A System for Aiding Creative Concept Formation

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Abstract—**This paper describes a system named AA1 (Articulation Aid 1) which aids human users in the formation of new concepts in the domain of engineering and science. From the viewpoint of concept formation, one main process of creation is divergent thinking in which broad alternatives are searched, and another process is convergent thinking in which a unique solution is sought. From the viewpoint of human activities, creation also includes the aspect of collaboration among people and the aspect of individual reflection, although they are interrelated. AA1, the system presented in this paper, supports divergent thinking during individual reflection. Engineers and scientists usually scrawl many notes on paper while exploring new possible concepts in the divergent thinking process. A system is needed to reflect the fragments of concepts that are not articulated yet and thereby stimulate the formation of new concepts. AA1 builds a two-dimensional space from the words the user provides. Looking at this space and other precedent spaces, the user can form new concepts little by little. The main feature of AA1 different from existing hypermedia systems and CSCW sytems is the strategy for building the space presented to the user. The system is as nonprescriptive as possible, but it gives stimulation for the user to form concepts that he could not by using only pencil and paper. Experimentation has shown that the space which AA1 displays can effectively help the user to build new concepts. The most prominent effect is that empty regions in the space automatically configured by the system often lead to new concepts.**

I. Introduction

THIS paper describes a system which aids creative concept formation by humans. There has been much work on concept formation by machine [33] in the domain of artificial intelligence and there has been much work on how concepts are represented in human mind [27], [40] in the domain of cognitive science. However, there have not been many studies on creative concept formation process in the human mind in engineers' and scientists' daily life, with a few notable exceptions (e.g., [30]). On the other hand, it is said that the last tasks which are not aided by computers in industry are the tasks which are concerned with concept formation. For example, it is very important to form new concepts of new cars in contemporary automobile design but the designers who form the concepts in automobile companies are using computers only for, e.g., word processing and data retrieval from database.

The system we give in this paper is a tool for aiding concept formation in the domain of engineering and science. In the domain of engineering, the designers should build new concepts of new industrial products; e.g., computer engineers should build new concepts for new computers. In the domain of science, researchers should build new concepts, too.

In this paper, we adopt a psychological view of concepts, i.e., we define a concept as a connection between a symbol in an external language such as natural language, and a chunk of information stored in the mental world. These chunks of information in the mental world include images, sounds, and other symbols in mental models [27]. For example, in automobile design, the designers form a new concept, say, "human-friendly car" as a concept for a new car. Here, the word "human-friendly car" is one symbol and is connected to much information such as the information on the shape of the car, power of the car, etc.

Concerning the term "creative," new research fields about creativity are emerging—for example, AAAI held a symposium on "Artificial Intelligence and Creativity" in March 1993 and an international symposium on "Creativity and Cognition" was held in April 1993 in the United Kingdom. In Japan, the Science and Technology Agency commenced support for research on systems for aiding creative activities in 1993 and the Ministry of Education is already supporting a basic research effort on concept formation and knowledge acquisition. Needless to say, creation covers very wide range of human activities—from art to industry and from individual cognition to social collaboration. The research project supported by the Science and Technology Agency will accordingly consist of eight research teams, which include computer scientists, cognitive scientists, sociologists, economists, and R&D managers from industry. Many aspects of creative activities should be revealed from now on. The author is leading one team in this project and the system presented in this paper is a pilot system the author built by himself as a feasibility study before the project is started.

Although there are still many unknown aspects of creative activities, there are some works which have investigated the structure of creation in engineering and science. Imai, Nonaka, and Takeuchi, who are economists, investigated the processes of innovative product development in American and Japanese industries [22]. They found that creative activities consist of several phases. They are the phases of concept formation, feasibility, definition, design, and production, and these phases overlap. Moreover, they found there are two kinds of processes in each phase. One is a process of divergent thinking, in which broad alternatives are searched. Another is a process of convergent thinking, in which a unique solution is sought. Inose, who is a scientist in electronic engineering, describes the process of creative activity as a unified process of positive and negative feedback among research, development, design, production, marketing, distribution, and consumption, and

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he points out that "flashes of intuition fostered by a keen sensitivity" are necessary in each component [23]. Gould, a biologist, says that "creativity, in short, is not predictable progress. It requires a measure of sloppiness, redundancy, and potential for inherently unpredictable change" [14].

The aim of this paper is to build a system for aiding at least one process in one phase of creative activity, namely, the process of divergent thinking in the phase of concept formation, where broad alternatives of new concepts are explored. This process includes two main interrelated aspects. One is individual reflection, and the other is collaboration among people. This paper mainly focuses on the aspect of individual reflection for the divergent thinking process, although the collaboration among people is also considered.

The analysis of creative activities by Imai mentioned above shows that target concepts must once become nebulous in the process of divergent thinking. This means that possible elements for forming new concepts, which are gathered by a researcher, remain nebulous in the researcher's mental world for some time before they are articulated into some concepts. The researchers incubate fragments or seeds of new concepts in their mind and they gradually or sometimes suddenly form them into a new concept. The system we build aims at enhancing this process.

To achieve this, we propose to use spatial arrangements of words as stimulation for the user to form new concepts. Compared to traditional decision support systems and recent groupware systems and mind tools, the proposed system has the feature that the system is as nonprescriptive as possible but gives effective stimuli. The most prominent effect is that the empty regions in the space automatically configured by the system stimulate the user to form new concepts.

Although the main purpose of the system is to aid the individual mental process of forming concepts, we cannot ignore the importance of social collaboration in creative activities. The system has the potential to be connected to or to become a part of systems for aiding collaboration.

We describe the idea of mapping words into Euclidean space and of using that space as a stimulus for the formation of new concepts in Section II. Section III describes how to use our system AA1 (Articulation Aid 1), and what kind of effects are expected. Here we also show how AA1 can be a part of a collaboration aid in the future. We give the results of experiments and the evaluation of the system in Section IV. We give comparisons to related works in Section V. Finally we give the conclusions.

II. Key Ideas of AA1

The term "concept formation" may have many meanings. Philosophers like Kripke claim that some "concepts" are not things that can be formed by humans but something that already exist in the real world [31]. Psychologists like Johnson-Laird claim that a "concept" is a chunk of information stored in a mental world [27]. In this paper, we adopt the psychological view, and we limit our interest to one central part of concept formation, that is, the articulation process. Articulation means the process of cutting and connecting symbols from nebulous mental world [16]–[19]. For example, experts often say "I know, but I cannot explain" [13]. This means that what the expert knows is not conceptualized yet. We must put cut-lines in nebulous mental world and assign a symbol to what is cut out. We call this process articulation and we believe this is a central and important part of concept formation.

A few researchers, especially philosophers and psychologists, have studied this first stage of articulation in the context of scientific discovery [6], [30]. The philosophical viewpoint most helpful to our study has been a Buddhist philosophy of language [25]. It says that there are several layers in our mental world and that there is a continuous flow of something like liquid in the bottom layer which can be a basis for creating symbols. Symbols sometimes appear from the crystallization of the liquid. We can find a similar image in Polanyi's philosophy of the "tacit dimension" [36]. Another philosophical viewpoint compatible with our study is that of Koestler [30]. He claims scientists arrive at a new idea by "bissocination," which is the collision of two different planes of association. It has been remarked that so-called tacit knowledge plays an important role in intelligence in the context of studies on artificial intelligence [26]. We believe that what Winograd claims recently on what kind of roles computers should play [43] also supports the assumption behind our study. Although each of these philosophical viewpoints gives us insights into the process of articulation of the mental world, they only give explanations of phenomena, and so we must develop our own methodology for aiding the articulation process in mental world.

For considering the methodology, let us recall what engineers and scientists do in the phase of individual reflection for exploring new concepts in their creative works. We find that they put seeds of concepts, which consist of a few words or hand-drawn figures, on paper using pencil and erase them and rewrite them. Although what scientists and engineers write on paper and how they give meaning to their own notes is idiosyncratic, we can say that they commonly reflect some of the fragments of their mental worlds onto paper and rearrange the concepts little by little.

The author finds two important points from the viewpoint of cognitive science in this paper-assisted concept formation process. One is the effect of externalization. The other is process of organizing concept. It is known, from the studies on cognitive science, that human beings do not achieve thinking process only with the internal mental world but also by using external memories and other tools like paper and pencil [35]. Writing notes is a process for fully utilizing the external memory. We can say that many works recently being done in the field of hypermedia have the purpose of enhancing this externalization. Then, what is the process of organizing concepts including such external world? A common scheme in cognitive science is to introduce the notion of microconcepts or microfeatures. We can explain the organization process of a concept by combination of microfeatures. We can say that researchers form new concepts by gathering and discarding many microconcepts, which are elements of concepts, in the writing process of research notes, which is the articulation process. However, in previous studies in cognitive science, the set of microfeatures are given in advance for the explanation or for the the implementation of a system (e.g., [42]), while it is difficult to consider a small finite set of microfeatures in the real activity of concept formation.

If it is a fact that a concept is organized by microconcepts and that we cannot give a finite set of microconcepts in advance, the system to aid the process of reflection must be a system from which microconcepts emerge. Recent works on externalization of mental world have come up short in this respect, because they assume a finite set of primitives for representing concepts. (e.g., [34]).

Now the question is how microconcepts can emerge from the usage of a system. Our answer to this question is to use a map of words. A key idea is that users can read microconcepts in empty place between words in a map. This is different from the working process of previous externalization tools. Previous systems provide a user with primitives for externalizing fragments of concepts and force the user to use the primitives. For example, one system provides a user with links like "Main Path," "Faulty Path," "Return Path," and the user connects fragments of text using those links [34]. Our system calculates and shows a user several maps configured by words, where the words are given by the user or have already been stored in the system. The meaning of the axes of the map and the connecting relations among the words are not given in the map. The user reads mciroconcepts for forming a new concept from the map by himself. For example, when a user finds a word "A" placed near a word "B", the user is often stimulated to consider which elements of the concept corresponding to "A" account for it being placed near "B". This evokes new microconcepts around "A" and "B", and this can assist the formation of new concepts.

The next question is then how the system can configure such a stimulating map when the system does not offer the user a set of predefined links for connecting words. One answer may be to give a user a simulated blackboard on the computer and ask the user to configure the space freely by himself. This is a brainstorming on computer [38]. While it is reported that such brainstorming on computer works effectively [38], this does not use the computation power and the storage power of computers fully. The previous brainstorming system on computer gives a substitute of a blackboard but the computer does not perform much calculation. The user gets back no more than he puts in. We believe that results of a certain type of calculation we describe below can offer a user more stimuli for forming new concepts than the substitute of a blackboard. Our answer is to apply a kind of multidimensional scaling method [28]. Our system does not force the user to use a set of predefined primitives for composing and connecting concepts but receives the least information on relations among words. The system asks the user which word has some strong relation with which word, without asking what the relation is. In other words, the system gives only one primitive, that is "some relation," which leaves the system the possibility to reveal hidden relations that were not noticed by the user. Based on this information on "some relation," the system calculates a space in which the words are configured. The basic idea itself is a traditional one in the studies of statistics, but our system differs from traditional usage of multidimensional scaling method in that the system interactively receives the information on the relation between the words and interactively shows the calculated space. Moreover, we exploit the existence of local-minimums of the solution for calculating the space, i.e., the system interactively shows the user different maps which are different local-minimums of the calculation. When combined with several useful functions which are described in the next section, this basic method works effectively for giving stimuli for concept formation.

Let us give a small example here. Let us assume that a researcher is trying to build the concept of a new computer. He may write some key words and figures on paper, e.g., "computer," "needs," "trends," "desk-top," "lap-top," "palm-top," "down-sizing," "work station," "personal computer," "computation speed," "memory size," "virtual reality," "game center," "office," "science," "amusement," etc. If he knows the KJ-method [29], he may write notes on cards and arrange them on a desk. If he knows the method of brain storming, he may write the notes on a blackboard. Our system AA1 gives two-dimensional space automatically built from the words the user gives. Here, to say what is the reaction between "workstation" and "lap-top" is a big job, but it is easy for the user to say whether or not "workstation" has a strong relation with "lap-top." The content of the relation and the context around the relation should be articulated in later stage of concept formation because the later articulation of the relation can preserve a wider possible world for concept formation. Words like "lap-top," "down-sizing," and "work station" are automatically put in one space as a result of calculation based on the multidimensional scaling method.

The mechanism of the calculation based on the multidimensional scaling method [28] is as follows. For example, if a word "A" has some relation with a word "B" and does not have any relation with a word "C", the distance between "A" and "B" becomes smaller than the distance between "A" and "C", and this rule is applied to all the pairs of words. The calculation of the space is done based on the steepest-descent method to minimize the stress that is the sum of values of how much a pair of words violates the rule. There can be several possible local minimums in this calculation. The user can see all these answers. These different configurations can correspond to different views to the same world. For example, a word "D" may come near "A", when "A" has some relation with "B" and "B" has relation with "D". This may surprise the user when he is unaware of the relation between "A" and "D". In a different local minimum solution, "F" may come near to "A". Such surprise can evoke the user to consider elements of concepts around the word "A", which can reveal the hidden relations among words which were not noticed by the user. Such surprise is difficult to get from usage of a mere blackboard because the blackboard cannot itself change the configuration of words.

In addition to the space made from the words the user gives, the system shows precedent spaces. Some of the precedent space are automatically built from words in text books and technical papers using the same method of multidimensional scaling where relations between words are got from the co-

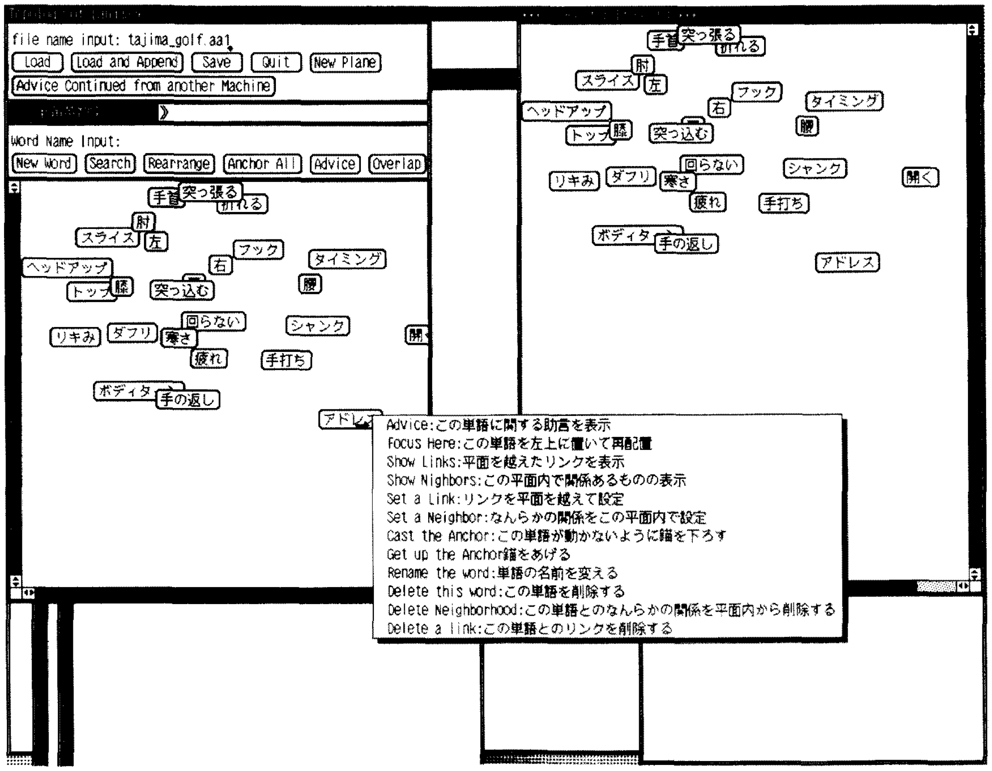


Fig. 1. Usage of the system AA1. The Japanese words automatically configured in the space are giving a partial reflection of the user's mental world. The user can change the configuration of the space using the functions shown in the menus, among others.

occurrence ratio of words in a sentence in the text. Others are spaces formerly built by other users for their concept formation. These precedent spaces play the role of stimulating the user to make analogies between different domains.

The features of our approach are compared to other approaches in Section V.

III. Usage and Effect of AA1

Fig. 1 shows an example of the usage of our system AA1. A user first gives some words which come up to his/her mind. He/she says to the system which word has some relation with which other word by mouse operation. He/she does not need to give the name of that relation. The system calculates a configuration of the words in two-dimensional space. The user can change the configuration of words in the space using the functions shown in the menu in Fig. 1 and other functions. Addition and change of words and relations can be done any time. The Japanese words in the space give a partial reflection of the user's mental world. This space may be meaningless for most observers especially for the people who do not understand Japanese. However, the space gives stimuli for promoting concept formation to the user who has interest in the world shown in the space; the user reads many things from the space.

What is read may be different from one user to another. This is no problem in the phase of individual reflection for divergence of concepts, because the user is trying to develop his own concept in this phase. However, the author expects that our system can work somewhat even in the phase of collaboration among people seeking for consensus. As shown in Section IV, a space built by one user can evoke discussion among people who share an interest. Another person can get inspiration from the space built by other user when explained by the user who built the space. If we augment our system to facilitate this explanation function, AA1 will become one element for groupware in future. As AA1 mainly works for giving stimuli for concept formation for one person by the calculation of space, which cannot be got by existing groupware systems, and the space built by one user can stimulate other persons in the groupware, stimuli for concept formation will in future come both from the result of computation by AA1 and from other persons.

Fig. 2 shows an example of a precedent space. Fig. 2 gives a part of the space automatically built from all the words used in one technical paper, where the relations between words were calculated based on the cooccurrence ratio of words in a sentence. Looking at those spaces, the user often makes an analogy between different spaces or sometimes makes a special inference, and he/she comes up with new words. He/she then places those new words and reconfigures the space.

The user can freely change the positions of any words by mouse operation. He/she can call a precedent space which may interest him/her by selecting "advice" from the menu.

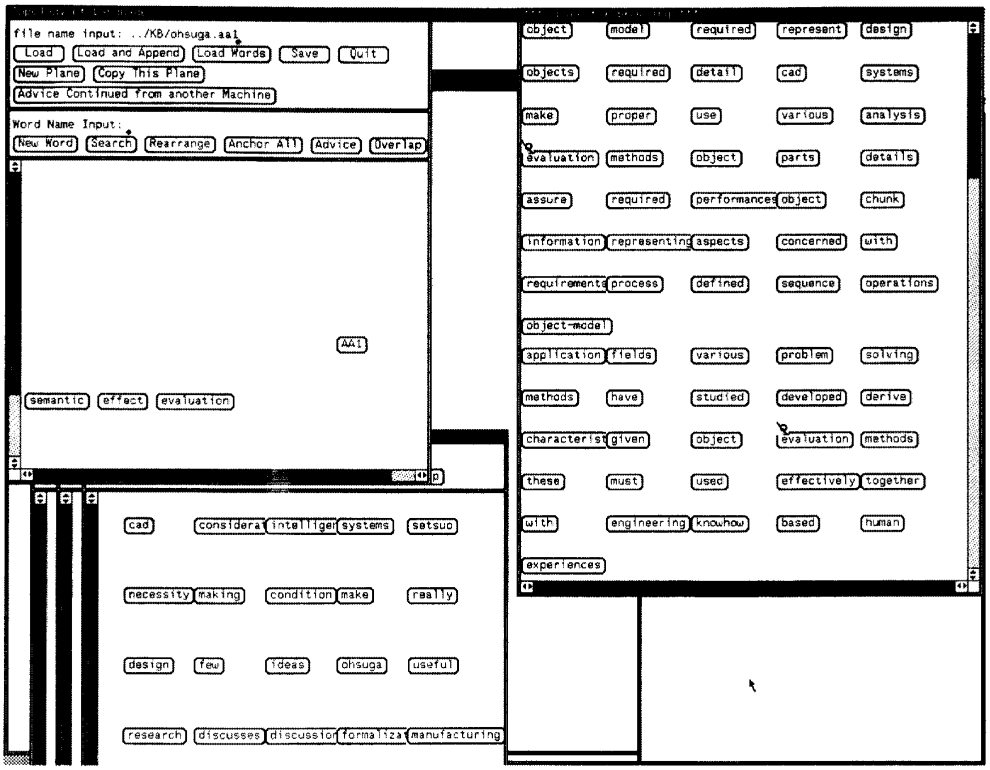


Fig. 2. A part of an example of precedent space. This space was automatically made from all the words in one technical paper.

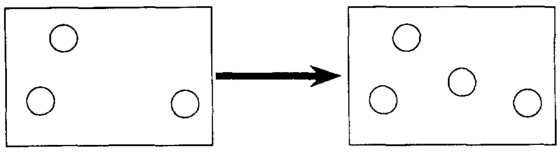
The call of a precedent space is done based on literal match of the words and the links among the space. He/she can put any links beyond the planes for later association. Different planes are intended to be used for different contexts. The user can easily copy one plane to another plane. Moreover, the user can overlap two planes into one plane. He/she can get different arrangement of words from same information of words and relations by changing the initial arrangement for the calculation of the space. This is done by picking one word and the "focus" button from the menu. He/she can "anchor" some words, thereby fixing the positions of those words and can making the system recalculate the space by moving the other words.

Here we figure out all the effects we expect from AA1. The experimental results are given in Section IV.

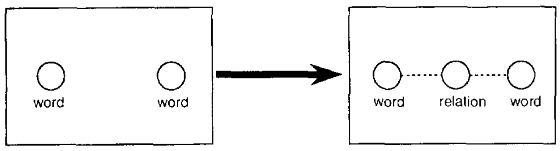
We first enumerate the typical ways in which a space is reconfigured, illustrated in Fig. 3. The user uses these forms of reconfiguration when they are unconsciously triggered by the space shown by AA1. The stimulus comes to the user as the shape of the figure formed by the words in the space. For example, if there is some empty place in the space, it often inclines the user to put some word in the empty place, as shown in Fig. 3(a). This means that the user reads microconcepts for forming a new concept in the empty place between words as described in Section II. Similarly, in the configuration shown as Fig. 3(c), the user finds meaningful microconcepts in the axes and uses them for forming new concepts. In this process, the microconcepts read by the user depend on the domain he/she is concerned with. If the meaningless words like "g001" and "g002" were arranged in the space, that did not give any stimuli for the user. The user of AA1 should always be a person who has enough knowledge in some domain and who is trying to make a new concept in that domain.

AA1 sometimes works for creative concept formation, but sometimes for just recalling a concept which he/she had already known. We classify such different types of effects in Table I. Every row in Table I corresponds to a state of mental world. For example, the first row is for the mental world where the image and sound or other information of a concept is clearly cut. Every column corresponds to the types of words.

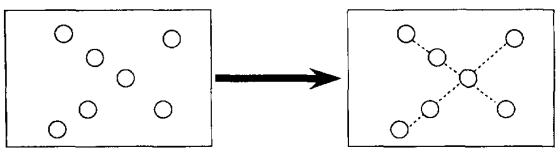
Although the effect of AA1 is open to the user and we cannot give the overall frame of the effect, we can analyze what kinds of information are already stored in the precedent spaces. In Fig. 4, we enumerate the relations for articulating the world which are embedded in the precedent space built in AA1 from all the words in one technical paper on an intelligent CAD system. We can expect that the user will notice the possibility of applying these relations for articulating his/her mental world by looking at the precedent spaces. We do not exclude the possibility that the user finds and uses new relations. So, we have not given these names of relations explicitly in the precedent space. The relations shown in Fig. 4 are the typical of the useful relations which we find looking at precedent spaces.



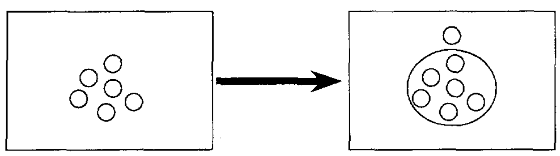
(a) detection of empty place



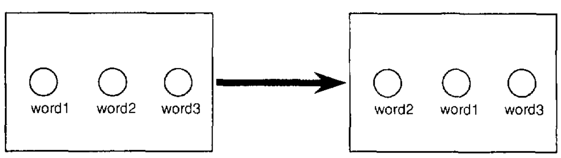
(b) detection of relation



(c) detection of axes
(special case of (b))



(d) detection of aggregation



(e) exchange of nodes

Fig. 3. General forms of reconfiguration. Each configuration of the left-hand side serves as a stimulus for prompting the user to reconfigure the space as shown in the right-hand side.

IV. Experiment and Evaluation

In this section, we show the results of experiments and evaluate the system AA1. First, we show two experiments on real usage of the system carried out in our university. We analyze these examples and investigate what happened during the usage of AA1. Second, we briefly give a result of experiment we carried out in cooperation with an automobile company. We applied AA1 to real group work in the task of creating the concept of a car for the 21st century. Through this experiment, we show that AA1 gave better results than ordinary brain storming. Finally, we summarize the evaluation of AA1 through the demonstrations of the system to about 170 persons, where different opinions about the system from people with different backgrounds are summarized.

First of all, Figs. 5–7 give one real example of the usage of AA1. In this experiment, the user was a professor of the University of Tokyo, who is studying intelligent CAD (computer aided design). This user tried to create concepts for a cooperation project among Compiegne University, Pennsylvania State University, and the University of Tokyo. When the experiment was carried out, the cooperation project had only the title of "cooperation among Compiegne University, Pennsylvania State University, and the University of Tokyo" and the members had just started to discuss what should be studied in the cooperation. (The background of this cooperation was that the professors from Compiegne and from Penn State, who were working in different domains, happened to be invited professors in the University of Tokyo at that time and became friends.) The members of this group had many ideas but they were not articulated yet. One member, who is a professor of the University of Tokyo, spent half a day using AA1 to form concepts for the project. What the user did was recorded in a file for later analysis and we asked the user the reasons for his actions after the experiment.

Let us see what happened in this example. In Fig. 5, the user has placed 14 words which came to his mind and made connections among the words. As we have explained before, he did not give the names of the connections but he just said, e.g., "KAUS" has some relation with "design" by mouse operation. The number of such relations drawn was 14. This means every word had some relations with about two words on average. (The current version of AA1 does not consider the direction of relation; all relations are treated as bidirectional.) AA1 gave the space shown in Fig. 5 by calculating the configuration among the words so that the distance between the words which have some relation is smaller than the distance between the words which do not have any relation. In this example, AA1 gave the space which naturally separated into three clusters the words related to the work in the three universities. The user, of course, knew that there were some distances among three universities, but he was not previously so conscious of it. He decided to place some word in an empty place to connect these separated clusters and he created the term "total engineering model" and made three more connections. As a result he got the space shown in Fig. 6. Looking at this space, many ideas came up to his mind. The user opened a new plane. He copied three words from the old space to a new plane and put 14 new words on the new plane and made 18 connections. By this operation, he finally got the space shown in Fig. 7. As the result, new concepts such as "spaghetti structure model of manufacturing" were created aided by the system. He showed this space to the members of the cooperation project in the next project meeting. This space effectively stimulated discussion leading to further elaboration of the research concepts of the project. For example, what should exist around the "spaghetti structure" was discussed.

Fig. 8 gives another example. In this experiment, the user was a graduate student who was a member of the university

TABLE I
TYPES OF EFFECTS WE CAN EXPECT FROM AA1

Word	Already Known by the User in this Context	Already Used by Someone in Some Context	Never Used (New Word)
Mental World			
Already clearly cut by the user in this context	recall	verbalization	nominalization
Already clearly cut by someone in some context	comprehension rediscovery	transfer metaphor	analogical abduction
Already unclearly cut by the user in this context, and now clearly cut	clarification verification	explication	coinage
Already unclearly cut by someone in some context, and now clearly cut	realization manifestation	transfer analogy	invention evolution
Never cut, and now somehow cut	incarnation	paradigm shift revolution	emergence discovery creation abduction conception

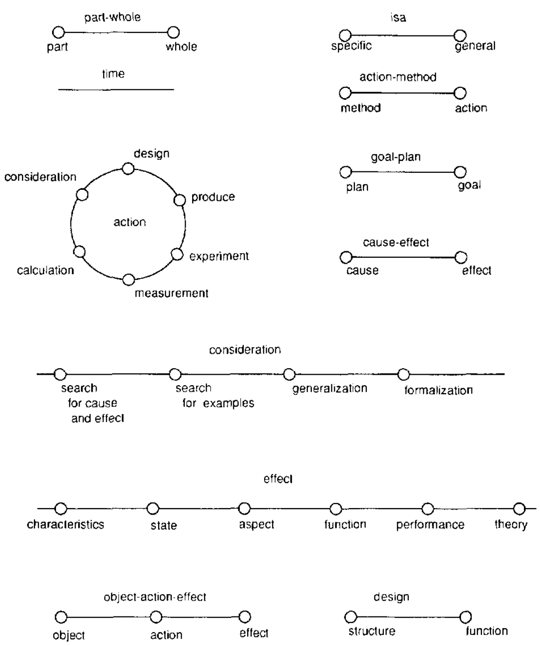


Fig. 4. Embedded relations in precedent space. These relations are detected in precedent space by the user and applied for forming new concepts. These are not explicitly shown in the system so as not to constrain users' free thought.

golf team. For testing the capability of AA1 for concept formation in the context of knowledge acquisition, we asked the user to form knowledge about the golf swing. The database of the precedent spaces contained the space built from all the words in a technical paper on an intelligent CAD system and the space built through the first experiment mentioned above.

He first entered the word "slice" which seemed to him an important problem. But after putting this word, he could not continue to give words. It seems he had many ideas about golf swing but they were in a nebulous state. He browsed the spaces of precedent examples and found a word "air flow" in the precedent examples. He thought "slice" had some relation with "air flow" and so he checked the words around "air flow." He found "attribute" and this word seems to have stimulated him effectively and he began to give many words.

Let us look in some more detail into the process of the usage of AA1 in these experiments. Looking at Fig. 6 afterwards, we can find that there are "part of" relations among the words "total engineering model," "manufacturing," "design," and "diagnosis"; that is, manufacturing is a part of the total engineering model, design is a part of the total engineering model, and diagnosis is a part of the total engineering model. So, we can say that the user found a term to combine the words "manufacturing," "design," and "diagnosis" using the "part-of" relation. In Fig. 7, what the user did can be analyzed as the process of finding a "system-function" relation between "KAUS" and "design," etc., and introducing the "function-application" relation and building a configuration among the words "diagnosis" and "diagnosis of product," etc. Looking at the process of Fig. 8, we can say that the user noticed the usefulness of the relation "object-attribute" and applied this relation to "slice" and gave other words.

Although we can analyze what the user did in this way afterward, the important point is that the users were never conscious about these general forms of rearticulation. The user never thought of the "part of" relation while using the system but he was concerned only about the content of the project. The content is what existed in his mental world. Many systems require the user to give, say, an "is-a" relation in the very beginning (e.g., [34]). But this top-down request usually does not work because he never articulated his world that way. Although the relation between "design" and "total engineering model" can be named "part-of" afterwards, the user never thought of that name. Moreover, there is possibility that the user could rearticulate the world considering that "design" is "isa" of "engineering". He was just searching a word for connecting three clusters, and the word "total engineering model" came to his mind. Similarly, he gave the word "diagnosis of product" by considering the image of the diagnosis system. The space AA1 showed activated the image and he came up with other words such as "diagnosis of design" and "spaghetti structure of the model." Although predefined links like "Faulty Path," "Return Path," and "Main Path" given by a system like that of Neuwirth [34] may be useful for some special phase in such special tasks as writing a document, the single relation "some relation" is better for the process of divergent thinking for exploring possible concepts, because words cannot necessarily be connected by predefined links in this process.

Another point is that AA1 gave more stimuli than those available from mere externalization of a mental world. We

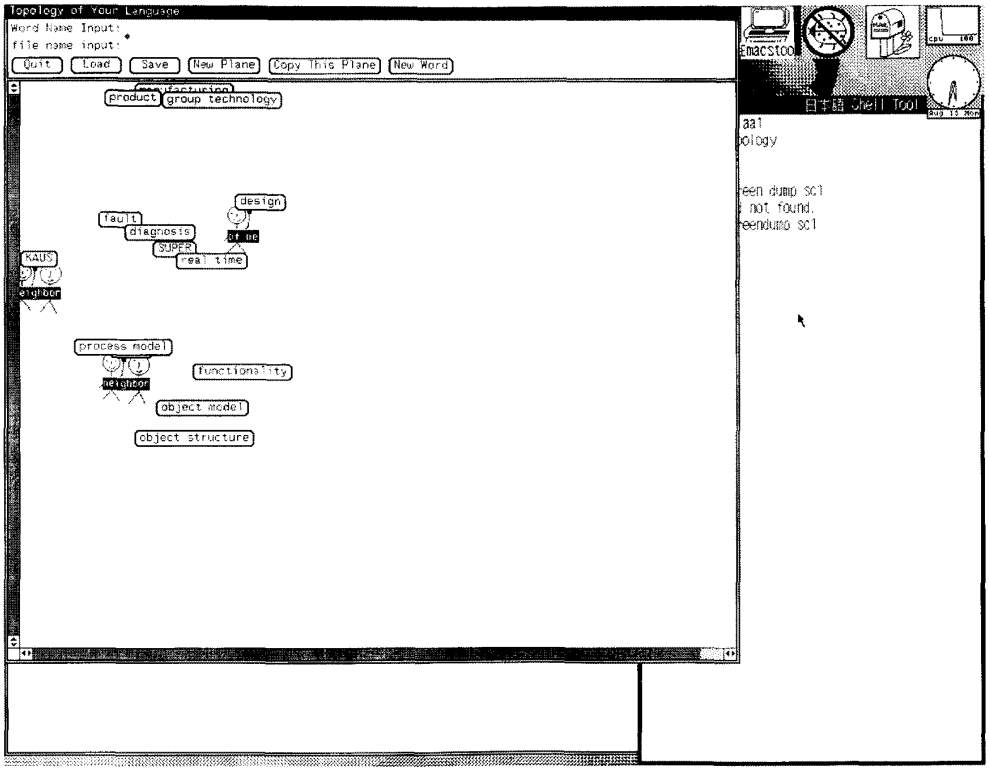


Fig. 5. An example of a space. The user gave the words and the relations. The result of the configuration of the space by the system gave three clusters. This configuration stimulated the user for forming a concept for combining the clusters.

think the fact that the first space built by the system surprised the user is remarkable. If he had externalized his ideas by ordinary means of using cards and pens or their substitutes on computers, he would probably have put the words in a configuration with no surprise and he could not have made interesting ideas. The surprise came from the calculation which revealed a hidden structure among the concepts. This conjecture is proved more explicitly below.

To summarize the preceding analysis, the user can find new words and new relations stimulated by the space AA1 shows, and this process depends on the content of his/her mental world. We have carried out a second experiment in cooperation with an automobile company. Some designers of a subsidiary company of Nissan Motors in Japan were interested in our system and tested it. As a test before introducing our system in their real design work, we tested our system by comparing the results of a meeting held without the system with the possible solutions available when the system was used. There was a real meeting in the company for discussing the concepts of a car in the 21st century. The participants were 10 persons from different divisions of the company. In the meeting, they used pens and small cards. They wrote ideas for a 21st century car on the cards. One title and many key words were written on each card. In the meeting, they wrote 100 cards and classified them into 15 concepts. Then they made a tree to describe the relations among the 15 concepts. The author's group borrowed those cards after the meeting. We put the 15 concepts in the system AA1. We judged the existence of some relations between the concepts based on the cooccurrence of key words written on the cards and put it in AA1. Since the content is secret for the company we cannot describe the details in this paper but the manager of the meeting showed substantial interest in the space AA1 built. The space calculated by AA1 revealed some meaningful hidden structure among concepts which were not noticed by any participant in the meeting. This proves that AA1 can play a role of one special participant in the meeting.

Finally we describe the results we got from the demonstrations of the system AA1 to about 170 persons. The demonstration of AA1 was done every time there were visitors to our laboratory. About 100 were Japanese, 50 were European, and 20 were American. About 30 people actually tested AA1 by entering ideas in their domain of interest. Others watched the experiment. All of them were professional researchers in engineering or in science.

First of all, speaking about the general idea of AA1, all the Japanese except one old scientist strongly agreed to the idea of cutting concepts out from a nebulous chunk of information. Five Europeans strongly agreed with the importance of the "nebulous mental world" and "articulation." There was no objection from Europeans. One American architect strongly agreed. One Japanese and two American computer scientists made strong objection against the "nebulous mental world." They claimed that the nebulous mental

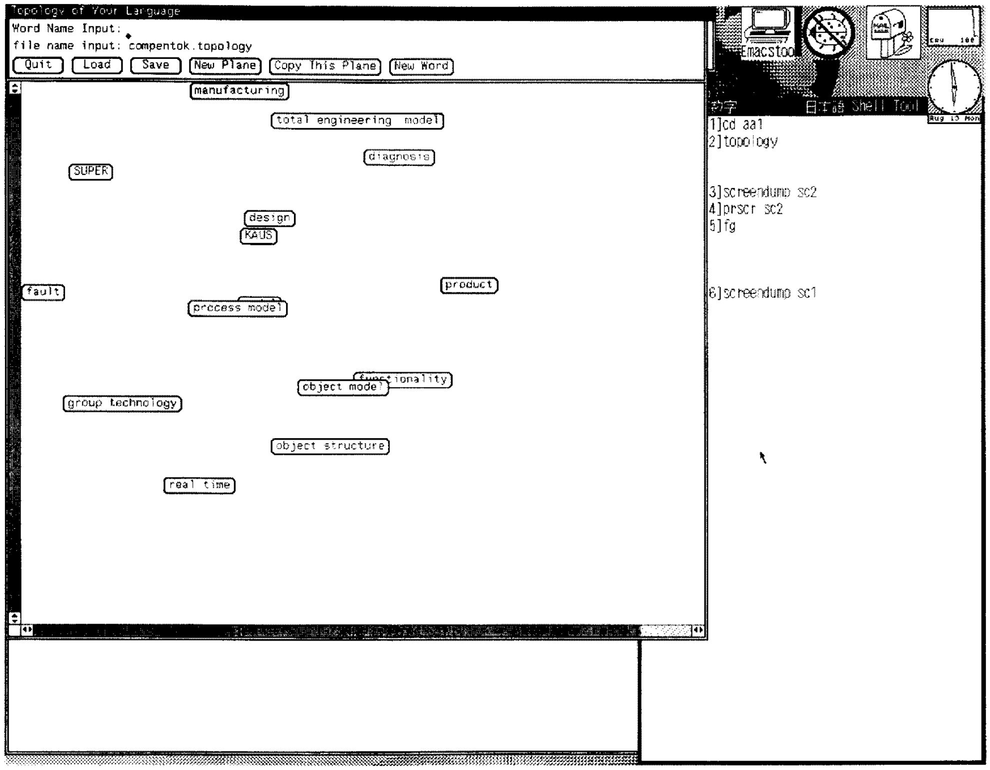


Fig. 6. An example of a space. One word the user gave drastically changed the configuration of words. This new configuration stimulated for forming further concepts.

world should not play a role in science and that the system should give concrete axes and predefined links in the beginning.

The first evaluation we get from every user is that the system is "interesting and easy to use." Every user begins to "play with" the system by entering words from his/her domain of interest. We think the evaluation that the system is interesting is important because many of the concept builders in industry are disinclined to use computers.

Every form of reconfiguration of the space in Fig. 3 was observed in the experiments but the most frequent and effective one was the detection of empty place. This means that the empty place effectively stimulates the discovery of nonarticulated concepts.

All the types of effect classified in Table I have not yet been confirmed in the experiment. The effects we have found most frequently have been "recall" and "creation."

Users requested several improvements:

- distinction of important words from unimportant ones.
- distinction of important relations from unimportant ones.
- three-dimensional preentation and three-dimensional rotation of space.
- a function to put hand-drawn figures in the space.
- functions to add annotations to terms in the space.
- domain-specific knowledge bases.
- directional relation.

As for the domain-specific knowledge base, we have implemented and tested an extended version which has a database of automobiles and functions of statistical analysis of the database [20]. As for the directional relation, we have implemented another extended version which can deal with relations that have directions [39]. For other requests, we do not have answers yet, although we think it possible to satisfy these requests by using the technologies studied in hypermedia. Especially, to give the functions to add annotations is an important requirement for using AA1 as one element of a groupware system in the future.

V. Related Work

First of all, we compare AA1 to other work done in the context of knowledge acquisition. Many researchers in artificial intelligence have studied knowledge acquisition systems. For example, the system built by Eisenstadt [10] is related to our system. The system Acquinus also has some features in common with our system [4]. However, our system has one very different feature. That is that we do not assume the existence of clear structure in the mental world in advance. What we have interest is rather the process of building structure in the mental world itself. Since the existence of some clear structure in the mental world is implicitly assumed in advance in the previous studies in knowledge acquisition and since the assumed structure does not necessarily correspond

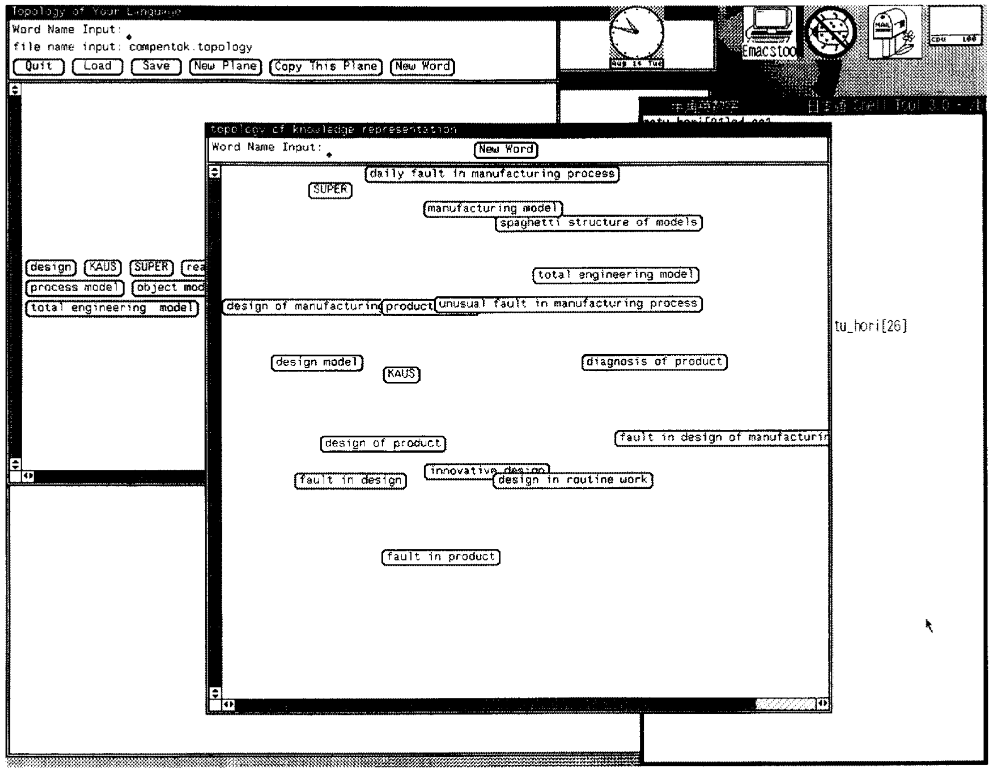


Fig. 7. An example of a space. The user made many new concepts.

to the actual structure in the mental world, the knowledge acquisition systems sometimes ask the users questions which the users think very difficult. For example, Acquinus asks the user to give a name for classifying a class of symbols from another class but the user sometimes cannot comprehend that structure because it is an artificial class useful for the computer but not a structure which existed in the user's mental world.

Secondly, we compare AA1 with other systems for groupware and systems for externalization of a mental world. Recently, there are many studies on aiding some part of concept formation in the domain of CSCW (Computer Supported Cooperative Work) and groupware [1], [5], and there are many studies of the application of hypermedia for similar purposes [9], [7]. However, most of this work only offers substitutes for papers, pencils, cards, blackboards, or meeting rooms. They do not use the computation power of computers effectively. Compared to this work, our system has the following four features.

- The system automatically calculates the configuration of the space of words. But the amount of information required of the user for the calculation is as small as possible. The resulted space sometimes surprises the user and gives more stimuli for forming concepts than a mere blackboard or some media where notes are arranged by the users themselves.
- Empty places in the space effectively stimulate concept formation.
- The primitives for representing semantics do not exist in the system in advance. The primitives, if necessary, evolve out of the space arrangement.
- The system has a database of precedent spaces and they stimulate the user's concept formation.

To clarify the importance of these features, we discuss Young's taxonomy here. Young defined three levels of support for Idea Processing systems [44].

1) *The Secretariat Level*—at which the computer is used essentially as a dynamic electronic blackboard, that is, as a device for capturing, storing, and mirroring back the user's thoughts in order to facilitate their modification and further development through human thinking processes.

2) *The Framework-Paradigm Level*—at which the computer system adds to its secretarial capabilities by also providing the user with selected frameworks appropriate to the organization of the user's thoughts, with frameworks consisting of both organized, labeled structures, as well as completed examples or sample entries to serve as both thought stimuli and guides to the user.

3) *The Generative Level*—at which the computer adds to the prior two types of capabilities the ability to automatically synthesize and display new ideas on associating elements previously stored in some data base structure or currently entered by the user.

Our system falls in category 3), considering the four features mentioned above. Most of the externalization or representation

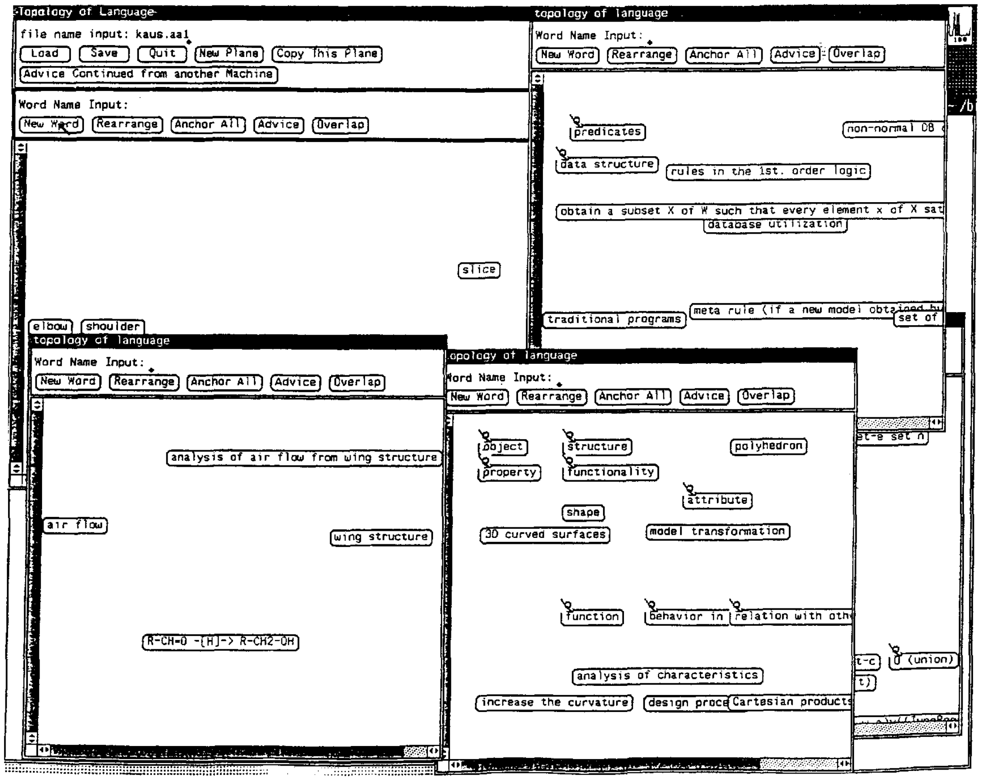


Fig. 8. An example of the usage. To articulate the world around "slice" in golf, the user referred to the precedent space around "air flow" for airplane design.

tools [34], [12], [2] fall in category 1) or 2). For example, Neuwirth and Kaufer analyzed the role of external representation in cognitive process of writing and proposed tools named Notes, Summary Graph, Synthesis Grid, and Synthesis Tree [34]. This work falls in category 2) because the system provides a user with a framework but does not actively give any new information. If one considers that it is not easy to get stimuli from a system, it is natural to seek for the possibility to get stimuli from other human beings. Groupware systems must work effectively in this sense. So they need not fall in category 3). In fact, most of the work on groupware and on CSCW (Computer Supported Cooperative Work) [32], [11], [8], [24] falls in categories 1) or 2). For example, the famous collaboration aid system Colab [38] resembles our system in that it provides a user with a space for brainstorming, but this work falls in category 2) because the space for brainstorming itself does not itself work actively. Compared to this, our system actively offers different views to the same world by automatic calculation of the space. This effect was proven useful in the experiment in cooperation with the automobile company. Compared to Young's work, which is claimed to fall in category 3) [44], our system shares the feature of using a database for giving the basis for analogical reasoning, but AA1 has the feature that it can give enough stimuli to the user even with a small database by calculating a space from the information given by the user; Young's system can work only when the database is big enough for making a new idea.

To use a topological map as a tool for analyzing concepts or knowledge is not new. We find an early example in the work of the philosopher Husserl [21]. There has also been a work on a data model based on the topology of concepts for a database [41]. In studies on pattern recognition, topological algorithms for the analysis of the similarity of figures have been invented [28]. Some researchers, including the current author, have considered the topological structure of meanings of words in natural language [37], [15]. Our originality lies in the interactive usage of the space of words for promoting the concept formation process. The space of words in our system does not aim at representing some semantic structure but aims at working as stimuli for concept formation. Even a space meaningless to a third observer is full of stimuli for a user who is struggling to create a concept in the domain the space concerns. This idea has been shown effective through the experiments.

VI. Conclusions

The system named AA1 proposed in this paper works effectively in the process of divergent thinking for exploring new concepts as part of the complex structure of creative activities. The main way the system helps the user is by revealing hidden structure in the form of map of words from the information given by the user. The information the user gives is words and connections among words; the user need not use predefined links nor give names to the connections but only has to identify the existence of some relation. The system worked effectively in experiments for forming new concepts.

While most previous systems for aiding the externalization of mental world fall in category 2) defined by Young [44], that is, they are systems which give frameworks for the externalization but do not make new information from given or stored information, the system AA1 falls in category 3), meaning that it can offer new information for stimulating the concept formation from the given information. The mechanism by which AA1 makes the "new information" is basically a method of multidimensional scaling long-studied in statistics. We have shown that this classic method works effectively when used in an interactive environment together with other functions such as browsing precedent database. However, the system cannot make totally new information beyond the given or stored information; the system just reveals hidden structures that were not noticed by the user. For getting totally new information, we must consider the use of information from other people. For this reason, AA1 should be connected to a groupware system in future. We have shown how AA1 may work in a group work.

The system is written in C and SUNVIEW and works on SUN and SPARC workstations. We have implemented a version which is written in C and X-window, too. The system has been distributed to six sites outside our university and is in use. Originally we intended to use the system in engineering and in science, but the people in marketing divisions are showing much interest in our system, too. In this sense, we think systems like AA1 which do not use a domain-specific set of predefined links have the potential to be used in a wide range of human creative activities. We are now planning the next version, considering requests received from the users as discussed in Section IV.

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