ELSEVIER

Artificial Intelligence 91 (1997) 71–84

Artificial Intelligence

Computer-aided thinking by mapping text-objects into metric spaces ★

Yasuyuki Sumi [a,*], Koichi Hori [b], Setsuo Ohsuga [c]

[a] *ATR Media Integration & Communications Research Laboratories, Seika-cho, Soraku-gun, Kyoto 619-02, Japan*

[b] *Faculty of Engineering, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113, Japan*

[c] *School of Science and Engineering, Waseda University, Okubo, Shinjuku-ku, Tokyo 169, Japan*

Received April 1996; revised June 1996

Abstract

This paper presents a system for computer-aided thinking. We propose the idea of reflecting the mental world indirectly into a metric space to support such human thinking activities as externalizing and forming new ideas. We use a method that maps text-objects into metric spaces for visualizing a user's thought space structure. Text-objects imply fragments of a user's idea, which have several keywords given by him/her. Spaces composed of text-objects are configured in the way "the higher the mutual relevance between a pair of text-objects is, the closer the text-objects are mapped". The relevance values among text-objects are calculated due to co-occurrence of their keywords. Results of experiments with our implemented system, named CAT1 (computer-aided thinking, version 1), show that users of the system can get effective stimuli for further thinking in creative concept formation. The paper also discusses the potential application of CAT1 to collaborative work by groups of people. © 1997 Elsevier Science B.V.

Keywords: Computer-aided thinking; Concept formation; Visualizing thought space structure; Computer-supported cooperative work

★ When this article was originally written, the authors were with the Department of Information Engineering, Graduate School of Engineering, The University of Tokyo.

* Corresponding author. E-mail: sumi@mic.atr.co.jp.

0004-3702/97/$17.00 © 1997 Elsevier Science B.V. All rights reserved.
PII S0004-3702(96)00058-6

1. Introduction

This paper describes a system for computer-aided thinking. Recently, much work has been done on computer-aided thinking, documentation aids, CSCW (computer-supported cooperative work), and groupware [1, 11]. These domains have the common objective of "supporting human creative activities" and depend on mutual interactions, although their research targets and approaches seem to differ. While mainstream AI (artificial intelligence) research focuses on making machines as intelligent as humans, the domains mentioned above emphasize that users themselves are responsible for creative activities and the only roles computers are to play are as mere tools that support human creativity [20]. The research described in this paper also falls into this category.

The aim of our research is the pursuit of an effective human-machine system for facilitating human creativity. We examine a model of human concept formation and collaborative work in groups. We employ an approach appropriate to this model, implement a prototype system, and give an experimental evaluation in this paper.

Supporting human creative activities requires an environment in which users can handle multi-modal information such as verbal, visual, sound, and other input type information. This paper concentrates on supporting human thinking with text. *Human thinking with text* means an activity to detect some structure in a user's ideas and documents represented verbally and then to arrange them as he/she might. This activity also involves extracting information that the user has not noticed, giving new ideas to the user. Language is not only a means to express human thought but also the foundation of human thinking because human thinking is often achieved using language. Consequently, the support of human thinking with text is critical for facilitating human creative activities.

We are developing systems with the following capabilities:

- to provide an environment in which users can recognize the structure of their thought spaces in order to encourage the bottom-up processing of creative concept formation;
- to offer effective stimuli for further thinking; and
- to respond to the dynamics of the thinking process.

We define the *thought space* as an externalized mental space consisting of fragments of ideas or knowledge and relationships among them in the activity of thinking. Our approach is to help users articulate their mental worlds by automatically mapping fragments of their ideas and personal knowledge into metric spaces. Articulation means the process of cutting and connecting symbols from a nebulous mental world. The automatic mapping is achieved by a statistical method according to the relevance between objects.

We introduce CAT1 (computer-aided thinking, version 1) in Section 2. In this section, we propose the idea of mapping text-objects into metric spaces which give stimuli for the formation of new concepts. Section 3 gives the results of experiments and evaluation of CAT1. We describe how to use CAT1 and the different types of observed effects. We also discuss the potential of CAT1 for use in collaborative work by groups of people. Section 4 gives a summary of the paper.

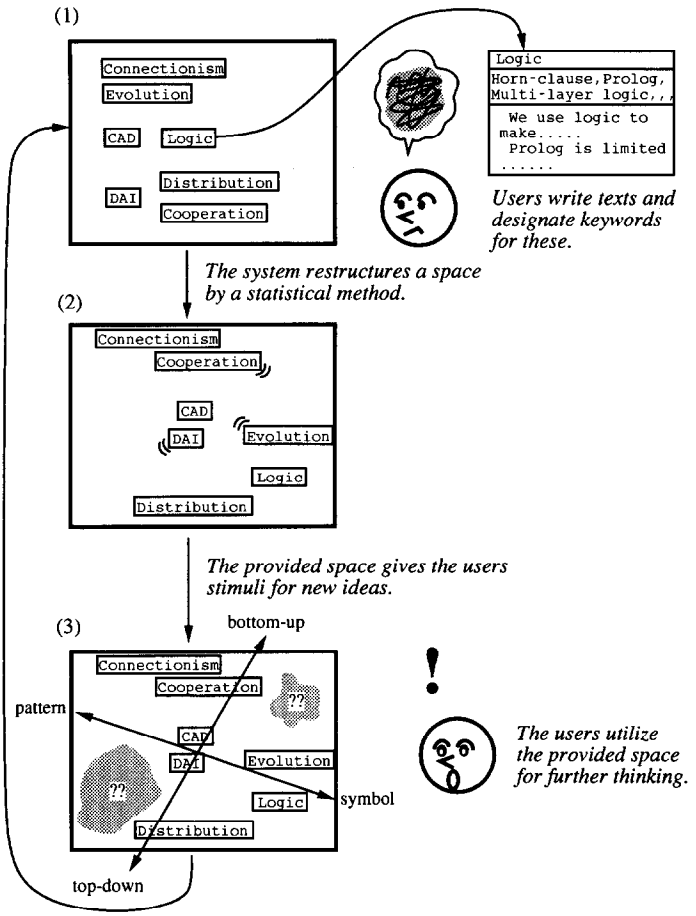


Fig. 1. Intended use of the system.

2. A system for computer-aided thinking: CAT1

2.1. Key idea of the system

In this section, we propose the idea of mapping text-objects given by a user into metric spaces to reflect his/her mental world. First of all, we will describe our goal image of the system we are developing (see Fig. 1).

(1), (2), and (3) in Fig. 1 represent spaces displayed on computer monitors; they are user's working spaces. The user writes down fragments of ideas that come to mind as virtual cards, called *text-objects*, and freely places icons of these text-objects in the spaces as in (1). The contents of these text-objects are memos from reading books and technical papers and discussions with other people. Each text-object has a title representing its content and several keywords designated by the user.

However, in such work, users sometimes lose the global structure of their own thought spaces, and run out of ideas. At such time, the users can request the system to provide a new space reconfigured for the current relationships among text-objects such as (2).

We expect that the provided space (2) will give stimuli to the user to detect primitives within his/her thought space, as shown in (3), and lead to new ideas. These primitives indicate the meanings of axes or clusters in the space that are recognized by the user. New ideas cannot be expected to come solely from the supplementation of knowledge fragments to pre-fixed systematized organizations. We propose that new ideas also come from the process of drastically restructuring organizations. The system presented in this paper is, exactly, a system that provides users the process of restructuring thought spaces consisting of text-objects from their mental worlds.

2.2. *Our approach*

2.2.1. *Mapping text-objects into metric spaces based on mutual relevance*

Our system maps text-objects into metric spaces based on the relevance among them. That is, text-objects having high mutual relevance are located closer in the space provided by the system.

The method of mapping objects into metric spaces itself is not new in the domains of psychology and engineering (e.g., pattern recognition). In this context, the similarity between objects is defined according to attributes that can be observed objectively. We apply this method to the mapping of subjective data, i.e., personal documents, by substituting *subjective relevancy* for *objective similarity*. In this paper, *objective similarity* means the degree of agreement of common attributes between a pair of objects. On the other hand, *subjective relevancy* is defined according to only those attributes selected by the individual based on his/her personal interests and viewpoints. Consequently, subjective relevancy cannot be understood as universal because the chosen attributes and their values are influenced by individual viewpoints.

2.2.2. *Bottom-up process of human thinking*

Thinking activities (e.g., writing documents, creating new ideas) require both top-down and bottom-up approaches. In this paper, we define a *top-down approach* as the process of breaking down abstract concepts into concrete instances. Conversely, a *bottom-up approach* is the process of extracting abstract concepts from concrete instances. In new idea creation, which is the target of our research, supporting the bottom-up process of the user's thinking is essential. Because the top-down approach in thinking generally causes usual thoughts, we can hardly expect new ideas from it.

Many systems developed in Japan that support idea formation from a set of fragments of verbalized ideas employ the *KJ-method* [13], which is a method of idea organization by repeating such steps as:

(i) gathering fragments of ideas on cards;
(ii) classifying these into groups hierarchically by detecting the order and relationships among them;
(iii) naming and linking these groups; and
(iv) utilizing the result for further thinking.

This method aims to encourage the bottom-up process of idea formation. In this sense, our approach is similar to the KJ-method. The important feature of our approach obviously different from the KJ-method is that our appróach provides a space reconfigured automatically based on the user's thinking. It is difficult in practice for users of the KJ-method to drastically restructure their working spaces. Consequently, the users often fall into a morass of usual thoughts. This translates into abandoning the bottom-up process indispensable for new ideas. On the other hand, in our approach, users can easily obtain information leading them to new viewpoints by restructuring their thought spaces, as described in Section 2.3. This slight difference between the two approaches is expected to cause great differences in the results.

2.2.3. *Primitives in thought spaces*

The essential feature of our approach is that primitives in thought spaces are not predefined by the system, but discovered by users after the spaces are provided to them.

Most existing systems that employ the strategy of mapping objects into spaces prepare some primitives, i.e., the meanings of axes of the spaces and several kinds of groups of objects [2, 5, 15]. These are predefined by the system developer or explicitly specified by users. However, this approach is questionable in its support of the bottom-up process of human creative activities. First of all, it is impossible to predefine primitives of a space that are going to be newly formed. Additionally, primitives predefined by a system developer can strongly restrict the thinking of users.

In the context of supporting the early stages of human creative activities, it is natural that primitives in thought spaces not be predefined but discovered dynamically by users in the repetition of restructuring their thought spaces. The system we propose represents thought spaces that reflect the dynamically changing mental worlds of users.

2.3. *Visualizing the structure of multi-dimensional spaces containing objects*

The method of determining distance by relevance is generally used to organize a set of objects having numerical relevance factors among them. That is, a couple of objects having high mutual relevance are located closer in a metric space. We adopt Euclidean spaces [1] where objects are mapped.

Suppose that you have objects among which the mutual distances are given. In order to completely express the multi-dimensional structure of the organization, it requires a space having $N-1$ dimensions at the maximum, while a space users can recognize at a glance is either one- or two-dimensional. Consequently, it would seem hopeless to visualize the structure of spaces organized with a large number of objects.

However, multi-dimensional spaces often have redundant dimensions; some of the dimensions have mutual dependency in spaces organized with objects collected by users for some purpose. Moreover, reconfiguration of a multi-dimensional space into a lower-dimensional space often reveals intrinsic dimensions of the original space.

[1] Euclidean distances d_{ij} between a pair of objects, $s_i(x_{i1}, x_{i2}, \ldots, x_{iDIM})$ and s_j, in a *DIM*-dimensional vector space are defined by the expression $d_{ij} = \sqrt{\sum_{k=1}^{DIM} |x_{ik} - x_{jk}|^2}$.

We employ the *multi-dimensional scaling method* [12, 14] to visualize the structure of a multi-dimensional space with a lower-dimensional space. The calculation of the space is done according to a gradient-descent procedure to minimize a criterion function, called stress, which is the sum of the values indicating how much a pair of objects violates the given distance, which is caused by reducing the number of dimensions. The stress of a lower-dimensional space containing a set of objects $S = \{s_1, s_2, \ldots, s_N\}$ is defined as follows:

$$Stress = \sqrt{\sum_{i=1}^{N} \frac{\sum_{j=1}^{N} (d_{ij} - \hat{d}_{ij})^2}{\sum_{j=1}^{N} d_{ij}^2}}$$

where d_{ij} is the Euclidean distance in the lower-dimensional space between s_i and s_j, and $\hat{d}_{ij}$ is the natural distance in the original multi-dimensional space.

There can be several possible local minima in this calculation. Different results by this calculation can bring different views of the same mental world, which can be stimuli leading users to new ideas.

2.4. Calculation of relevance values among text-objects due to co-occurrence of their keywords

In the last section, we explained how to map objects among which the relevance values are given into a lower-dimensional space. Here, we explain how to define the relevance between pairs of objects.

It may seem natural that users are able to quantify relevance values of a pair of objects directly. However, it is a burden for users to specify and manage relevance values for all pairs of objects in a consistent manner. In the case of one of our previous systems, AA1 (articulation assistant, version 1) [10], the mapped objects are short sentences and the relevance between the objects is explicitly given by the user. In the case of CAT1, we employ another data structure for the objects, i.e., the mapped objects represent titles of memos written by users, and they have several keywords specified by the users. These keywords are components of the objects, and used in the automatic calculation of relevance values between the objects. This means that users of CAT1 need not explicitly specify the relevance between the objects.

In this paper, we employ the plausible heuristic "the more common keywords a pair of text-objects has, the higher the mutual relevance between the text-objects is". CAT1 calculates the relevance value between the pair of text-objects by counting the weight values of the common keywords, which are subjectively designated by the user. Then, CAT1 displays to the user the whole structure of a space containing the text-objects in a visual representation. Accordingly, users can be allowed to concentrate on their thinking for such activities as revising texts and designating keywords locally, not losing the big picture.

Concepts in a user's mind have influence on other concepts unconsciously. For example, a user may detect a relationship between a pair of concepts, i.e., "A" and "B", from some viewpoint, and another relationship between "A" and "C" from another viewpoint. In using CAT1, these relationships among concepts in the user's mind are mixed and

resolved into matrix data of text-objects and keywords. When CAT1 constructs a space, there is a possibility of falling into one of the local minima. That is, the same data can lead to different results depending on the initial configuration of spaces. Accordingly, a local minimum solution may make a user notice a relationship between two text-objects, "A" and "B", and a different solution may reveal another relationship between "A" and "C". Moreover, still another solution may reveal a relationship between "B" and "C" mediated by "A" owing to the small number of dimensions in the space provided by CAT1. In this way, CAT1 can bring up several viewpoints of a user's thought space that the user may still be unaware of. After all, our target is the divergent process in the early stages of thinking activities rather than the convergent process, e.g., grouping of cards in the KJ-method.

3. Experiments and evaluation

3.1. Personal thinking with research memos

This section shows an example of using CAT1 for individual reflection with research memos. We illustrate the effects of CAT1 observed in using it and give an evaluation.

3.1.1. Management of text files with visual interface

In ordinary computer systems, in order to sort research memos written on computers, we give unique names expressing their contents to these files, or classify these files hierarchically into directories. However, it is troublesome to restructure existing classifications. As a result, it is hard to notice possible relationships between text files once they are classified into separate groups. Moreover, preparing appropriate classes beforehand is very difficult.

As Fig. 2 shows, CAT1 enables a user to visually manage text files with information of their relationships. The space provided by CAT1 can make the user notice new relationships between text files written under different circumstances. Considering that human thinking such as the creation of ideas and memorization is often accompanied by association, we can say that a tool such as this would have a great effect on human thinking activities.

Hypertext, on which many existing systems for computer-aided thinking are based, is an effective means of supporting human association. Nevertheless, some problems with hypertext systems have been pointed out [3]:

- *disorientation*: the tendency for a user to lose his/her sense of location and direction in a nonlinear document; and
- *cognitive overhead*: the additional effort and concentration necessary to maintain several tasks or trails at the same time.

Both problems are due to the fact that these systems support no global view of the user's working space. We expect the method described in this paper, in which the system shows a configuration of text-objects in metric spaces as a global view of the user's thinking space, to provide a solution to these problems.

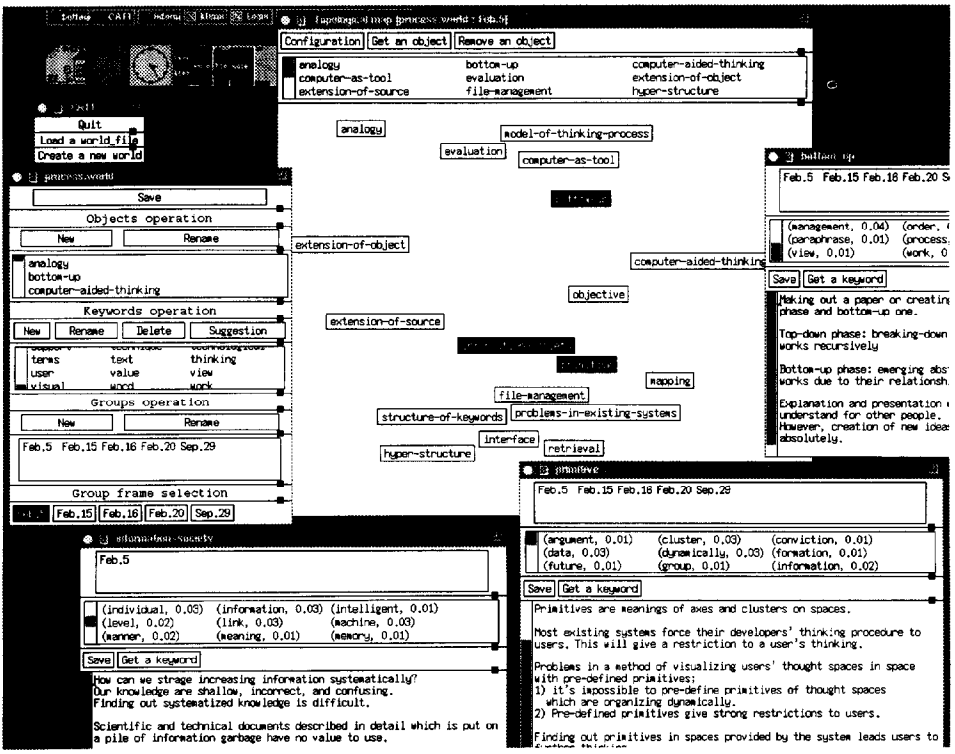


Fig. 2. Usage of CAT1.

3.1.2. Stimuli that lead to new ideas

Fig. 3 is an example of a thought space built by one of the authors using CAT1. The text-objects mapped in the space indicate his research memos. The notes in the space were written by him after CAT1 provided the space. In this section, we analyze the effects of this space on his thinking. We find primitives in this space, which explain the global structure of the user's interests and lead to new ideas.

First, we find two text-objects, "objective" and "computer-aided thinking", located in the center of the space. These texts correspond to the main subject of our research. It seems that these ideas are suitable for the core of our research since the text-objects including them are located in the center of the space.

In fact, we can see three axes stretching from the two text-objects. Let us examine the first axis named "approaches and methods". We notice that abstract subjects are located in the center of the space and concrete subjects are located toward the end of the axis. This indicates that "primitive" and "mapping" are key issues in our research, and that "structure of keywords" and "hyper-structure" are concrete discussions related to these issues.

The second axis is named "future work". The user discusses, in a text-object "information society", methods for dealing with mass information in our society today and

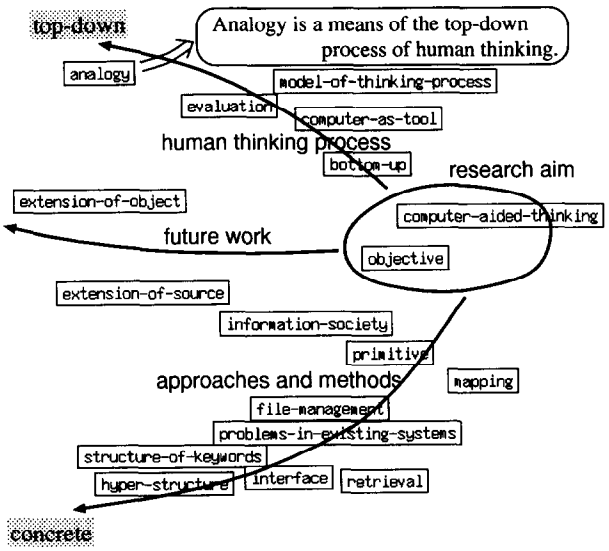


Fig. 3. An example of a thought space containing research memos.

requirements for the extension of information capable of being dealt with. The other two text-objects "extension of object" (extension of objects for information processing) and "extension of source" (extension of sources supplying information) show the direction of future work.

The third axis is named "human thinking process". The subject "bottom up", which we are mainly considering, is located near the center of the space. Then, we notice a subject "computer as tool", which suggests using a computer as a tool (i.e., an extension of paper and pen) for the activity of human thinking. Furthermore, we can see the subject "analogy" at the end of the axis. At this time, the user, one of the authors, began pondering about the pair of top-down and bottom-up processes regarding thinking. He noticed a new relationship between the pair and another concept "analogy", which did not seem on the surface to be relevant to the pair. That is, two ideas came to the user's mind at the same time, namely, "the outside of the axis corresponds to top-down" and "analogy is a means of the top-down process of human thinking". Moreover, since the axis stretches in the same direction as the axis "future work", an idea struck him that analogy will be an important issue relevant to supporting human thinking activities in engineering in the future.

From the above analysis, we can say that spaces provided by CAT1 closely reflect the mental worlds of users, and give users effective stimuli leading to further thinking.

3.1.3. Effects of aiding human communications

We have described effects of aiding individual reflections in the previous sections. Now, we discuss another potential of CAT1, i.e., supporting human-to-human communications in collaborative work.

Fig. 3 may be uninterpretable except to the user who created it; nonetheless we emphasize that such visual information is useful in group discussions. In collaborative work by groups of people, personal subjective information, which may be uninterpretable by others at first glance, should also be handled. For that reason, we consider it important to convey the interpretations of personal thought spaces to other colleagues as shown in the previous section.

Most previous systems for CSCW and groupware try to represent arguments and knowledge of participants in collaborative work with objective forms [4, 19, 20]. This approach seems natural in the phase of channeling participants' thoughts in one direction. However, this approach restricts the participants' freedom in exploring new ideas in the early stages of collaborative work.

On the other hand, the configuration of the space provided by CAT1 strongly depends on the subjectivity of the user. Accordingly, the user tries to give his/her colleagues not only an explanation about each text-object, but also the meanings of axes and clusters characterizing the global structure of the space containing these text-objects. As a result, CAT1 brings not only a set of elements composing each participant's thoughts but also the structure that organizes them to a group collaboration. This factor is essential for communications in collaborative work, and hence it is important to design systems for CSCW and groupware that facilitate this aspect of collaboration.

3.2. *Conveying subjective views to others*

To further evaluate the potential of CAT1 in supporting human communications in collaborative work, we performed the following experiment.

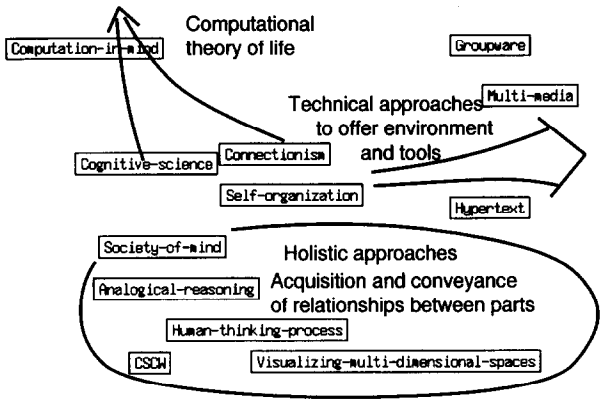
> The subjects using CAT1 were two researchers who had common interests. The two users were given several topics[2] relevant to their common interests, and they independently built their thought spaces containing these topics as text-objects with CAT1. Contents and keywords were freely given by each user.

Fig. 4 shows two spaces separately built by two users, A and B, with CAT1. Each space in Fig. 4 has notes, written by each user, that explain the structure of his thought space in the same way as Fig. 3.

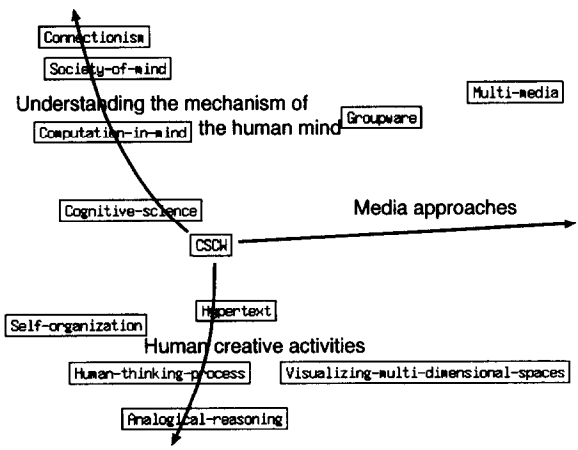
First of all, we notice that these spaces are similar in the global structures. That is, each space consists of three groups of text-objects and, furthermore, these combinations of text-objects are also very similar. This result is acceptable since the two users have been doing their research work in the same environment on similar issues.

However, two points attract our attention. First, the two users gave different interpretations to groups having almost the same set of text-objects. More specifically, both spaces have similar groups of text-objects in the lower part, but their interpretations differ. User A interpreted this group as "holistic approaches—acquisition and conveyance of relationships between parts", while user B interpreted the group as "human creative activities".

[2] The given titles of the text-objects corresponded to 12 topics, i.e., "CSCW", "connectionism", "hypertext", "multi-media", "society of mind", "analogical reasoning", "groupware", "visualizing multi-dimensional spaces", "cognitive science", "computation in mind", "human thinking process", and "self-organization".



(1) User A's thought space



(2) User B's thought space

Fig. 4. Two spaces built separately by different users with CAT1.

Second, although the two spaces bear a close resemblance to each other in their global structures, some text-objects are located in clearly different parts of the spaces. For example, user B regards "society of mind" only as a kind of mechanism of the human mind, while user A pays attention to the relationship between "society of mind" and "analogical reasoning" in the context of the "human thinking process". The interpretation of user B is very general, but superficial. On the other hand, user A's reading of "society of mind" located in his thought space attracts the other's interest. A subjective viewpoint like this is also seen in the space of user B. That is, Fig. 4(2) shows that user B considers "hypertext", which is generally regarded as one of the various media approaches, in the context of human creative activities.

As shown above, the way of understanding the meanings of concepts can be slightly different between even people who are expected to verbalize in the same way and take notice of the same relationships among several concepts in their minds. The use of CAT1 reveals these differences with visual information, and rescues people in collaborative work from unconscious communication gaps due to differing viewpoints.

Note that the interpretations of the two spaces, described above, were acquired through actual discussions between the two users, A and B, with each showing his space to the other and both reviewing differences between the two spaces. In fact, one of user A's questions led user B to a new idea he had not noticed beforehand. This is one of the significant effects of this approach expected in daily collaboration. CAT1 can be seen as one method that enhances this effect.

3.3. Support of group meetings

We are also considering how to support meetings, which are typical creative activities by groups of people. We experimented with CAT1 using documents from a meeting at an automobile design company. The documents used in this experiment included more than a hundred cards written by participants in a brainstorming-type meeting. Each contained only one or two lines of fragmented sentences, including very rough phrases freely associated by the participants. When we borrowed the documents, these cards had already been classified in three hierarchies, from a detailed classification to a rough one, by the chairperson who presided over the meeting. Needless to say, this classification was nothing but a very personal one and thus temporary. We restructured this classification with CAT1. We utilized about thirty groups in the detailed classification by the chairperson as text-objects because the cards themselves were too small as text-objects.

As a result of the experiment, we obtained other reconfigurations of the space that represented a global structure of the meeting, not bound by the previous classification. This enabled the chairperson to notice a new semantic structure of the meeting that was not noticed during the meeting. Moreover, spaces provided by CAT1 enabled other people not in the meeting to imagine what subjects were discussed in the meeting and how its topics diverged.

The experiment described in this section was achieved using static data. Currently, we are considering the use of CAT1 as a shared screen to browse and control meetings in real time.

4. Conclusions

This paper has proposed a method for computer-aided thinking by mapping text-objects into metric spaces. We have described two points that characterize our approach in contrast to previous work on computer-aided thinking. First, we believe that primitives of spaces, e.g., axes, groups, links, etc., should be not predefined but discovered by the users themselves while constructing the space of objects. Second, although most of the previous work on CSCW and groupware had mainly focused on objectively forming

each participant's thoughts and knowledge in order to add them to a common product, our proposal is that supporting collaborative work necessitates another approach that encourages users to convey their subjective thoughts and personal knowledge to others. We have given several examples with the implemented system CAT1 in actual research work and meetings, which show that spaces provided by CAT1 offer effective stimuli for the creation of new ideas.

Supplement

This translated paper presents work that was accomplished by November 1992. Since then, several works related to this have been done by the authors' group. Hori [6–8] describes a model of human creative concept formation and our approach in detail. Sumi et al. [18] present another system derived from CAT1 that facilitates collaborative concept formation by groups of people. Hori and Ohsuga [9] introduce a notion of computer-aided thinking for software development by integrating these approaches and knowledge-based automatic programming techniques. This idea was partially realized in [16]. Currently, we are considering application of the method of visualizing personal views by a statistical method, to facilitate a novel type of communications in networked virtual communities on the Internet [17].

References

[1] 7th Symposium in International Institute for Advanced Study of Social Information Science, *Toward Systems Supporting Human Creativity*, (Fujitsu Laboratories Ltd., 1991) (in Japanese).

[2] J.M. Bowers and S.D. Benford, eds., *Studies in Computer Supported Cooperative Work* (North-Holland, Amsterdam, 1991).

[3] J. Conklin, Hypertext: an introduction and survey, *IEEE Comput.* (1987) 17–41.

[4] J. Conklin and M.L. Begeman, gIBIS: a hypertext tool for exploratory policy discussion, in: *Proceedings CSCW-88* (1988) 140–152.

[5] M. Eisenstadt, J. Domingue, T. Rajan and E. Motta, Visual knowledge engineering, *IEEE Trans. Softw. Eng.* **16** (1990) 1164–1177.

[6] K. Hori, A model for explaining a phenomenon in creative concept formation, *IEICE Trans. Inform. Syst.* **76** (1993) 1521–1527.

[7] K. Hori, A system for aiding creative concept formation, *IEEE Trans. Syst. Man Cybern.* **24** (1994) 882–894.

[8] K. Hori, A model to explain and predict the effect of human-computer interaction in the articulation process for concept formation, in: H. Kangassalo and Y. Tanaka, eds., *Information Modelling and Knowledge Bases* **7** (IOS Press, Amsterdam, 1996).

[9] K. Hori and S. Ohsuga, Computer aided thinking for software development, in: *Proceedings Pacific Rim International Conference on Artificial Intelligence '92*, Seoul (1992) 203–208.

[10] K. Hori and S. Ohsuga, Word space processor for assisting the articulation of the mental world, in: S. Ohsuga, H. Kangassalo et al., eds., *Information Modelling and Knowledge Bases* **3** (IOS Press, Amsterdam, 1992) 182–197.

[11] H. Ishii, Supporting collaborative work and human interface, in: S. Ohsuga, ed., *Human Interface* (Ohmsha, Japan, 1992) 1–17 (in Japanese).

[12] O. Kakusho and R. Mizoguchi, A new algorithm for non-linear mapping with applications to dimension and cluster analyses, *Pattern Recogn.* **16** (1983) 109–117.

[13] J. Kawakita, *A Method of Idea Organization* (Chuko-Shinsho, Japan, 1967) (in Japanese).

[14] J.B. Kruskal, Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis, *Psychometrica* **29** (1964) 1–27.
[15] C.M. Neuwirth and D.S. Kaufer, The role of external representations in the writing process: implications for the design of hypertext-based writing tools, in: *Proceedings Hypertext-89* (1989) 319–341.
[16] Y. Sumi, Support system for building software requirement models, Ph.D. Thesis, Department of Information Engineering, University of Tokyo, Tokyo (1996) (in Japanese).
[17] Y. Sumi, K. Nishimoto and K. Mase, Facilitating human communications in personalized information spaces, in: *Proceedings AAAI-96 Workshop on Internet-based Information Systems*, Portland, OR (1996).
[18] Y. Sumi, R. Ogawa, K. Hori, S. Ohsuga and K. Mase, Computer-aided communications by visualizing thought space structure, *Electron. Commun. Japan, Part 3* **79** (10) (1996) 11–22.
[19] T. Winograd, Where the action is, *BYTE* (1988) 256–257.
[20] T. Winograd and F. Flores, *Understanding Computers and Cognition* (Ablex, Norwood, NJ, 1989).