segments**	**Total**	**Link Index**
Blindfolded (BF)	BF 1	0.125	0.122	0.060	0.307	1.20
	BF 2	0.161	0.155	0.066	0.383	1.68
	BF 3	0.143	0.140	0.055	0.338	1.28
	av	***0.143***	***0.139***	***0.060***	***0.343***	***1.39***
	sd	*0.018*	*0.017*	*0.006*	*0.038*	*0.257*
	BF 4	0.240	0.220	0.093	0.553	2.48
	BF 5	0.224	0.193	0.082	0.499	2.18
	BF 6	0.188	0.189	0.105	0.481	2.50
	av	***0.217***	***0.201***	***0.093***	***0.511***	***2.39***
	sd	*0.027*	*0.017*	*0.012*	*0.037*	*0.179*
Sketching (SK)	SK 1	0.137	0.124	0.077	0.337	1.41
	SK 2	0.157	0.150	0.065	0.373	1.48
	SK 3	0.124	0.131	0.044	0.299	1.20
	av	***0.139***	***0.135***	***0.062***	***0.336***	***1.36***
	sd	*0.017*	*0.013*	*0.017*	*0.037*	*0.146*
	SK 4	0.227	0.203	0.098	0.529	2.41
	SK 5	0.176	0.125	0.071	0.372	1.68
	SK 6	0.184	0.175	0.063	0.422	1.76
	av	***0.196***	***0.168***	***0.077***	***0.441***	***1.95***
	sd	*0.027*	*0.040*	*0.018*	*0.080*	*0.400*

BH: entropy of back links FH: entropy of forelinks
HH: entropy of horizonlinks

In general backlink entropy is higher than forelink entropy, with the exception of one sketch session (SK 3) and one blindfolded session (BF 6, small difference). SK 3 received the highest rank by the judges in the categories of “Innovative” and “Creative”. Can this indicate that forelink entropy reflects idea generation potential based on new initiations which may reflect creativity? The relationship between forelink entropy and creativity needs further investigation and is inconclusive based on these results.

The horizonlink entropy is much lower than forelink and backlink entropies due to this fundamental dissimilarity. Forelink and backlink entropy examines links in each move, but horizonlink examines the degree of cohesion and incubation of the segments. This measure needs further exploration.

3.3. ENTROPY IN THE FIRST HALF AND SECOND HALF OF THE SESSIONS

In this section we explore whether the entropy drops half way through the blindfolded design process due to working memory limitations. In Table 2 we can see the total number of segments dropped after 20 minutes in the blindfolded session but looking at the linkographs the density of links does not appear to drop. If we use the segment at 20 minutes to divide the linkographs, we can calculate to see if entropy drops as the cognitive activities drop. Figure 6 shows the division to calculate the entropy of the first and second half of a linkograph. We compare to determine if there is a significant difference between the blindfolded and sketch conditions. We chose 20 minutes as a demarcation, based on a previous study, where the first three participants' cognitive performance under blindfolded conditions dropped below their performance under sketch conditions, after around 20 minutes ((Bilda and Gero 2007)).

In this calculation we ignore those links outside the shaded triangles in Figure 7. The results in Table 4 show that in both conditions there is a drop in entropy in the second half of the sessions. Under the sketch condition, five of the six sessions has lower entropy in the second half; conversely half of blindfolded sessions have higher entropy. There is no direct relationship between cognitive activities drop and entropy drop.

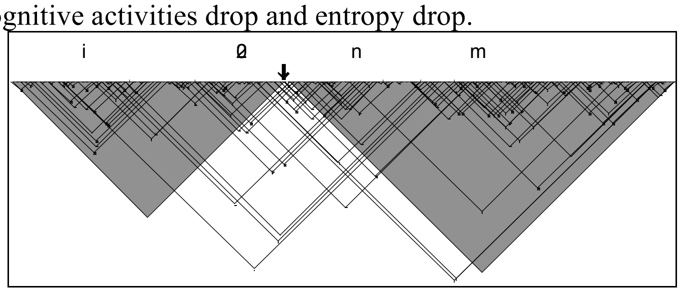


Figure 7. Calculating the entropies of the first and second half of the linkograph; only links within the gray triangle are counted

Generally, the entropy per segment of the second half of the session is lower than the first half. This parallels our assumption that entropy measures the opportunities for idea generation. In the second half, designers are approaching the end of a session and the design converges to a particular approach, therefore fewer opportunities occur for idea development. Consequently the entropy values would be lower in the second half compared to the first. What accounts for the increases of entropy in three of the BF sessions?

TABLE 4. Total normalized entropies of each session; those sessions without entropy drop after 20 minutes are highlighted

	Blindfolded Entropies/Segment		**Sketch Entropies/Segment**	
	First 20 min	The rest	First 20 min	The rest
Architect 1	0.343	0.411	0.450	0.398
Architect 2	0.650	0.498	0.484	0.448
Architect 3	0.406	0.441	0.461	0.518
Architect 4	0.743	0.670	0.783	0.588
Architect 5	0.911	0.679	0.603	0.529
Architect 6	0.857	0.875	0.652	0.540

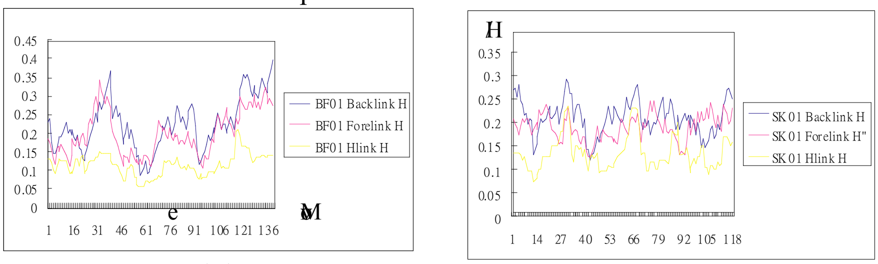
In order to understand what is happening to the idea links we have to refer back to formula (3) plotted in Figure 5. Either a heavily linked or a sparsely linked second half linkograph will have low entropy values. Reviewing the 12 linkographs, we conclude they all fit into the second case; that is the linked ideas are sparse. A higher value of entropy implies more linkage among segments, hence better integration of ideas. According to Table 4, half of the blindfolded sessions have higher entropy in the second half of the session. This might suggest that working with limited visuo-spatial working memory under the BF condition, does not have a noticeable impact on the inter-connectivity of ideas as compared to the SK condition.

3.4. CHANGE OF ENTROPY OVER TIME

From the linkographs of Figures 7 and (number of segments in) Table 4, it is easy to infer that the entropy varies across the time line. In this section we explore the change of entropy over a design session to see if the entropy will decrease toward the end of a session.

There are two approaches for monitoring these changes, one uses a fixed time frame as a reference window as in Figure 7, and the other uses a fixed number of segments as the width of window. It is easier to use fixed number of segments as reference as the procedure can be readily automated. Figure 8 shows A1's backlink, forelink and horizontal link entropy changes, using 28 segments as a window width. Figure 9 is the corresponding linkographs.

We can identify two regularities in these graphs: the relationship between the three types of link entropies, and the overall trend. The backlinks, forelinks, and horizontal links vary in the same direction. The trend of the variation shows the same pattern.



(a) (b)

Figure 8. Change of entropy (a) in blindfolded condition (b) in sketch condition

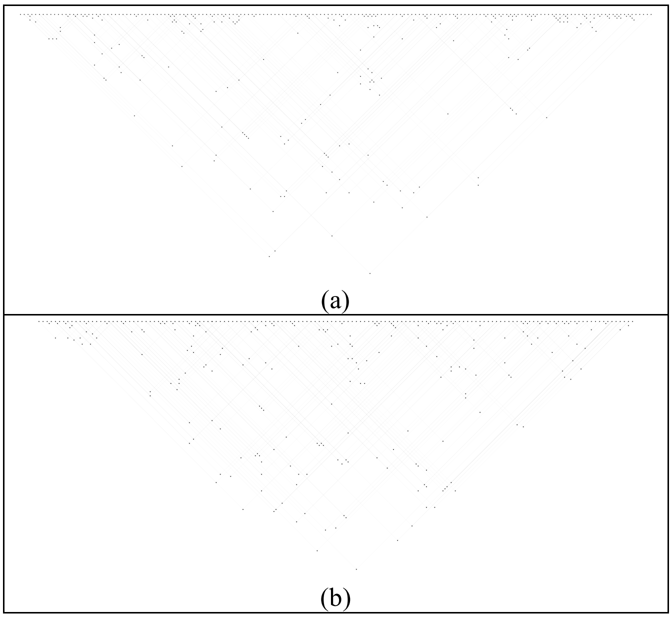
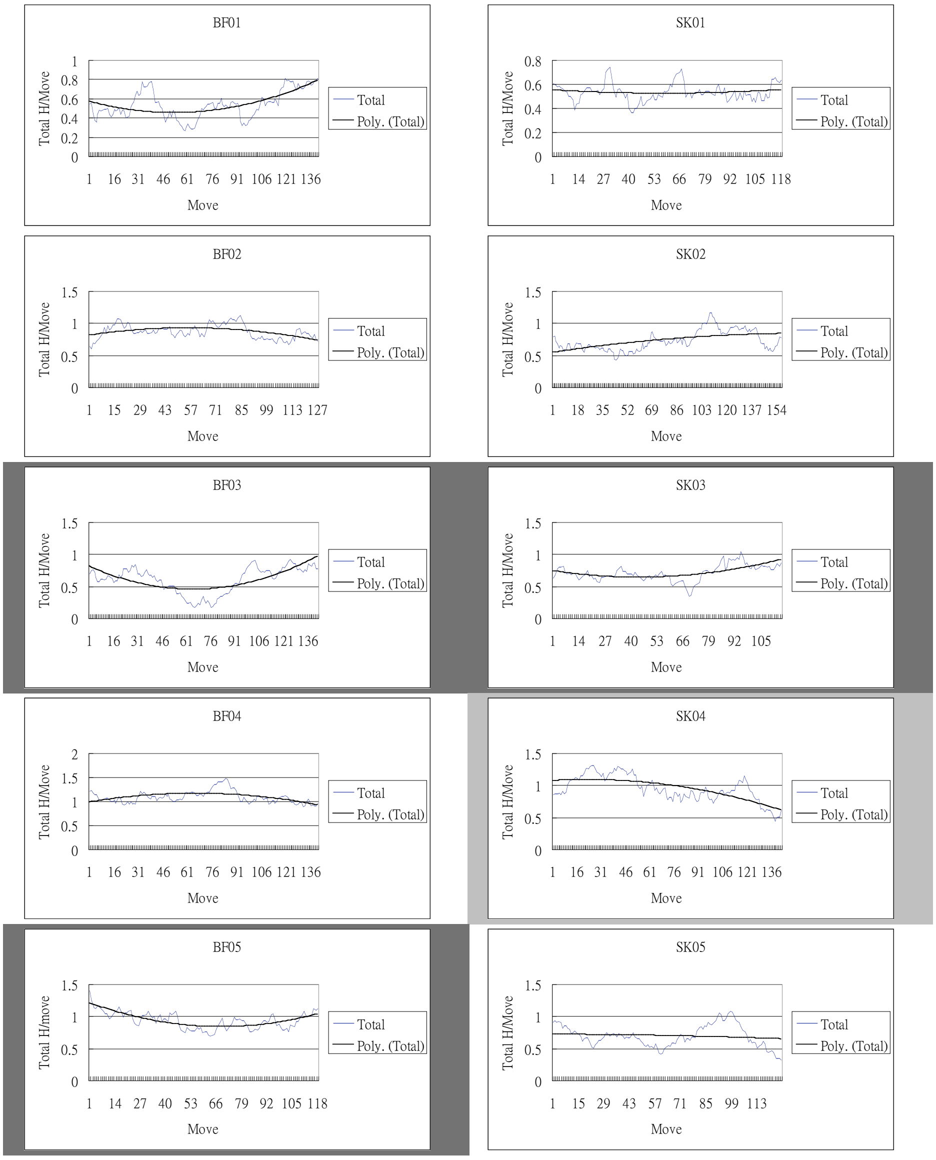


Figure 9. (a) Linkograph of the blindfolded session, (b) Linkograph of the sketch session

Figure 10 shows the overall trends for all the twelve sessions with a quadratic (second degree) polynomial fit of the total normalized entropy. There are three basic shape of a quadratic equation: linear, "n", and "u" shape. The "u" shape trend suggests that the entropy values are climbing toward the end of the session, whereas the "n" shape trend suggests the opposite. It can be observed that this trend remains the same in each architect's blindfolded and sketch session. Can this represent the style of thinking? More studies are needed to relate the graphs and the qualitative analysis. Another interesting observation is that the top three highest scored sessions have an “u” shape curves and all the bottom three lowest scored sessions have a “n” shape curves.



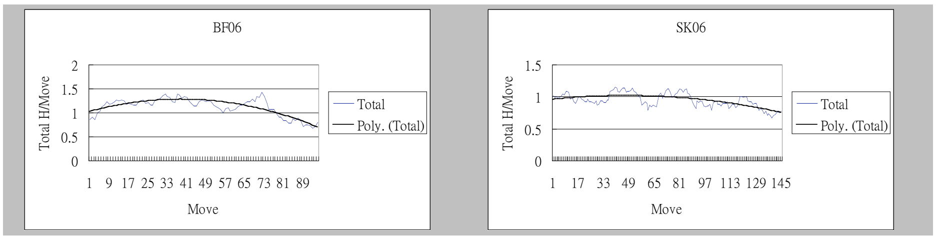


Figure 10. Polynomial fit of the total normalized entropy, with the 3 highest and 3 lowest scored sessions highlighted in darker and lighter gray respectively.

As explained in the previous section higher entropy towards the end of the session suggests better inter-connectivity of ideas. Can this better integration of ideas towards the end suggest the quality of a session, and hence receive better score? There are insufficient cases to validate this; however, this is an instance that suggests the design outcome could be related to the change of entropy of the linkograph that is worth investigating.

4. Conclusions

Kan and Gero (2006) showed that an entropy measure of linkographs could be a useful tool to measure idea development. In this paper we tested this method: 1) whether this measurement gives any meaningful result with twelve design sessions in two different conditions; and 2) if working memory limitations has an impact on the potential for idea development – better integration of ideas in these cases as indicated by our entropy measure.

The results in this paper are: 1) there were indications that linkograph entropy reflects design outcome; 2) that the integration of segments (ideas) did not necessarily decrease after some time during the use of imagery alone.

All but one blindfolded sessions had higher entropy than their corresponding sketch sessions (Table 3). This paralleled the results of the judges – all the blindfolded sessions received better score than their corresponding sketch sessions. The session which had forelink entropy higher than backlink entropy received the highest rank in the categories of “Innovative” and “Creative”. Further investigations are required to study these speculations.

Bilda and Gero (2007) suggested that the cognitive load (working memory load) might be related to perceptual activity rather than functional activity. The visuo-spatial tasks which require executive resources in working memory might create the cognitive load, but not necessarily the concept/meaning formation. Similarly, assuming that idea development in imagery is concept-related rather than figure-related; results in this paper support these previous findings.

In conclusion, entropy measurement of linkographs provides a way of interpreting linkographs which requires further inquiry, and using this measurement we find evidences that the visuo-spatial working memory load does not have negative effects on idea development. Further, we hypothesize that idea development could be dependent more on a conceptual modality than the visuo-spatial modality.

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