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# VIRTUAL MODELING OF CONCEPT GENERATION PROCESS FOR UNDERSTANDING AND ENHANCING THE NATURE OF DESIGN CREATIVITY

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## ABSTRACT
In this study, we attempt to capture the nature of the concept generation process by finding an effective thinking pattern for creativity. We consider a space composed of chain processes of concepts that are both explicitly evoked in the concept generation process and inexplicitly imaged as a thinking space, and we focus on two viewpoints—structure and latent sensitivities. The former refers to the structure of the thinking space; the latter, the latent concepts that are inexplicitly imaged in the thinking space. From these viewpoints, we propose a method for modeling a virtual thinking space using a semantic network, and we quantitatively analyze its pattern. As results, we found that there is a significant correlation between the structure and the creativity and that the model could clarify the nature of design creativity in the concept generation process. These findings suggest that factors that affect the evaluated creativity score for design idea are closely related to the structure of the thinking space. This indicates that there might exist an effective thinking pattern for creativity; thus, this model could be used for enhancing design creativity.

*Keywords: Design creativity, concept generation process, modeling, structure, latent sensitivities*

## 1 INTRODUCTION
Creativity in design has been the focus of a large number of studies that have endeavored to support the creative design process. The design process is usually discussed in the framework of concept generation vs. its evaluation. In this study, we focus on the concept generation process as an important phase in creative design. In other words, the design process considered in this study is not on the goal-oriented design problem solving. For example, C-K theory [1] has been proposed as a methodology for design problem solving; this methodology offers richer models, where creativity is included. Our design process in this study corresponds to the process that expands the partition in C-K theory. Thus, we attempt to generate a novel design idea without the requirement of a specific goal by using the designer's knowledge.

In this study, we attempt to capture the nature of the concept generation process with the aim of proposing a method to support creative design, i.e., a method to enhance the creativity in the *design thinking process*, which is the thinking process by which a designer comes up with a design idea. The term "concept" refers not only to the image of an object but also the object (natural and artificial) in mind. Liu et al. (2003) also assumed that the concept generation process was related to the generation of a novel design idea [2], and Chiu and Shu (2007) proposed a methodology that involved enhancing the concept generation process by using verbs as stimuli [3]. Although "concept generation" is assumed to be related to the generation of novel design ideas, the detailed process of generation leading to the formulation of creative design ideas and the mechanism of generation (i.e., how designers generate novel design ideas) have not yet been identified.

In this study, we attempt to find an effective thinking pattern for creativity in the concept generation process in order to capture its nature. Here, *thinking pattern* is a characteristic of the design thinking process and an effective thinking pattern for creativity is a thinking pattern related to a design idea that obtains a high score in an evaluation of creativity. Thus far, many researchers have conducted studies on the thinking patterns behind creative design by attempting to understand and elucidate the design thinking process, and various factors have been extracted from the methods presented in these studies. Goldschmidt introduced "linkography," which is a method to visualize a designer's thinking pattern by drawing links between small units that constitute the design protocol [4]. Linkography can represent the pattern of a designer's thinking. Many studies have used linkography to find the factors affecting the design thinking process by observing their pattern of thinking [5]–[11], and have attempted to elucidate the design thinking process using these factors. These studies have shown the effect of pattern analysis on the concept generation process.

These methods are based on protocol analysis [12]. Although protocol analysis is useful for understanding the design thinking process, it is a superficial analysis in nature and can sometimes be inadequate for analyzing the design thinking process, especially in the case of creative thinking, because it takes into consideration only the explicit concepts that appear in the protocol. It is difficult for a designer to explicitly represent his/her thoughts, and certain inexplicit concepts always exist in the thinking process. Furthermore, another issue to be solved in linkography is that the small units are linked based on common sense, and hence, it is difficult to ensure the reproducibility of the linking process. Designers from different backgrounds might produce different linkographs from the same protocol.

In this paper, we propose a method for finding thinking patterns in the concept generation process; this method can fundamentally solve the problems mentioned above. We take into consideration a *thinking space,* which is defined as the space composed of chain processes of concepts that are explicitly evoked in the concept generation process as well as those that are inexplicitly imaged. On the basis of this consideration, we propose a method for modeling a *virtual thinking space* using semantic networks by using a computer and quantitatively analyze the pattern of the modeled thinking space using network theory. This model can clarify the nature of design creativity in the concept generation process.

## 2 VIEWPOINT OF THIS STUDY

We focus on two viewpoints. The first is the "structure of the thinking space," in which we assume that the structure of a thinking process is related to creativity in the concept generation process. The second is "latent concepts," which are the inexplicitly imaged concepts in the thinking space. On the basis of these two viewpoints, we create a virtual model of the concept generation process.

### 2.1 Structure of thinking space

As described above, Goldschmidt [4] introduced and extended a method called linkography. This method is used to visualize a designer's thinking process by linking small units that constitute the design protocol and to effectively represent the structure of a designer's thinking process. She called the visualized design protocol a "linkograph" and defined certain indicators for the linkograph as measurements of design productivity. These indicators can be regarded as features of the structure of the thinking process. She showed that the more developed a design, the higher is its link index, which is the ratio of the number of links to the number of units.

Many studies have used this technique to gain a deeper understanding of the design thinking process, for example, to study the segmentation of protocols in accordance with designers' intentions [5], to link categories between imaged concepts that are identified as primary units in the protocol [6, 7], and to develop a novel real-time-based indicator called link depth [8]. In an attempt to acquire quantitative information from linkography, Kan and Gero [9, 10] suggested a method for acquiring information from a linkograph by using Shannon's entropy method. Chou [11] adopted a pattern-matching algorithm for the entropy method.

More recently, Georgiev et al. [13] proposed a design method by focusing on the meanings of a design that was structured using concepts evoked in the concept generation process. By measuring the convergence of concepts, they integrated a computer's divergent thinking and a designer's critical thinking. Harakawa et al. [14] clarified that there is a strong relationship between the extension of thinking during the design process and the level of creativity in the design ideas, and that this extension of the thinking space is also a structural feature.

These studies focused on visualizing the design protocol, i.e., in the thinking space, and interpreted the design protocol by using its structural features. This implies that they considered the effect of the structure when finding thinking patterns. Thus, we propose the following hypothesis.

> "Factors that affect the evaluated creativity score for a design idea are closely related to the structure of the thinking space."

Using this hypothesis, we attempt to find effective thinking patterns for creativity in the concept generation process by clarifying the relation between the structure of the thinking space and the evaluated creativity score for design idea. A thinking space is represented as a network, with concepts evoked in the concept generation process as nodes and the relationships between them as links. Many researchers have applied the notion of a "network" for analyses in various domains and fields such as a human language structure [15], biological concept network [16], semantic network structure [17], and cognitive insight model [18]. Further, the notion has also been used in the field of information management for the development of a keyword extraction algorithm that uses a small-world structure [19] and in an analysis of the interrelationships among documents in a corpus [20]. In this study, by employing the notion and theory of a network, we construct a network representing a thinking space as a model of the concept generation process and analyze its structure in order to find thinking patterns. Figure 1 shows an image of the thinking space and its structure.

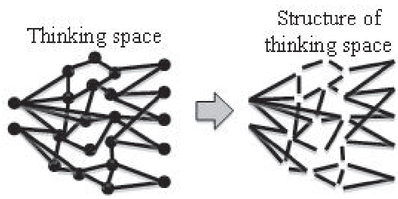



*Figure 1. Image of the thinking space and its structure*

## 2.2 Latent concepts

It is assumed that designers cannot explicitly represent all of their thoughts; however, we can consider the thinking space to be exclusively composed of chain processes of concepts that are explicitly represented (for example, protocol analysis using linkography). In some studies, this matter has been discussed based on the notion of something being "latent," which means that that thing remains hidden. Many fields of design have focused on latent sensitivities.

As an example, one study focused on the idea of a "latent function" in order to construct a design methodology for artifacts suitable for an environmentally conscious society [21]. A latent function [22] refers to the total behavior of an entity that can be observed under any circumstance. In other words, although the behavior of an entity observed under a certain circumstance (known as a visible function) is unique, different behaviors are observed under different circumstances, and the sum total of these behaviors is known as the latent function. A latent semantic approach for studying design team communication was proposed by Dong [23]. Latent semantic analysis [24] is a method used in natural language processing, particularly in vectorial semantics, for extracting and representing the contextual-usage meaning of words, that is, the meaning of words hidden in the context, by performing statistical computations on a large corpus of text. Dong empirically showed that a similarity between the use of language by different designers helps to bridge the indirect relationships between the components of knowledge in each designer's mind, and thus, the "psychological similarity between thoughts" can be modeled on the basis of language by using latent semantic analysis.

These researches indicated that latent sensitivities can be used to extract functions or relations that cannot be expressed explicitly. In this paper, we consider the latent concepts that are involved in the thinking space by modeling virtual chain processes of concepts evoked in the concept generation process; that is, we assume that the concepts (nodes) appearing in the virtual model involve latent concepts.

# 3 PURPOSE AND METHOD

The purpose of this study is to propose a "virtual modeling method for the concept generation process," which involves the notions of "structure" and "latent concepts," by using a semantic network. In this paper, we verify the effectiveness of the constructed model by clarifying the relationship between the structure of the thinking space and the evaluated creativity scores for design ideas.

## 3.1 Target concept generation process

In this study, we adopt the process of synthesizing two concepts (hereafter referred to as *base concepts*) as the basis for capturing the process of generating ideas during the design process. This concept synthesizing process is typically used when the design idea is new concepts created from given base concepts [25, 26]. Figure 2 shows an image of the concept synthesizing process.


*Figure 2. Concept synthesizing process*

## 3.2 Virtual modeling of the concept generation process

In this study, we propose a method for modeling a *virtual thinking space* using a semantic network and quantitatively analyze its pattern using network theory. This model can capture the nature of the structure of a thinking space that involves not only explicitly evoked concepts but also latent concepts, which are inexplicitly imaged during the concept generation process.

### *3.2.1 Semantic network*

Recently, there have been some studies in the design domain that have used semantic networks. Semantic networks have structures composed of the semantic relations between words, such as the hypernym-hyponym relation and associated relations. In actual practice, semantic networks are useful when searching for links between words. To be specific, semantic networks can be used to search for virtual chain processes of concepts, from base concepts to *design idea features* (explained later).

As described above, Georgiev et al. [27] proposed a design methodology based on the significance of the relatedness or similarity between the paths of two concepts by employing the lexical database WordNet [28] as a semantic network and measuring the relatedness or similarity with the concept evaluation tool within its database [29]. Nagai and Taura [30] clarified the influence of a number of associative concepts, which are derived from the base concepts for design creation; they also explained the role of action concepts during the process of concept synthesis. In order to clarify these two points, they used two concept dictionaries that can be regarded as semantic networks—the Associative Concepts Dictionary [31] and the EDR Electronic Dictionary [32]. These two dictionaries were used by Harakawa et al. [14] to measure the distance between the base concepts and the words in the design protocol.

Since semantic networks do not depend on the designer's background, they are suitable for the virtual modeling of the concept generation process, and the virtual thinking space constructed on the basis of these networks can be reproduced with the help of a computer.

### *3.2.2 Virtual thinking network construction*

Figure 3 shows a virtual model of the concept generation process. To construct this model, we use design idea features as a substitute for the design idea and construct a network representing the virtual thinking space. The design idea features considered in this study are terms described by the designer, who is required to list the terms that explain his/her design idea. Although the design idea features do not indicate the design idea, we construct a virtual thinking space by using them. A semantic network is used for searching virtual chain processes of concepts during the concept generation process, that is, the paths from the base concepts to design idea features. The concepts that are found in each of these paths, other than the base concepts and design idea features, we are called *virtual concepts*; these concepts are assumed to involve latent concepts in the concept generation process. We construct a network in which the searched paths are considered as a representation of a virtual thinking space (hereafter referred to as a *virtual thinking network*). Thus, virtual thinking networks consist of two types of nodes: (1) explicit concepts that are assumed to be imaged explicitly in the process design thinking and (2) latent concepts. We extract the structure of the thinking space from this virtual thinking network and analyze it.

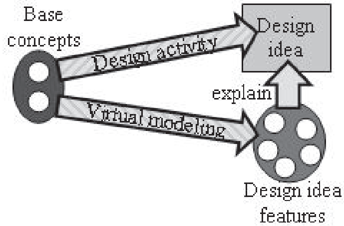



*Figure 3.Virtual modeling of the concept generation process*

Figure 4 shows the construction of the virtual thinking network. This modeling method consists of the following four steps:

Step 1: Searching for paths between a base concept and a design idea feature (see the first diagram in Figure 4). Here, a concept is expressed as a word, and a path is a set of direct links joining one word to another. Since words have multiple meanings (polysemy) in the semantic network, multiple paths between the base concept and the design idea feature are extracted from the semantic network.
Step 2: Extracting virtual concepts that appear in the paths between the base concepts and the design idea features (see the second diagram in Figure 4).
Step 3: Drawing a network with the virtual concepts as nodes and the links as the extracted paths (see the third diagram in Figure 4).
Step 4: Extracting the structure of a virtual thinking network as the structure of the thinking space (see the fourth diagram in Figure 4).

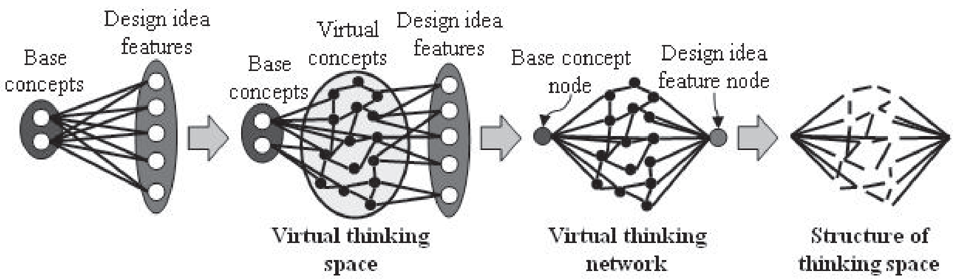



*Figure 4. Construction of the virtual thinking network*

### 3.3 Structure analysis

By using network theory, we analyze the structure of the thinking space extracted from the virtual thinking network in order to find an effective thinking pattern for creativity within this space. Using the network, we prepare a graph consisting of a set of *nodes* and a set of *links* joining the nodes. Although a wide range of statistical criteria exist in network theory, in this study, we use a few important criteria to characterize our thinking network. We chose the same network statistical criteria as those in the study of Steyvers and Tenenbaum [33]. They used the criteria to examine whether semantic networks have a structure that is necessarily different from that of other complex natural networks.

On the basis of the assumptions stated below, we apply these criteria to clarify the relation between the evaluated creativity score and the structure of the thinking space. In addition, this clarification corresponds to a verification of the ability of our model to find an effective thinking pattern for creativity.

- $n$, $<k>$, and *Density* can indicate the expansion of the thinking space.
- $C$, $L$, and $D$ can indicate the complexity of the thinking space.

As mentioned in Section 2.1, the extension of the thinking space during the design process relates to the evaluated creativity score for a design idea [14]. Therefore, the extension of a virtual thinking network can be considered as a clue to find an effective thinking pattern for creativity. Whereas, human knowledge is like a complex network composed of pieces of knowledge and the relations between them, and its complexity appears in an individual's thinking space during the design process. Moreover, the designer's creativity depends on his/her knowledge. Therefore, we believe that the complexity of a virtual thinking network can be considered as a clue to find an effective thinking pattern for creativity.

Table 1 summarizes the definitions of the network theory criteria used in this study. The number of nodes $n$ denotes the number of concepts, which are expressed as words, appearing in each network. The number of links that are joined to a node is called the *degree*, and the average degree $<k>$ is the average number of links joining a node in the network. If a network involves numerous nodes and links, it is considered to be large; i.e., the network has an expansion. Thus, these criteria could indicate the degree of expansion of a network.

Two joined nodes are said to be *neighbors*. The probability that the neighbors of an arbitrary node are neighbors to each other is defined by the clustering coefficient $C$. In terms of network topology, a high probability signifies the existence of "shortcuts" or "triangles" in the network. The presence of shortcuts or triangles is common in complex networks. In other words, $C$ indicates the complexity of the network. Figure 5 shows an example of the calculation of $C$ in this study. We calculate $C$ by taking the average of $C_i$:

$$C_i = T_i \Big/ \binom{k_i}{2} = 2T_i / k_i(k_i - 1) \qquad (1)$$

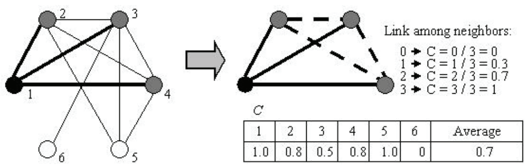



*Figure 5. Example of the calculation of the clustering coefficient*

where $T_i$ denotes the number of links between the neighbors of node $i$, and $k_i(k_i - 1)/2$ denotes the number of links that would be expected between the neighbors of node $i$ if they formed a fully joined subgraph. $L$ denotes the average of the shortest (or geodesic) paths between the nodes over the entire network, i.e., the shortest path among the sets of links comprising the paths between the nodes, and the diameter of the network, $D$, denotes the longest path in the set of shortest paths. The values of these parameters decrease with the complexity of the network, and therefore, these criteria can indicate the degree of complexity of the network. The clustering coefficient $C$ of a network is inversely proportional to $L$ and $D$. In other words, if $C$ has a significant correlation to the evaluated creativity scores for the modeled design ideas, then $L$ and $D$ could also have a significant correlation.

The *Density* of a network indicates the sparseness of the network and is calculated by dividing $<k>$ by the size $n$ of the network; thus, the network has a high sparseness when *Density* is low.

*Table 1. Definitions of terms in network theory*

| Term | Definition |
|---|---|
| $N$ | Number of nodes |
| $<k>$ | Average degree (degree = number of links) |
| $C$ | Clustering coefficient |
| $L$ | Average length of the shortest path between a pair of nodes |
| $D$ | Diameter of the network (the largest number of steps required to move from one node to another, or the longest path among the shortest paths) |
| *Density* | Sparseness of the network (the percentage of how a node is joined to other nodes) |

## 4 EXPERIMENT

The design idea used in our experiment was adopted from the design experiment conducted by Nagai et al. [33]. We modeled the thinking space for each design idea by using WordNet as the semantic network. The network analysis tool Pajek [34] was used to visualize and analyze networks for terms in network theory. Using Pajek 1.23, we visualized the constructed networks and calculated the value of the terms in network theory, which are listed in Table 1. WordNet was used in a Linux environment, while Pajek was loaded on the Windows operating system.

### 4.1 Design idea

In the design experiment conducted by Nagai et al. [33], 22 Japanese students were required to design a new design concept from two base concepts; in other words, the students were asked to carry out concept synthesizing. Using the concepts of SHIP-GUITAR and DESK-ELEVATOR as the base concepts, they were required to sketch, explain, and list design idea features that could explain their design ideas (see examples in Table 2). They came up with 20 design ideas for SHIP-GUITAR and 19 design ideas for DESK-ELEVATOR. The creativity of their design ideas was evaluated by 11 evaluators on the basis of practicality and originality [35] on a scale of 1 to 5. It was found that the creativity of each design idea did not depend on the number of design idea features.

*Table 2. Example of design idea*

| Base concepts | Sketch | Explanation | Design idea Features |
|---|---|---|---|
| SHIP GUITAR |  | A guitar that produces sound by the vibration of strings from the motion of the boat and waves in water. It is a boat that can be used as an instrument and be hired for leisure. | Leisure<br>Concert<br>Open air<br>Reaction<br>Sport<br>Exciting<br>Resonance |

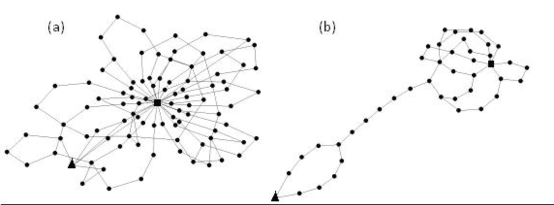
### 4.2 WordNet

WordNet [26] is a huge electronic lexical database that contains information on the manner in which human beings process language and concepts. The development of the WordNet database was started in 1985 by George A. Miller and his colleagues. Currently, the database comprises over 150,000 words. Words are organized in hierarchies and are interconnected by various semantic relations such as synonym, hypernym-hyponym, and meronym. The advantage of using WordNet as a huge semantic network is that it is practically useful for searching for links between words.

In this experiment, concepts were expressed as words. In WordNet, links are presented only between words belonging to the same POS (part of speech; for example, noun-noun). Thus, we performed two preprocesses. First, we accurately translated Japanese words into English. Next, we replaced all the verbs and adjectives with their corresponding nouns. After these processes, a virtual thinking network was constructed according to the network construction method explained in Section 3.2.2.

### 4.3 Results

We constructed networks for all of the design ideas created by the participants. Figure 6 shows two examples of virtual thinking networks drawn using Pajek and their corresponding creativity (practicality and originality) and term values. We could state that (a) is an example of a network with high creativity, whereas (b) is an example of a network with low creativity. The values of the statistical network criteria were computed using Pajek.




| | Practicality | Originality | $n$ | $<k>$ | C | L | D | Density |
|---|---|---|---|---|---|---|---|---|
| (a) | 3.6 | 3.5 | 93 | 2.69 | 0.06 | 3.88 | 9 | 2.89% |
| (b) | 2.2 | 2.7 | 43 | 2.33 | 0 | 6.26 | 16 | 5.41% |

*Figure 6. Examples of virtual thinking networks, (a) with high creativity and (b) with low creativity. ▲ is the base concept node, and ■ is the design feature node.*

## 5 ANALYSES

We examined the relationship between the structure of the virtual thinking network and the evaluated creativity scores for the design ideas. In order to verify our hypotheses in Section 2.1, we analyzed the correlations between the evaluated creativity score and the network terms listed in Table 1. If correlations existed, then they could act as clues for finding an effective thinking pattern for creativity in the concept generation process.

### 5.1 Correlation analysis

As shown in Table 3, we found that <*k*> and *Density* had significant correlations with the evaluated originality score ($p = 0.028$, $p < 0.05$, and $p = 0.018$, $p < 0.05$, respectively). Graphs depicting these correlations are shown in Figures 7 and 8. The results suggest that the <*k*> and *Density* indicate the significant fact that the polysemy of a word plays an important role in the expansion of the thinking space; this is similar to divergent thinking. Further, the number of nodes $n$ had a marginally significant correlation to originality ($p = 0.073$, $p < 0.1$; see Figure 9). This suggests that $n$, which is the number of concepts evoked in the concept generation process, affects design ideas. From these results, we suggest that $n$, <*k*>, and *Density*, which can represent the expansion of the thinking space, affect originality.

We also found that $L$ had a significant correlation to originality ($p = 0.047$, $p < 0.05$). The graph depicting this correlation is presented in Figure 10. This correlation implies that the complexity of the thinking space may also affect originality, i.e., the higher the complexity, the better is the design idea. This suggests that $L$ plays an important role in elucidating the nature of creativity. However, we could not find a significant correlation between either of the parameters $C$ and $D$ and creativity.

*Table 3. Correlation coefficients. Data includes all 39 design ideas, 20 design ideas for SHIP-GUITAR and 19 for DESK-ELEVATOR.*

| | Creativity | ***n*** | **<*k*>** | ***C*** | ***L*** | ***D*** | *Density* |
|---|---|---|---|---|---|---|---|
| Practicality | Pearson Correlation Coefficient | 0.058 | 0.133 | 0.005 | –0.264 | –0.222 | –0.117 |
| | Significance Level | 0.725 | 0.420 | 0.974 | 0.104 | 0.174 | 0.477 |
| | N | 39 | 39 | 39 | 39 | 39 | 39 |
| Originality | Pearson Correlation Coefficient | $0.290^{+}$ | $0.352^{*}$ | 0.103 | $-0.320^{*}$ | –0.201 | $-0.378^{*}$ |
| | Significance Level | 0.073 | 0.028 | 0.533 | 0.047 | 0.220 | 0.018 |
| | N | 39 | 39 | 39 | 39 | 39 | 39 |

**1% level of significance by the standard (both sides); *5% level of significance by the standard (both sides); +marginal significance

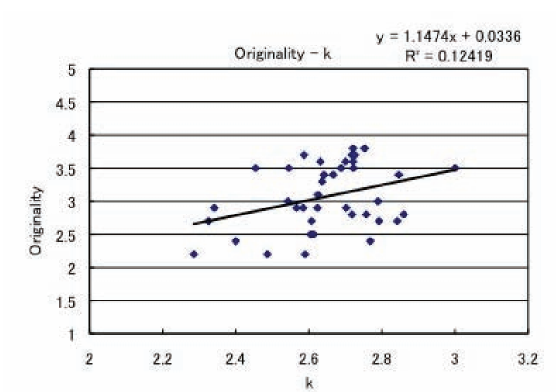



*Figure 7. Correlation between the originality and <k>*

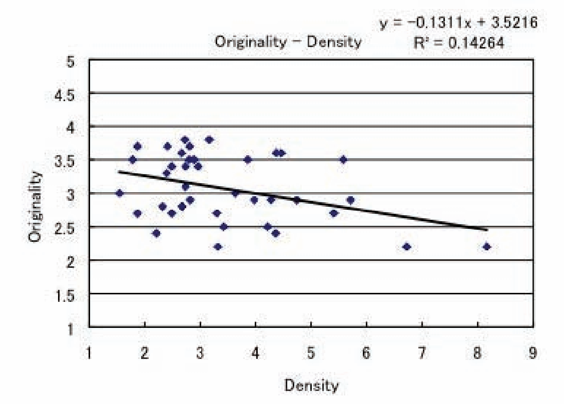



*Figure 8. Correlation between the originality and Density*

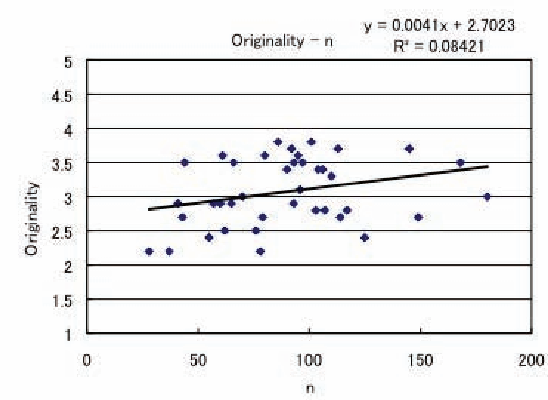



*Figure 9. Correlation between the originality and n*

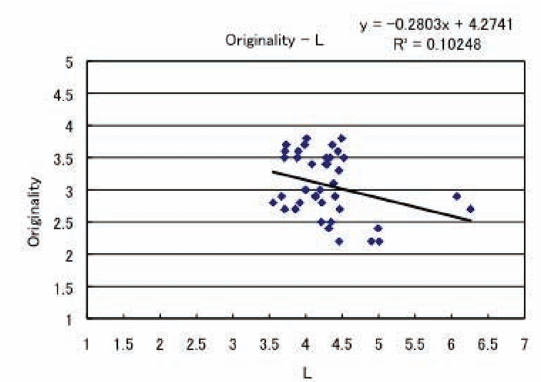



*Figure 10. Correlation between the originality and L*

### 5.2 Meaning of correlation

Figure 11 illustrates the relationships among the elements in our study. We constructed a network that represented a virtual thinking space by using the design idea features as substitutes for a design idea created by the concept synthesizing process. We then examined the correlation between the network structure and the evaluated creativity scores for the design ideas and found a significant correlation between the creativity score and $<k>$, *Density*, and $L$; the correlation between the creativity score and the number of nodes $n$ approached significance. These results indicate that the factors affecting the evaluated creativity score for a design idea are related to the structure of the thinking space. This suggests that our virtual thinking model may represent certain creative aspects of the actual concept generation process. Therefore, there might be an effective thinking pattern for creativity in the concept generation process. Thus, the "structure of the thinking space" is useful for understanding the nature of design creativity.

The parameter $<k>$, which is a feature of the network, is based on the same notion as the link index observed in linkography. The link index can indicate the relation between design thinking and creativity, i.e., the more developed the design, the higher the link index. The linkography is defined by each designer using common sense. Although the thinking space constructed in this study was a virtual model, the result obtained was in good agreement with the thinking space constructed using common sense. This means that our virtual thinking model, which is reproducible, takes common sense into consideration. Thus, a humanly constructed semantic network can be useful for modeling a thinking space in the concept generation process.

"Latent concepts," which are involved in the concept generation process, were found to be useful for understanding the nature of design creativity. We took latent concepts into consideration by modeling the concept generation process virtually.

These findings suggest that our virtual thinking network is effective for understanding and enhancing the nature of design creativity.

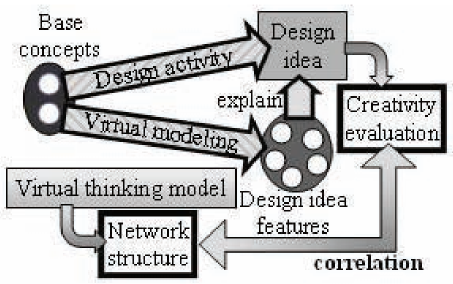



*Figure 11.Relationship between the structure of the virtual thinking model and the evaluated creativity score for a design idea*

## 6 CONCLUSION

In this paper, we attempted to find an effective thinking pattern for creativity in the concept generation process in order to capture its nature. We adopted the concept synthesizing process, which is a typical concept generation process. We considered a space composed of chain processes of concepts that are both explicitly evoked in the concept generation process and inexplicitly imaged in a *thinking space* and proposed a method for modeling a virtual thinking space using a semantic network. We also quantitatively analyzed the nature of the thinking space using network theory. We focused on two viewpoints—the structure of the thinking space and latent concepts. The effectiveness of our model was verified by clarifying the relation between the structure of the thinking space and the evaluated creativity score for a design idea. In the experiment, we found a significant correlation between the two; thus, this model could clarify the nature of design creativity. These findings suggest that the factors that affect the creativity of a design idea are closely related to the structure of the thinking space. In addition, as an experimental result, we found that our virtual thinking model is capable of representing certain creative aspects in the actual concept generation process, that is, the concept synthesizing process. This leads to the conclusion that there might exist an effective thinking pattern for creativity, and hence, this model could be applicable for enhancing design creativity.

In a future study, we will attempt to extract and apply the thinking pattern in order to support the enhancement of design creativity.

The structural analysis methods used in this study were based on the research of Steyvers and Tenenbaum [17]. In future, we will further examine the structure of creative thinking using other criteria and methods from network theory and observe the properties of the creative thinking pattern.

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