

Characterizing innovative processes in design spaces through measuring the information entropy of empirical data from protocol studies

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Abstract

This paper reports on a study characterizing design processes and the potential of design spaces through measuring the information entropy of empirical data derived from protocol studies. The sequential segments in a protocol analysis can be related to each other by examining their semantic content producing a design session's linkograph, which defines the design space for a design session. From a linkograph, it is possible to compute the probabilities of the connectivity of each segment for its forelinks and its backlinks, together with the probabilities of distance among links. A linkograph's entropy is a measure of the information in the design session. It is claimed that the entropy of the linkograph measures the potential of the design space being generated as the design proceeds chronologically. We present an approach to the automated construction of linkographs by connecting segments using the lexical database WordNet and measure its entropy. A case study of two design sessions with different characteristics was conducted, one considered more productive and creative, the other more pragmatic. Those segments with high entropy and those associated with high rates of change of entropy are analyzed. The creative session has a higher linkograph entropy. This result indicates the potential of using entropy to characterize a design process.

Keywords: Design Processes; Entropy; Information Analysis; Protocol Studies

1. INTRODUCTION

Information entropy models of design processes are generally based either on formal models of designing or on a simulation of a design activity (El-Haik & Yang, 1999; Summers & Shah, 2003; Khan & Angeles, 2011; Krus, 2013). They describe the stages, information, or complexity of a design process or of designed artifacts. For example, by considering the design process as a process of decreasing uncertainties of the designed artifact or increasing the information of the design artifact, Krus (2013) used design entropy to quantitatively describe the design process.

This paper reports on a study characterizing design processes in two design spaces through measuring the entropy of empirical data derived from protocol studies. We consider the design space as a changing space of potentialities that a designer creates as she progresses along with what design variables to consider. Some of these variables are semanti-

cally associated. We conjecture that the number of variables and pattern of associations affect the potentiality, hence the innovativeness of a design process.

Protocol analysis transforms verbal utterances and gestures captured during designing into a sequential string of symbols from a limited alphabet of symbols called codes. The sequential segments can be related to each other by examining their semantic content in a process called linkography, producing a design session's linkograph; a linkograph is claimed to be able to capture the design process (Goldschmidt, 2014). Shannon's entropy (Shannon, 1948) is a measure of information based on the probability of occurrences of events. From a linkograph, it is possible to compute the probabilities of the connectivity of each segment for its forelinks and its backlinks, together with the probabilities of distance among links. We conjecture that a linkograph's entropy, a measure of the information of this probability of connection, will be able to characterize a design session quantitatively. Entropy has been used to as a way to characterize design fixation (Gero, 2011), because entropy drops indicate a decrease in potential in the design space. In this paper we examine entropy's

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connection to characterizing innovative processes in design space.

In the classic paradigm of viewing designing as problem solving (Simon 1969), the notion of design problem space is defined by *states*, *operators* that move the design from one state to another and *evaluation functions* that assess the design solution state. In Schön's (1983) reflection-in-action paradigm, designers under a situation *name* and *frame* those factors/issues, and make *moves* to provide a solution, and then *evaluate* the moves. Dorst (2015) suggested *framing* is the key to design abduction and *reframing* is the key to achieving innovative solutions. In this paper we consider innovative processes and creative activities as synonyms. We use the reflection-in-action paradigm and consider the actions of *naming*, *framing*, *moving*, and *evaluating* define the design space by introducing variables. The design space cannot be predicted and is situational; however, post facto measurement can be carried out on extant designs. We conjecture that the vocabularies in a design protocol contain information on the *naming* and *framing* of their design space, and the linkographs of the protocol comprise the characteristics of the design space shaped by *moves* and *evaluations*.

The paper is structured as follows. A brief introduction to entropy is provided along with an example of its use in text analysis. This is followed by an outline of the two design sessions that form the basis of the case study. A qualitative analysis of the two design sessions is presented. Linkographs and linkograph entropy are described. The linkograph entropy and text entropy of each of the two design sessions is calculated and compared and conclusions drawn.

2. INFORMATION AND ENTROPY

Claude Shannon, the developer of information theory, suggested a measure of information associated with a communication source called entropy (Shannon, 1948). He suggested that the amount of information carried by a message is based on the probability of its occurrence. If there is only one possible outcome, then there is no need to communicate additional information because the outcome is known. To illustrate this with a simple example, consider transmitting a piece of information consisting of 10 ON|OFF signals and 1 of them is OFF but the others are ON. The probability of an OFF symbol, $p(\text{OFF})$, is 0.1, and the probability of an ON symbol, $p(\text{ON})$, is 0.9. Consider the following two cases:

1. If the first signal the receiver gets is an OFF symbol ($p = 0.1$), then no further transmission is required as the following signals carry no additional information. This, a stochastic process, assumes that the receiver knows the total number of signals (10), the probabilities of the symbols (ON/OFF), and that the total probability equals 1 ($p(\text{ON}) + p(\text{OFF}) = 1$).
2. If the first signal being transmitted is an ON symbol ($p = 0.9$), then the receiver is uncertain of the value

of the next signal. Transmission is still required to complete the information.

Shannon derived the entropy H , the average information per symbol in a set of symbols with *a priori* probabilities, as

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

where p_i are the probabilities of occurrence of each symbol.

2.1. Entropy of protocol strings: Vocabulary richness in framing the design space

In the study of language, text entropy had been seen as a measure of vocabulary richness (Dale et al., 2000). Torres (2002), using Eq. (1), defined the entropy of a text T with λ words composed from n different words by

$$H_T(f_1, \dots, f_n) = \frac{1}{\lambda} \sum_{i=1}^n f_i [\log_{10}(\lambda) - \log_{10}(f_i)], \quad (2)$$

where f_i $i = 1, \dots, n$, is the frequency of each i -word in the text T .

In this equation, with the same number of words in a text, a higher variety of words will yield a higher text entropy. To compare texts with different numbers of words λ , a kind of "relative entropy" H_{rel} is introduced. It is defined as the quotient between the entropy H_T of the text and the maximum entropy H_{max} , multiplied by 100 to turn it into a percentage:

$$H_{rel} = \frac{H_T}{H_{max}} \times 100. \quad (3)$$

The maximum entropy H_{max} occurs when the text has all different words, that is, the entropy of a text with the same number λ of words in which each word occurs only once (i.e., $n = \lambda$, $f_i = 1$). With Eq. (1) it becomes

$$H_{max} = \frac{1}{\lambda} \sum_{i=1}^n 1 [\log_{10}(\lambda) - \log_{10}(1)] = \log_{10}(\lambda). \quad (4)$$

Text entropy has been used to examine vocabulary richness of poetic text (Popescu et al., 2015).

Popescu et al. (2015) calculated the text entropy of 146 of Eminescu, the Romanian poet's, poems (https://ro.wikipedia.org/wiki/Autor:Mihai_Eminescu). "Entropy is maximal if all entities have the same frequency of occurrence. But in that case of vocabulary richness of the texts is also maximal" (p. 147). They suggested that entropy "can textologically be interpreted as measures of *vocabulary richness*" (p. 148).

3. TWO DESIGN SESSIONS

In this study, data were obtained from a CRC for Construction Innovation project (<http://www.construction-innovation.info/>).

In that project, *in vitro* studies were conducted with five pairs of architect designers, and each pair was given three design tasks (of the same level of complexity and abstraction), one each in three different collaboration settings: face-to-face, Internet shared drawingboard, and three-dimensional (3-D) virtual world (15 sessions in total). One objective of the original study was to investigate the impact of virtual environments on design behavior (Maher et al., 2006). They found that the designers switched between problem and solution spaces more frequently in the face-to-face settings. The same designers focused more on object synthesis and visually analyzing the representation in the 3-D virtual world. In this paper two face-to-face sessions, with different characteristics, were used. In both sessions, the designers were asked to design a contemporary art gallery. They were given 30 min to generate a conceptual design. Judging by the design outcomes, a creative and productive session (Session A) was selected together with a less productive and pragmatic session (Session B) for this exploration.

3.1. Qualitative analysis of the two sessions

The more productive design session, Session A, can be divided into four stages or episodes, based on the design activities recorded in it. In the first episode, the two designers dealt with the requirements and site (about 3.5 min); in the second episode, they analyzed, planned, and developed concepts in the plan, Figure 1a (total time about 9 min); in the third episode, they developed the 3-D form in elevation, Figure 1b–d (about 9 min); and in the fourth and final episode, they worked on the layout in the plan until the end (the remaining 8.5 min), but they did not finish it within the 30 min allocated for the session. They produced six sheets of drawings, which was the highest number of sheets in terms of design output of all design sessions. This session has been qualitatively assessed as a creative session with an innovative solution by the panel of researchers that contained architectural educators and design researchers.

In Session B, the designers only worked on the plan. They spent about 4 min studying the brief without verbalizing, and then used another 5 min understanding the required areas in relation to the site coverage; in particular, the location of the external exhibition. At about 10.5 min they discussed the location of the cafe and kitchen. At around 14 min into the session, one designer found that the cafe was not in the requirements. The locations of service dock, entrance, workshop, and store were discussed; Figure 2a. At around 17 min, the location of the entrance along with its glazing was proposed. After that they worked out the location of stairs, toilets, and offices together with its size in the second level; Figure 2b. They did not finish the design in the time allocated. This session was qualitatively assessed, by the same panel

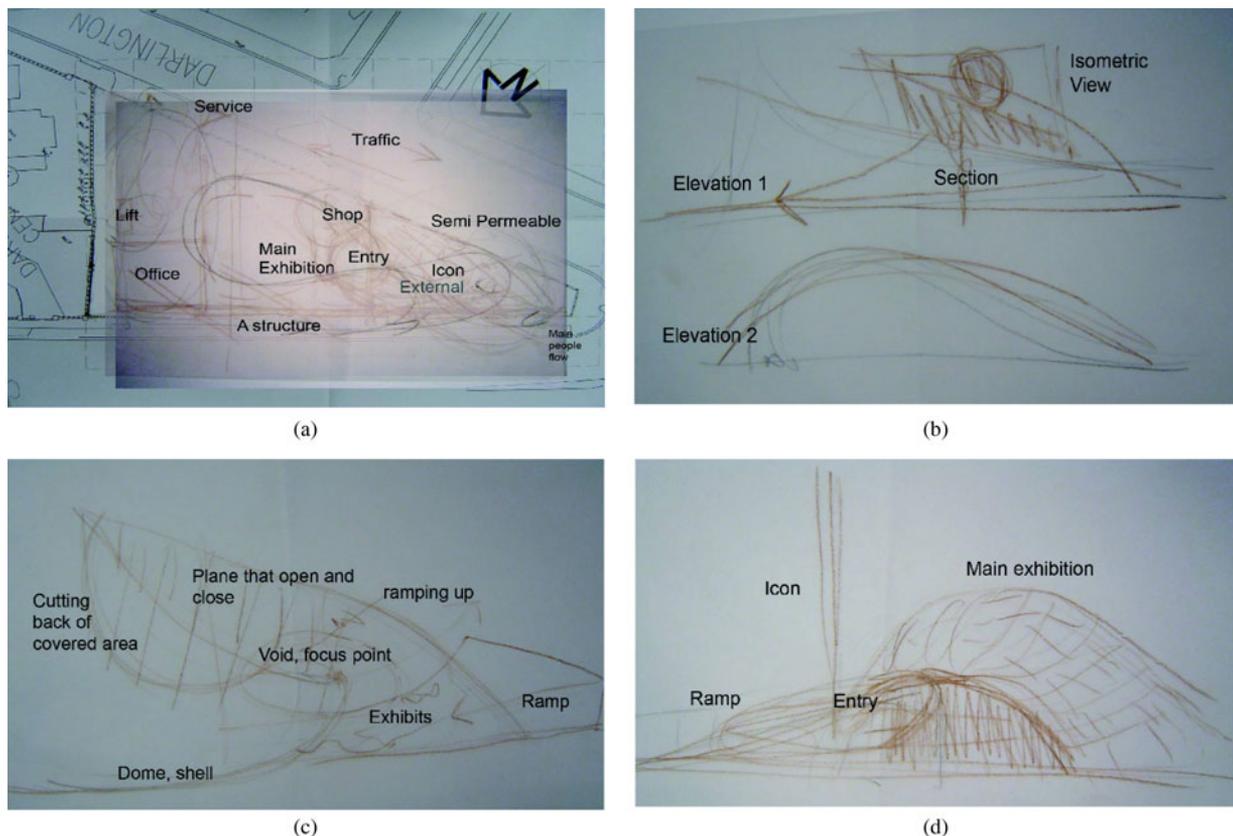


Fig. 1. Drawings and sketches from design Session A. (a) The first two sheets of drawing. (b) Section, elevation, and three-dimensional view of the proposed gallery. (c) The plan of an organic shaped building. (d) Elevation of the gallery.



Fig. 2. (a) Ground-floor plan and (b) second-floor plan of Session B.

used to assess the results of Session A, as a pragmatic session. We conjecture that the text entropy of the more creative and productive session's protocol will be higher than that of the pragmatic session.

3.2. Text entropy of the two sessions

Table 1 shows the results of the relative text entropy and the text entropy from measuring the transcripts of the design protocol of the two sessions. Comments by transcriber such as "Inaudible" were removed, as were utterances by the experimenter. The main directly observable difference between the two design sessions' transcriptions is the word count. Both sessions have very similar (2% difference) relative entropies, and the creative session has a slightly higher text entropy (9% difference).

These results suggest that text entropy and relative text entropy of the design protocol might not be able to be used to characterize differences between the two qualitatively different design sessions.

We then use turn taking and pauses to segment the design protocol. We counted the words in a segment and calculated the entropy and relative entropy of each segment of the two sessions. The variations of the relative text entropy, entropy, and the word count are shown in Figures 3 and 4. The \log_{10} scale is used in the vertical axis. In the creative session, there were 11 segments that had zero entropy because they either had one word like "maximum" or numbers like "1400" or repeated words like "no, no"; there were 8 such incidences in the prag-

Table 1. The word count, relative entropy, and text entropy of the two sessions

Session A (Creative)	Session B (Pragmatic)	Difference (%)
Word count = 4387	Word count = 2288	63
Relative entropy = 63	Relative entropy = 64	-2
Text entropy = 2.3	Text entropy = 2.1	9

matic session. These "zero" value data point were not displayed in the logarithmic scale. Apart from the density of the data points (the creative session has more segments), no differences in patterns were observed. Table 2 summarizes the average word count, relative text entropy, and text entropy of the two sessions together with the percentage differences and the two-tailed *t* test probabilities. The significant differences are the word count per segment (16%) and the text entropy (8%). However, the relative text entropy does not differentiate the two sessions.

To further investigate, we divided the design protocol into six equal portions. This divides Session A into six 69-segment sextiles and Session B into six 42-segment sextiles. This is approximately 5 min per sextile. The intention is to examine if there are any regularities within a session and compare the two sessions through this lens. The word counts, entropy values, and the paired *t* test results are tabulated in Table 3. Again, there are significant differences in the word counts and text entropy but not in relative entropy. The conjecture of using vocabulary richness as a measure of the *naming* and *framing* variables for innovative processes in a design space is not supported by the evidence from this case study.

4. ENTROPY OF LINKOGRAPHS

4.1. Linkography: Sematic connections shaping the design space

Linkography, which is a technique used in analyzing design protocols, has been reported to reveal the quality of a design process (Goldschmidt, 1992, 1995) and the creativity of the ideas (van der Lugt, 2003; Goldschmidt & Tatsu, 2005). A linkograph is constructed by breaking design protocols into smaller units called a "move" or "segment" (we will refer to them as moves) and then connecting them by a coder using domain knowledge and commonsense. Sequential "moves" are placed along the horizontal axis. When two "moves" are related, they are joined by a "link." The second column of Table 4 shows some examples of linkographs. The design

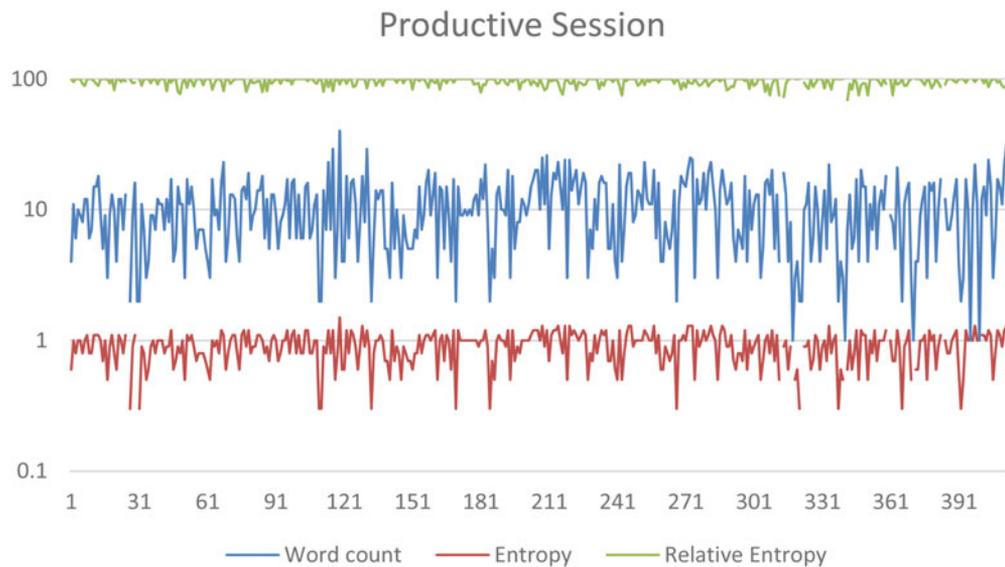


Fig. 3. Relative text entropy, entropy, and the word count of the creative session.

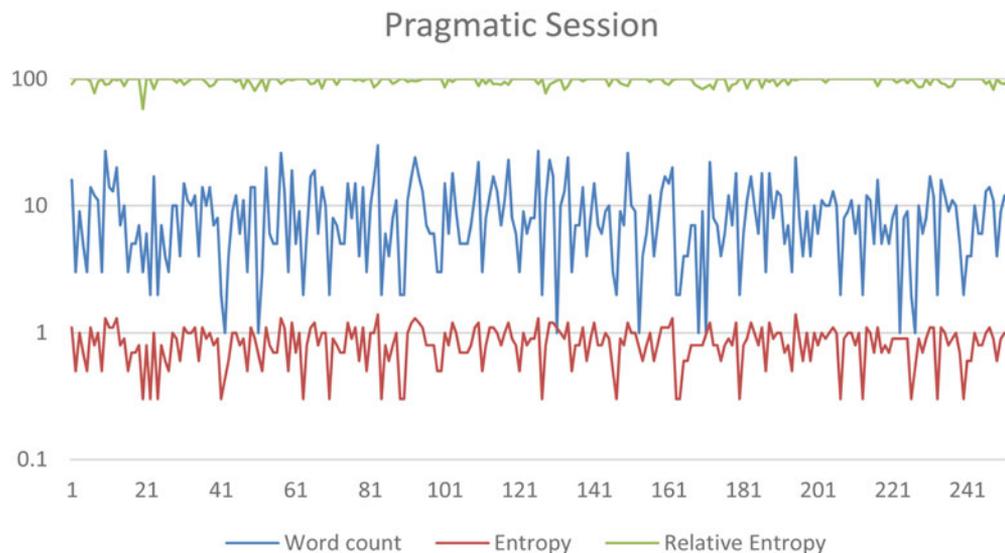


Fig. 4. Relative text entropy, entropy, and the word count of the pragmatic session.

process can then be examined in terms of the patterns of move associations. Goldschmidt (1992) identified two types of links: backlinks and forelinks. Backlinks are links of moves that connect to previous moves. Forelinks are links of moves that connect to subsequent moves. Conceptually, forelinks and backlinks 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, p. 196). Link index and critical moves are measures devised as indicators of design productivity. A link index is the ratio between the number of links and the number of moves. Critical moves are design moves that are rich in links (Goldschmidt, 1992, 1995). Design productivity is positively related to the link index and critical moves;

higher values of link index and critical moves indicate a more productive design process. Later, Goldschmidt and Talsa (2005) provided empirical evidence that quality outcomes, creativity, hinge on good ideas or what she called critical moves. Der Lugt (2003) used the same method, with some extensions to trace the design idea generation process and empirically verified the correlation between creative qualities of ideas and the good integratedness of those ideas.

4.2. Linkograph entropy

Kan and Gero (2005) proposed an approach, based on Shannon’s information theory, to measure the information in linkographs. They suggested that a rich idea generation pro-

Table 2. The per-segment average word count, relative entropy, and text entropy of the two sessions

Session A (Creative)	Session B (Pragmatic)	Difference (%)	<i>t</i> Test (<i>p</i>)
Word count = 10.62	Word count = 9.07	16	0.001 < 0.05
Relative entropy = 92.67	Relative entropy = 93.23	-1	0.682 > 0.05
Text entropy = 0.89	Text entropy = 0.82	8	0.003 < 0.05

Table 3. The word count, text entropy, and relative entropy of the two sessions subdivided into six sextiles

Transcript A (Creative)			Transcript B (Pragmatic)			Paired <i>t</i> Test (<i>p</i>)	
λ	H_{rel}	H_T	λ	H_{rel}	H_T		
624	76	2.1	363	76	2	Word count	0.0002 < 0.05
779	73	2.1	406	73	1.9	Relative entropy	0.1891 > 0.05
706	74	2.1	413	73	1.9	Text entropy	0.0001 < 0.05
893	71	2.1	382	75	1.9		
665	73	2.1	383	75	1.9		
720	73	2.1	341	75	1.9		

cess is one where the structure of ideas is well integrated and articulated, and there are a variety of moves/segments connections. They argued that an empty linked linkograph can be considered as a nonconverging process with no coherent ideas, and a fully linked linkograph represents a fully integrated process with no diversification. For an n -segmented linkograph there will be n symbols, $\{\phi, S_2-S_1, S_3-S_1, \dots, S_n-S_1\}$; Table 4 shows the symbols used to represent a four-segment linkograph.

Later Kan and Gero (2008) suggested another method to measure entropies based on the conceptual difference between forelink and backlink. They calculated the entropy of each segment in rows, within the rectangles of Figure 5a and b, according to “linked” or “unlinked.” Horizonlink, in Figure 5c, carries the notion of distance/time between the linked moves.

Using “linked” and “unlinked” as the symbols, the probability of “linked,” $p(\text{linked})$, will be the frequency (or number) of “linked” nodes divided by the total number of nodes in that row. Similarly, the probability of “unlinked,” $p(\text{unlinked})$, will be the number of “unlinked” nodes over the total number of nodes in that row.

There are only two symbols, putting their probabilities in Eq. (1), the entropy of each row becomes

$$-p(\text{linked})\text{Log}(p(\text{linked})) - p(\text{unlinked})\text{Log}(p(\text{unlinked})),$$

where $p(\text{linked}) + p(\text{unlinked}) = 1$. (6)

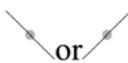
Kan and Gero (2008) suggest that “forelink entropy measures the idea generation opportunities in terms of new creations or initiations. Backlink entropy measures the opportunities according to enhancements or responses. Horizonlink entropy measures the opportunities relating to cohesiveness and incubation.”

Table 5 shows four hypothetical cases with five design moves together with their cumulative entropies. The cumulative entropies are the summation of forelink, backlink, and horizonlink entropies of all rows.

5. CONSTRUCTING LINKOGRAPHS WITH WORDNET

Linkography has been criticized for its lack of objectivity in the construction of links, which is primarily based on the discernment and interpretation of the coders. The process of constructing a linkograph is very time-consuming and cognitively demanding (Kan, 2008), making it difficult and impractical to construct very large data sets to study and compare. Some coders utilize a search function to help finding “moves” with similar semantic contents (Bilda, 2006). We propose an automated method for the construction of linkographs by connecting “moves” using the English lexical database WordNet (Fellbaum, 1998). WordNet uses the concept of cognitive synonym (synset) to group words into sets. Words within a synset are connected by meaning. Synsets are also interlinked by means of conceptual-semantic and lexical relations. Synset IDs are assigned to every word. That is, words in the same synset share the same synset ID.

Table 4. The symbols used to represent a four segment linkograph

						
Symbol	ϕ	ϕ	ϕ	$S_2 - S_1$	$S_3 - S_1$	$S_4 - S_1$

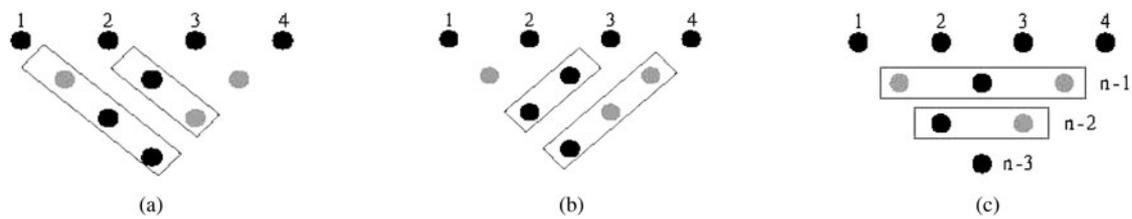


Fig. 5. Abstracted linkograph for entropy measurement, back dots denote “linked” between moves and gray dots denote “unlinked.” (a) Measuring entropy of forelinks of each row, (b) measuring entropy of backlinks of each row, and (c) measuring entropy of horizonlinks (Kan & Gero, 2008).

Table 5. Hypothetical linkographs, their interpretations, and their entropies (Kan & Gero, 2008)

	Linkographs	Interpretations	Entropy
Case 1		Five moves are totally unrelated, indicating no converging ideas, hence very low opportunity for idea development.	0
Case 2		All moves are interconnected, this shows that this is a total integrated process with no diversification, hinting that a premature crystallization or fixation of one idea may have occurred, therefore also very low opportunity for novel idea.	0
Case 3		Moves are related only to the last one. This indicates the process is progressing but not developing, indicating some opportunities for ideal development.	5.46
Case 4		Moves are interrelated but also not totally connected, indicating that there are lots of opportunities for good ideas with development.	8.57

As a word can have more than one meaning, it can belong to more than one synset and hence several synset IDs. For example, the word “surface” contains 10 synset IDs and 6 of them belong to the noun group.

A program was written to consult WordNet 3.0 to find the synset IDs of all the nouns of each segment. Only nouns were used in this study because adverbs and adjectives may produce undesirable links. For example, not only would all the segments that contain the adverb “on” be linked but also they would be linked to those with the adverb “along.” Another program was written to connect the segments.

To illustrate the algorithm, we use three segments (Table 6) from the protocol of the DTRS 7 engineering session (McDonnell & Lloyd, 2009; Kan et al., 2010). It concerned creating a new thermal printing pen; the context of these three segments was to draw analogies from other sources that generate ideas for keeping the print head in contact

Table 6. Three selected protocol segments from the engineering session of DTRS 7

(a) Needs to follow a contour
(b) The sledge manages to keep level
(c) Is like this it stays flat but the bit you hold onto can be at different angles

with the media with an optimum angle despite users’ wobbly arm moment. Segment (a) is 11 segments distant from Segment (b), and Segment (b) is 18 segments distant from Segment (c).

In WordNet a synset ID is assigned to every word, and words in the same synset share the same synset ID. As a word can have more than one meaning, it can belong to more than one synset and hence several synset IDs. In the database, each word has an entry by the six-place predicate:

s(synset_ID, w_num, ‘word’,
ss_type, sense_number, tag_count).

The synset ID encodes information about the syntactic category of the synset. The synset ID starting with 1 contains only nouns, 2 stores the verbs, 3 denotes the adjectives, and 4 denotes the adverbs. The meaning and usage of the other predicates will not be discussed here as they are not used in this work.

Table 7 shows protocol segment (b) with all its synonyms and number of synset sets the words belong to, in this example we use noun, verb, and adjective but without adverb. We can observe that the list of synset IDs is shorter than the list of synonyms.

Our algorithm contains two main parts. The first part uses a loop querying WordNet database to get a list of synset ID for each word in a segment and then unites those lists; this list

Table 7. The synonyms and synset ID of Segment (b)

Word	Synonyms	Number of Synset
Sledge	Sled, sleigh, vehicle; maul, sledgehammer, hammer; transport; travel, journey	5
Manage	Pull off, negotiate, bring off, carry off, manage, succeed, win, come through, bring home the bacon, deliver the goods; deal, care, handle, control, command; cope, get by, make out, make do, contend, grapple, deal, act, move; oversee, supervise, superintend, administer, administrate; wangle, finagle, achieve, accomplish, attain, reach; wield, handle, manipulate	7
Keep	Support, livelihood, living, bread and butter, sustenance, resource; donjon, dungeon, stronghold, fastness; hold, cell, jail cell, prison cell; maintain, hold; continue, go on, proceed, go along, act, move; hold on, have, have got, hold; prevent; observe; maintain; record, enter, put down; lodge accommodate; retain, continue, keep on, prolong, sustain, keep up; stay frest, stay, remain, rest; observe, celebrate, keep; restrain, keep back, hold back, inhibit, bottle up, suppress; preserve, protect; grow, raise, farm, produce; keep open, hold open, save, reserve, hold, book; store; confine, detain; cook, fix, ready, make, prepare	25
level	Degree, grade, property; grade, tier, rank; degree, stage, point, state; altitude, height; spirit level, indicator; horizontal surface, surface; layer, stratum, place; floor, storey, story, structure, construction; aim, take, train, take aim, direct; raze, rase, dismantle, tear down, take down, pull down, destroy, destruct; flush, even out, even, change surface; charge, point aim, take, train, take aim, direct; level off, change surface; flat, plane, even, unwavering, steady; horizontal; tied, equal	19

Table 8. The Synset ID list of the three segments

Segment	Total No. of Distinctive Synset ID	No. of Intersections of Synset ID Within Segments		
		(a)	(b)	(c)
(a) Needs to follow a contour	31	NA	0	1
(b) The sledge manages to keep level	56	0	NA	3
(c) Is like this it stays flat but the bit you hold onto can be at different angles	123	1	3	NA

contains nonrepetitive distinct synset ID. A second loop is used to get the union list of synset ID for each segment; column two of Table 8 shows the total number of synset IDs of their corresponding segment.

The second part of the algorithm loops through all the segments to find intersecting elements (same synset ID). In this example, Segments (a) and (c) have the one intersecting synset ID with the set of words [follow, be]. Segments (b) and (c) have three intersecting synset IDs, which are the words: [hold, keep], [keep, maintain hold], and [flat, level, plane].

In this three-segment example, there are seven different linkographs possibilities. A human coder might produce (a)–(b) and (b)–(c) links but the WordNet synonym sets produce (a)–(c) and (b)–(c) links; however, they will produce the same entropy.

The above example connects “nouns,” “verbs,” and “adjectives”; however, in this study we explore connecting only the nouns as this produces a uniform bias across all results, which allows them to be directly compared. In addition, a condition was added to only connect segments with four or more common synset IDs. This was to account for unwanted associations. For example, although WordNet ignores pronouns, “I” in WordNet has the noun meaning of iodine, one, single, and

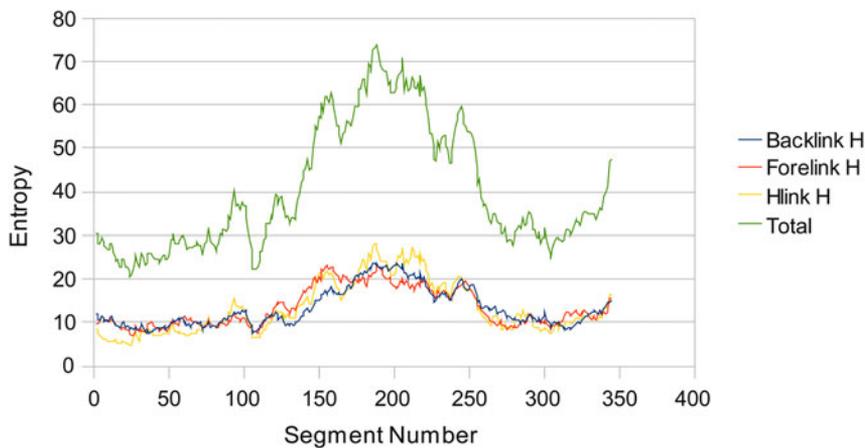


Fig. 6. Variation of entropy of the creative session normalized using a 5-min, 69-segment window.

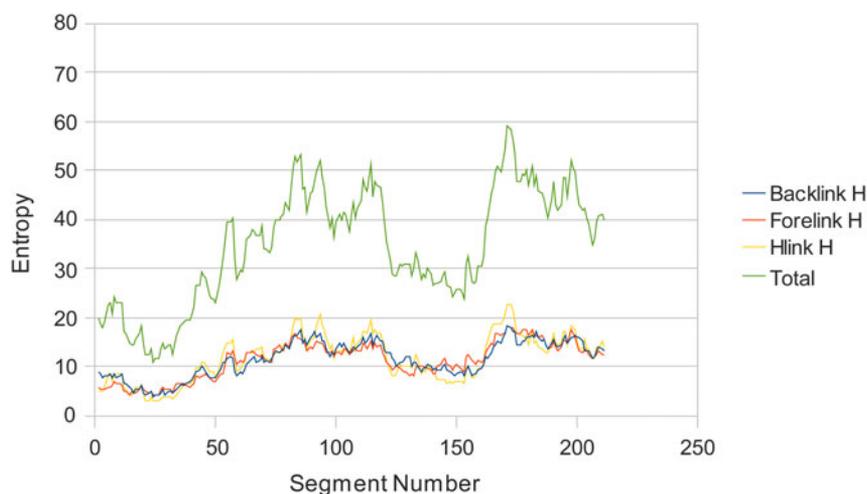


Fig. 7. Variation of entropy of the pragmatic session normalized using a 5-min 42-segment window.

Table 9. Linkograph entropy of sessions

Session A (Productive)	Session B (Pragmatic)	Difference (%)
413 segments	252 segments	48
Linkograph $H = 226$	Linkograph $H = 187$	19
69 segments/5-min window	42 segments/5-min window	15 ^a
Average H for 5-min window = 40.15	Average H for 5-min window = 34.59	

^a With t test, $p = 0.0000 < 0.001$.

unity. We do not want to link segments with only the connection to “I.” Similarly, we do not want to link the segments with the words “here,” “there,” “why,” and so on.

6. LINKOGRAPH ENTROPY OF THE TWO SESSIONS

The entropies of the linkographs, produced by using Eq. (6), of the productive session and the pragmatic session are 226 and 187, respectively. The productive session has much higher entropy than the pragmatic session (about 19%). We further examine the dynamic variation of entropy during the session. Figures 6 and 7 show the variation of entropy with segment numbers of the two sessions. We normalized the results using the 69- and 42-segment window as the division to measure the text entropy. Assuming the segments were equally distributed, this results in a 5-min window. The average entropies of this 5-min window of the creative and pragmatic sessions are 40.15 and 34.59, respectively. Table 9 summarizes the results of the entropic measurements.

7. RESULTS

According to our hypothesis, a higher entropy indicates more creativity. In the productive/creative session, Session A, the

Table 10. Comparing critical moves and word counts of three individuals from study described in Goldschmidt (1995)

	Ivan	John	Kerry
CM ⁷	24.3	43.3	32.4
f-CM ⁷	28.6	42.8	28.6
Words (%)	30.27	44.96	22.63
Words per segment	7.85	11.65	8.25

entropy peaks at segment 189 (entropy = 73.84). The entropy stays above 60 from segment 178 to 222. Segment 178 was the time that the designers started to draw Figure 1b. The entropy measured at segment 222, with a 69-segment window, covered segments until segment 291. This period, 114 segments, resembles the third episode when they drew Figure 1b–1d. In this period, they discussed new ideas and proposed shapes such as the idea of a ribbon, a triangular prism with a hole in the middle, a focus to grab attention, ramps to go to the roof, rediscussed inside–outside relationship, and the details of the plan and the section of the proposed building. In this episode, they produced three sheets of drawing out of a total of six here.

Despite the large difference in word counts between the two sessions (4,387 vs. 2,288), the text entropies are very close. Table 10 shows a word count study of the team protocol data from the 1994 Delft Protocols Workshop (Cross et al., 1996) that was used to compare with a previous study (Goldschmidt, 1995) that indicates creativity. It summarizes the percentage of three product design engineers’ (Ivan, John, and Kerry) critical moves with seven links (CM⁷) and forward link critical moves with seven or more links (f-CM⁷); f-CM⁷ was believed to indicate creativity (Goldschmidt, 1995).

With these word count studies, one is tempted to conjecture that there is a relationship between the numbers of words in the utterances and the number of design ideas. However, if a designer repeatedly verbalizes the same idea over and

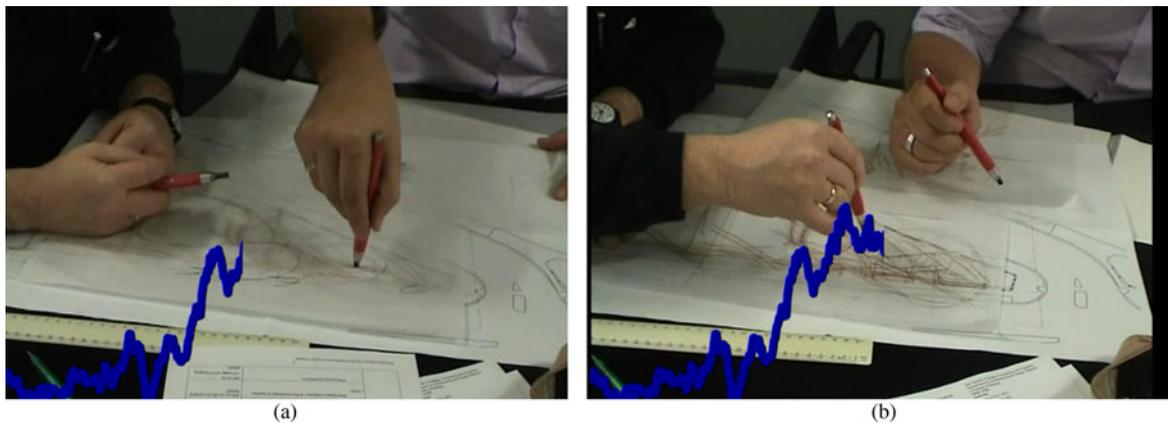


Fig. 8. Entropy variation graph overlaid on the video: (a) frame-grabbed around segment 178, and (b) frame-grabbed around segment 222.

over, it will not contribute to the productivity and creativity. Therefore, word counts of design protocol alone might not be a reliable measure of productivity and creativity.

The productive, creative, session not only has a higher word count but also has a higher linkograph entropy than the pragmatic session, 226 against 187. The difference is about 19%. We also measured the entropy with a window of 5 min; the creative session has 345 windows and the pragmatic session has 211 windows. The average entropies of this 5-min window of the creative session and the pragmatic sessions are 40.15 and 34.59, respectively. The difference is about 15% (with very high confidence of the difference), which is less than the differences in the word count. However, if we look in more detail into the creative session, the period of the highest entropy (segment 178 to 291) was the most productive episode. They produced three sheets of drawings (out of six) within this period (about 8 to 9 min), and as a consequence of these drawings the session was identified as the most creative session. This measurement matches well with the qualitative analysis. When we compare this productive period with the word count, Figure 3 and Table 3, the word count of this period falls into the third and fourth row of Table 3. Although the words per segment in this period (114 segments) is 12.9, which is higher than the average, the variations of word counts and text entropy in Figure 3 do not reflect these differences. However, the entropy variation correctly identified the productive/creative period. Figure 8 shows the entropy variation graph overlapped with the video; Figure 8a and Figure 8b were captured around segment 178 and 222, respectively. In this case study the entropy of the linkograph of the creative session is higher than the pragmatic session; the entropy variation graphs help to identify the creative/productive period of a session that characterizes design processes.

8. CONCLUSIONS

The research reported in this paper focuses on measuring design information in a specific way. Information measured

here is abstracted from the network of connected thoughts of the designers. We are not measuring the exchange of information required by different parties of a design team to complete their tasks (Tribelsky & Sacks, 2010).

The exploration of design information and cognitive processes started in the 1960s. Eastman (1968) used protocol analysis to investigate the processing of information in design. He suggested that “the structure of information used in design” were highly interdependent with the memory retrieval techniques for searching information. He also conjectured that “retrieval techniques for human memories” “may turn out to be one of the most significant variables influencing creative design capabilities” (Eastman, 1968, p. 80).

Linkography is based on the concept of connectivity of protocol segments; Kan and Gero (2009) considered the connected links in a linkograph represent design processes such as formulations (*naming* and *framing*), synthesis (*moving*), reformulations (*reframing*), analysis (a kind of evaluation), and evaluations. We postulate that these design processes, derived from the linkograph, capture the vocabulary richness in the segments and define the design space.

Designing involves the designer deciding either explicitly or implicitly what variables to consider. In doing so, she creates a space of potentialities: the design space. If that space can be structured suitably, it becomes possible to measure that potential. By treating the linkograph obtained from empirical data from protocol analysis as a structured design space (a graph), it is possible to use information theory to calculate its entropy. This quantitative information allows for the characterization of the creative activity in a design session; activity that is usually distinguished only qualitatively. The linkograph entropy provides us another layer of information about empirical data that otherwise is not obvious. The results presented in this paper indicate the possibility of using an entropic measure to characterize creative/innovative processes during the design process within a design space.

With current voice recognition technology, it is becoming possible to directly transcribe a design protocol from real-

time recording. This transcription can then be segmented based on activities (such as turn taking and pauses) and syntax connecting words (such as because or therefore). As the construction of linkograph and the calculation of entropy are all automated by using WordNet and programs, it may shortly be possible to produce a near real-time entropy graph. This graph can be used as a potential indicator of creative activity during the design process. Based on the results in this case, the notion of using a linkograph to characterize design spaces and the method of automating the process are worthy of further study.

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