Individual Differences in a Spatial-Semantic Virtual Environment

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This article presents two studies concerning the role of individual differences in searching through a spatial-semantic virtual environment. In the first study, 10 subjects searched for two topics through a spatial user interface of a semantic space. A strong positive correlation was found between associative memory (MA-1) and search performance (r = 0.855, p = 0.003), but no significant correlation was found between visual memory (MV-1) and search performance. In the second study, 12 subjects participated in a within-subject experimental design. The same spatial user interface and a simple textual user interface were used. The effects of spatial ability (VZ-2), associative memory (MA-1), and on-line experience were tested on a set of interrelated search performance scores. A statistically significant main effect of on-line experience was found, $F(6, 4)$ = 6.213, p = 0.049, two-tailed. In particular, on-line experience has a significant effect on the recall scores with the textual interface. Individuals experienced in on-line search are more likely to have a higher recall score with the textual interface than less experienced individuals. No significant main effects were found for spatial ability and associative memory. Subjects' comments suggest a potentially complex interplay between individuals' mental models and the high-dimensional semantic model. Qualitative and process-oriented studies are, therefore, called for to reveal the complex interaction between individuals' cognitive abilities, domain knowledge, and direct manipulation skills. A recommendation is made that spatial-semantic models should be adaptable to suit individuals and tasks at various levels.

Introduction

The role of information visualization and virtual reality techniques in modern information systems has become increasingly important. These techniques are designed to help us to deal with the vast amount of information available across geographically distributed resources, for example, access an information space, make sense of a complex process, and forage social activities in a virtual environment. On the other hand, these techniques may widen the gap between interactive performance due to individual differences. Understanding the role of individual differences in virtual environments becomes a significant and challenging issue for us to tackle. In this article, we emphasize the sense of a structure as people interact with a virtual environment. It is this structure, we argue, that can reflect the influence of individual differences on visual navigation through a virtual environment.

The first comprehensive introduction of individual differences into human–computer interaction (HCI) is Egan's seminal work (1988), which inspired many studies in the field over the last decade. More recently, Dillon and Watson (1996) presented a thought-provoking review of the study of individual differences and its position in the field of HCI. They identified several areas that are potentially fruitful for HCI to pursue. According to Dillon and Watson, a core number of basic cognitive abilities have been reliably and validly identified, and these cognitive abilities influence the performance of specific tasks in predictable ways. In particular, they recommended that psychological measures of individual differences should be used as a basis for establishing context and achieving a greater degree of generalizability of HCI findings.

Information foraging is a broad term, including a wide variety of activities associated with assessing, seeking, and handling information sources. The term "foraging" refers both to the metaphor of organisms browsing for sustenance, and to indicate a connection to the more technical optimal foraging theory found in biology and anthropology. Information foraging theory is essentially an ecological approach to the study of information-seeking behavior (Pirolli & Card, 1995). The theory adopts optimal foraging theory in biology and anthropology, which analyses the value of food-foraging strategies and whether they should be adapted given a particular situation. The information-foraging theory applies similar trade-off analytical techniques in modeling the value of information gains against the costs for the user.

Dourish and Chalmers (1994) discussed three types of metaphors for the design and use of an information space:

spatial navigation, semantic navigation, and social navigation. A spatial metaphor provides users various cues in association with an underlying spatial model, such as a room, a city, or landscape. Semantic navigation focuses on how users can effectively search in an information space based on semantic relationships. Instead of focusing on geometrical or semantic cues, the idea of social navigation suggests that a good strategy is to follow the clustering of like-minded individuals in an information environment.

Our work focuses on structuring and maintaining a virtual environment in such a way that users can benefit from semantic cues conveyed through a spatial-semantic model. A key to this work is a spatial-semantic metaphor. In such virtual environments, semantic structures are transformed and characterized by geometrical and topological properties. Similar documents are clustered together within the virtual environment to reduce the costs for the user.

In virtual reality-based information systems, it is crucial for designers to understand the usability of 3D representations and how these visual representations affect people's ability to handle information systems. The tension between a spatial model and the latent semantics has drawn much attention from a number of research communities. This increasing interest also highlights the importance of understanding the role of individual differences in adapting effective navigation strategies in an information space, especially in which spatial ability and other cognitive abilities may prove to be crucial. Until recently, there has been little data and few criteria for assessing the effectiveness and usability of 3D interfaces and a wide variety of visualization techniques (Sutcliffe & Patel, 1996).

In this article, we present two empirical studies in an attempt to explore the relationships between individual differences and searching in a spatial-semantic virtual environment. In particular, we focus on individual differences in terms of three cognitive factors: spatial ability (VZ-2), associative memory (MA-1), and visual memory (MA-1). In the first study, correlation relationships between the two memory factors and search performance are analyzed. In the second study, spatial ability and associative memory are examined in an experimental design on similar information foraging tasks.

The rest of this article is organized as follows. First, we review related studies concerning individual differences in visual navigation. Then we introduce the design of the spatial interface. Next we describe the two empirical studies and their major findings. Finally, conclusions are made based on these findings.

Individual Differences in Information Spaces

Benyon and Höök (1997) presented an interesting overview of individual differences and navigation through an abstract information space. They identified three categories that information navigation could be supported: using appropriate metaphors, using virtual reality and 3D interfaces, and using adaptive interfaces that accommodate individual differences in users navigation ability. The essence of navigational behavior, either in an information space or in a physical world, is clearly described in their article:

How do people work out how to reach their destination? The answers to this question are many and, often, unsurprising. People use maps and guides. They exploit landmarks in order to have something to aim for and to recognize a place when they arrive or use "dead reckoning" at sea when there are no landmarks.

In reality, capabilities, preferences, and different skills vary from one individual to another. For example, as shown by Streeter and Wonsiewicz (1985), some individuals like using maps and some not; some prefer graphical representations, and others like verbal instructions.

Spatial Ability

Spatial ability of an individual often refers to the ability to manipulate or transform the image of spatial patterns into other arrangements (Eckstrom, French, Harman, & Derman, 1976). The role of spatial ability in navigating through information structures has been studied over the last decade, ranging from the use of large file structures, database systems, hypermedia, and virtual reality-based spatial models. For example, Vicente and Williges (1988) found that spatial ability affected users ability to navigate a large file structure. Campagnoni and Ehrlich (1989) reported that users with good spatial ability used the top-level table of contents less frequently than users with lower spatial ability, suggesting that a good spatial ability may help one to visualize how the information is organized. Benyon and Murray (1993) found a clear influence of spatial ability on navigation in a database with a command interface. They showed that many limitations on subjects' performance on the command interface, which related to their spatial ability, could be overcome with experience. On the other hand, not all the limitations of low spatial ability were compensated by high experience.

More recently similar results with a hypermedia system were reported in Dahlbäck, Höök, and Sjölinder (1996). They found the strongest correlation was between users abilities on tests of the mental rotation of images and the completion time of tasks. The fastest subject completed the tasks 19 times faster than the slowest subject. More interestingly, their study suggests researchers to distinguish the spatial ability for problem solving in the physical world and the spatial ability for problem solving in abstract information spaces.

The meta-analysis in Chen and Rada (1996) synthesized findings in experimental studies concerning individual differences in terms of cognitive styles, learning styles, and spatial ability in using hypertext systems. The meta-analysis tested the hypothesis that users with better spatial ability will be able to use hypertext more efficiently. The hypothesis was supported by a combined effect size ($r = 0.45$), which is in a range between medium and large. The meta-analysis also found that graphical maps reduced the differ-

FIG. 1. An object–number pair could be used in an associative memory test.

ences in dependent measures ($Z = -3.37$, $p = 0.03$, one-tailed).

The relationship between spatial ability and visual navigation in a virtual reality-based spatial user interface was studied in Chen and Czerwinski (1997). Spatial ability (VZ-2) was strongly correlated with the accuracy of sketches made by subjects after they searched through a spatial semantic model, which was very similar to the one used in the studies in this article. The spatial ability was positively correlated with the differences between the main structure in the spatial layout and the sketched made by individuals ($r = 0.774$, $p = 0.004$, one-tailed). Similarly, a strong correlation was also found between spatial ability and the secondary structures in the spatial layout and structures memorized by individuals ($r = 0.591$, $p = 0.036$, one-tailed).

Associative Memory

According to Carroll (1974), associative memory refers to the ability to recall one part of a previously learned but otherwise unrelated pair of items when the other part of the pair is presented. This factor involves the storage and retrieval of information from intermediate term memory. Individual differences observed in such conditions may be largely due to the successful use of strategies such as rehearsal and using mnemonic mediators (Fig. 1).

In our work, the spatial user interface was designed to represent latent semantic structures in a virtual world. Each document is displayed as a colored sphere in the spatial layout. The authors' initials of the corresponding document are displayed next to the sphere. There are several reasons why we are interested in the role of associative memory in visual navigation. First of all, we expected that a good associative memory should help a user to build up a mental map of the virtual environment relatively quicker based on both the graphical and textual cues available in the spatial layout. We further hypothesized that if users can develop their own mental maps, they could probably benefit from these mental maps in their navigation. The role of a virtual world is not to replace individuals' mental maps; instead, it was designed to stimulate and help users to develop their mental maps more easily and more intuitively.

Due to the fundamental role of the spatial metaphor used in our virtual environment, we also consider another cognitive factor—visual memory. Visual memory is the ability to remember the configuration, location, and orientation of figural material. According to Eckstrom et al. (1976), visual memory involves cognitive processes different from those used in other memory factors. We, therefore, hypothesized that a good visual memory should enable users to memorize and locate local structures more efficiently; thus, more effective information search and information foraging is possible (Fig. 2).

In the two studies reported in this article, associative memory was measured in terms of MA-1 scores as described in Eckstrom et al. (1976): visual memory was measured by MV-1 scores, and spatial ability was measured by VZ-2 scores. An important issue concerning measuring the performance of information seeking is how the relevance of a document to a given task is judged. The problems with using recall and precision as a measure for evaluating interactive information retrieval are now well known, especially when the relevance is judged by domain experts, rather than the searchers themselves (Veerasamy & Belkin, 1996). They found that some topics appeared to be easier than others in terms of the extent to which they benefited from the visualization tools. They also noted the problems of finding enough subjects to account for intersubject differences, and of being able to account for intertopic differences.

In the first study, we used the results returned from LSI as the basis and superimposed these results over the spatial model to derive a short list of relevant documents more appropriate to the specific tasks. In the second study, subjects varied in their knowledge of the content domain. Therefore, we used pooled answers among all the subjects to derive the hit list. A similar method was used by Green (1998).

The Spatial Interface

The virtual environment used in subsequent studies was designed to reveal the underlying semantic structure of a subject domain—human–computer interaction (HCI). This semantic structure was automatically derived from a collec-

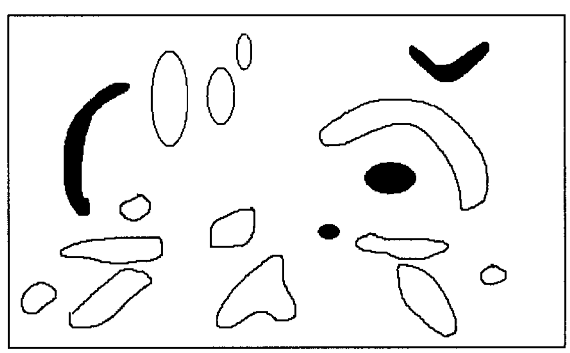

FIG. 2. An example in a visual memory test.

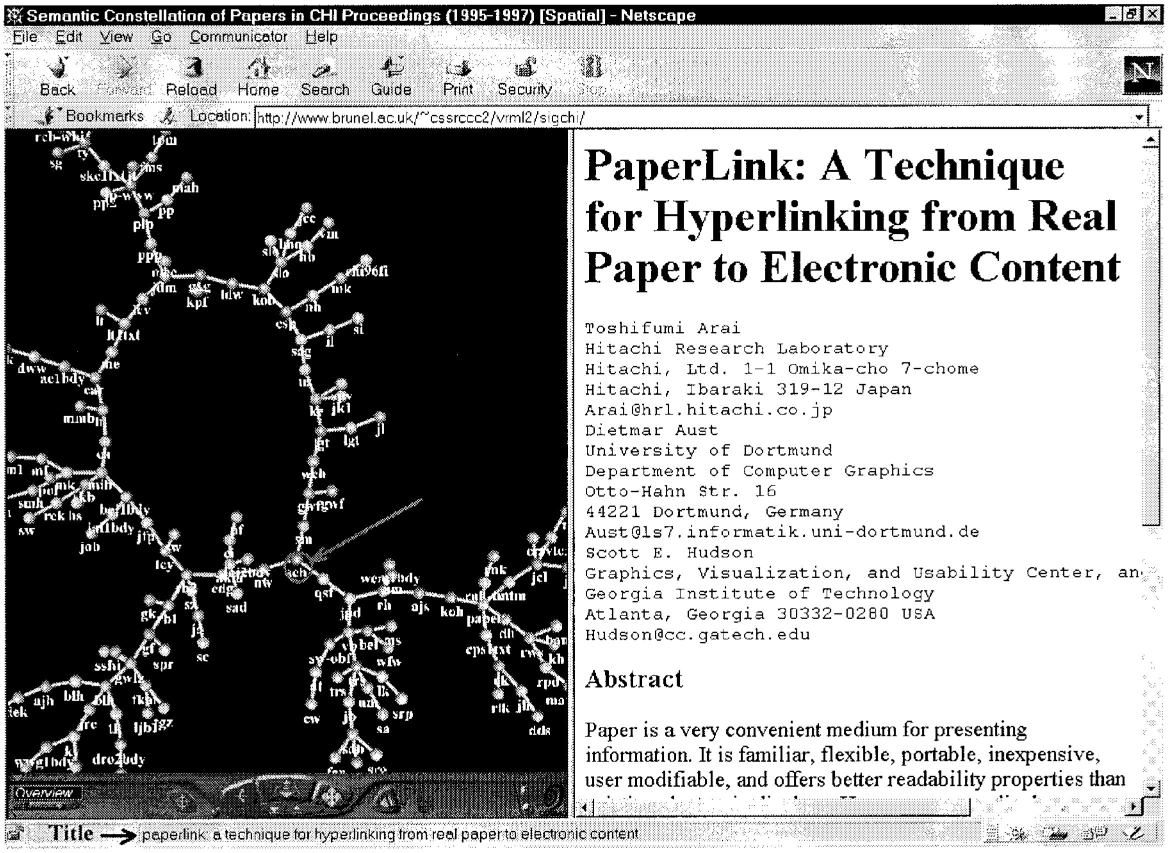

FIG. 3. The spatial interface used in both studies.

tion of 169 articles from three consecutive ACM CHI conference proceedings, namely CHI'95, CHI'96, and CHI'97 (1995–1997). The detailed structuring and modeling techniques and the latest development can be found in (Chen, 1998a, 1998b, 1999). In essence, the content similarity between a pair of articles in the proceedings was computed according to Latent Semantic Indexing (Deerwester, Dumais, Landauer, Furnas, & Harshman, 1990), which is a sophisticated indexing technique developed for information retrieval. The most salient connections among the similarity data were extracted by using a technique called Pathfinder network scaling (Schvaneveldt, Durso, & Dearholt, 1989), which can provide more accurate details on local structures than the widely used multidimensional scaling techniques (MDS). This semantic space was then rendered in Virtual Reality Modeling Language (VRML) 2.0, and made accessible on the World Wide Web (WWW). Users can walk and fly through the semantic space. It is also in effect a zoomable user interface. The design rationale was to reduce the tension between maintaining a focused view and a global view of the context.

Given that the document collection is presented in semantically related clusters in the virtual environment, we are particularly interested in whether users would find the semantic cues provided by the spatial model useful for information retrieval. What is the impact of an understanding of the latent semantics on individuals' search strategies?

In both studies, the user interface was used with the Netscape Communicators and Cosmo Player 2.0 VRML viewer plugin. The screen was split into two frames. The virtual world was displayed in the left-hand side frame. The right-hand side frame was used to display the abstract of an article selected from the virtual world. Articles were visualized as colored spheres in an associative network. The initials of authors of each article labeled the node in the user interface. If the user clicked on the sphere, the abstract would appear in the righthand side frame. The overall landscape was designed according to the theory of cognitive maps (see Chen, 1998a, for details about the design). The spatial interface used in both studies is shown in Figure 3.

The spatial interface was designed to enable users to find more related papers by exploring neighboring documents in a cluster containing a located document. Figure 4 is a screenshot of a new version of the spatial interface (not included in these two studies). This version supports both visualization and search so that users can visually navigate through the semantic space and locate the information they need. We used this facility to derive search performance scores in both studies described in this article. In this spatial-semantic model, we submitted a complex query to LSI. The top 20 articles returned by LSI were superimposed over the global semantic space (see Fig. 4). According to the Clustering Hypothesis (van Rijsbergen, 1979), relevant documents tend to cluster. In this screenshot, top-ranked arti-

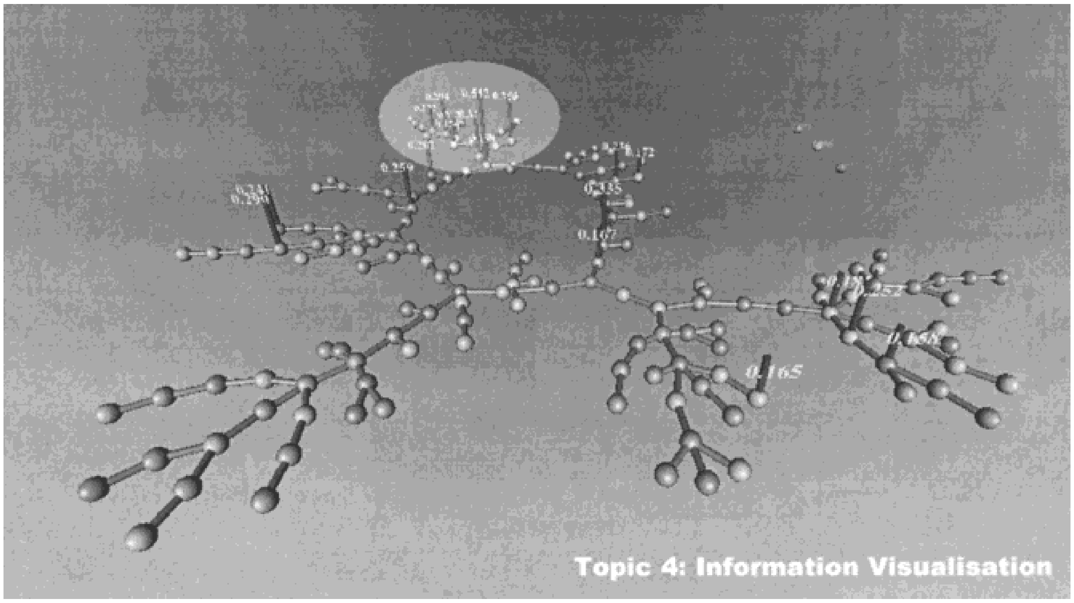

FIG. 4. Top 20 answers returned by LSI for topic 4 in Study II (not made available to subjects in Study II). The highlighted area shows a group of articles relevant to the topic.

cles appear to be clustered, especially at the far end of the network.

Study I: Cognitive Factors of Memory

The first study aims to explore the relationship between two cognitive factors: namely associative memory and visual memory, and visual navigation performance with the spatial interface. The analysis will focus on corresponding correlation coefficients.

Subjects

Ten subjects, six males and four females, participated in the first study. The age of the participants ranged from 25 to 40. All subjects were computer literate. Their experiences with virtual environments were diverse.

Procedure

The user interface used in this study was based on a spatial model of the semantic space of 169 papers published in recent three ACM SIGCHI conference proceedings (1995–1997). To minimize the network disturbances, local copies of the abstracts of these articles were stored on a web server at Brunel University. The experiment was conducted on a Windows NT 4.0 with 233 MHz CPU and 32 Mb RAM, with a 17-inch display monitor. Cosmo Player 2.0 was used as the VRML plugin viewer to the Netscape Communicator 4.

The study included a pretest and a posttest. In the pretest, associative memory scores (MA-1) and visual memory scores (MV-1) were obtained 1 day before search sessions based on the factor-referenced tests in Eckstrom et al. (1976).

A brief tutorial was given to subjects about the basic controls of the Cosmo Player 2.0 before the search. Subjects were allowed to try the new user interface until they were ready to start. Subjects were given two search topics. They were told to find as many relevant papers as they could for the first topic within 15 minutes. For the second topic, they were told to stop once they found five relevant papers. Following the design of our earlier study of spatial ability and visual navigation (Chen & Czerwinski, 1997), subjects were asked to sketch the spatial layout of the search space at the end of the first search session. When subjects completed the second topic, they were asked to name the cluster of articles in the semantic space. This was designed to find out what subjects could remember after having searched through the spatial user interface. Subjects were instructed to save relevant documents into a dedicated local directory on the computer.

Qualitative and quantitative performance measures were collected during the test session, because the first task requests subjects to find as many documents as possible regarding a given topic, which would have biased recall. Traditional measures of information retrieval performance, namely recall and precision, were not used in this study. Because the key component in the spatial user interface is a spatial-semantic model generated based on LSI, the estimates of search performance should reflect this underlying grouping structure, especially when this structure becomes visible to users in the spatial interface.

We used the keywords that appeared in the task descriptions to formulate a search query. The top 20 articles returned by LSI were regarded as the short-listed documents

TABLE 1. Pearson's correlation coefficients between memories and task scores.

Memory tests	Associative memory (MA-1)		Visual memory (MV-1)	
Performance scores	Pearson	Sig. (two-tailed)	Pearson	Sig. (two-tailed)
Task 1 (LSI_G)	0.855	0.006	0.180	0.670
Task 2 (LSI_G)	−0.575	0.136	−0.649	0.082

for the given topics. Because the spatial model of the semantic space was based on the semantic proximity generated by LSI, the performance score was proportional to the number of top 20 papers found in an individual's answer list. Top 20 papers selected were also weighted by associated relevance ratings from LSI. If a subject's answer list corresponds to the top-half of the top 20s, this subject would have a higher performance score than someone who may have the same number of top 20 hits, but only distributed in the low-half of the top 20s.

Results

The number of abstracts saved by each individual was positively correlated with memory associated test in Task 1. As we predict, subjects with better memory perform better tasks. Subjects would need to explore the article's content more deeply, especially subjects without a background in this area. Using a more general-purpose collection of documents could be ideal. Table 1 lists Pearson's correlation coefficients regarding the two memory factors. Associative memory was strongly correlated with the mean recall scores of Task 1 ($r = 0.855$, $p = 0.006$).

Spatial memory

All the subjects included a central circle in their sketches. However, the detailed structures vary from one another. Figure 5 includes four sketches of the spatial layout of the underlying semantic space. These sketches were made by subjects who had highest performance scores as well as the ones who had lowest performance scores.

In sketch (a), the subject was able to remember most details about the surrounding branches and strokes inside the central circle. The details were the most accurate. The subject who sketched this structure achieved the highest scores in both recall and precision. The sketch in (b) was very interesting: most links were omitted from the structure, but the sketch still gave an accurate outline of the structure. This sketch shows the branches that he visited several times in greater detail. In sketch (c), although the overall recall was not accurate, the subject depicted the branches that he searched, especially the branch that he started with. Finally, in sketch (d), the structure was coarse. This subject had the

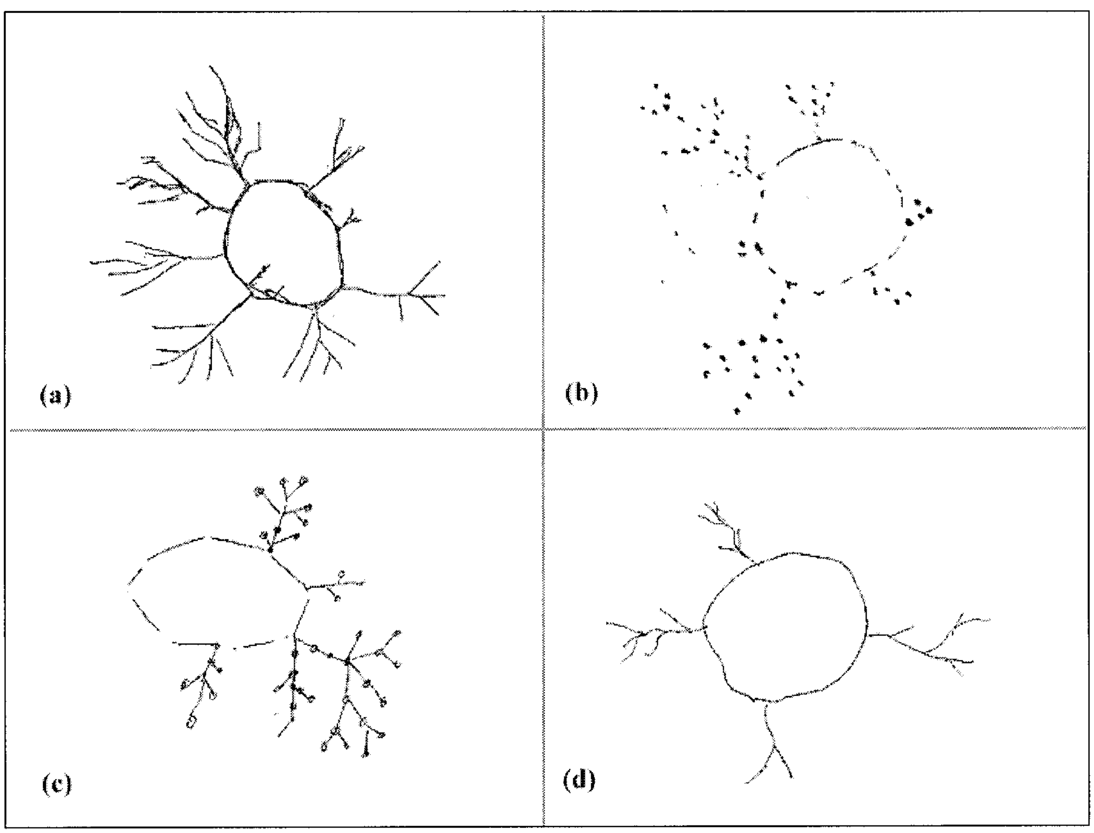

FIG. 5. Sketches of the spatial layout of the semantic space searched.

TABLE 2. Global appealing of the user interface.

Global appeal (1–5 Likert scale, with 1 = disagree and 5 = agree)	Mean	SD
I would recommend this software to others.	3.30	1.49
I like it.	2.90	1.20
I would use this software on a regular basis	2.78	1.56

lowest recall score for the first topic. These sketches may provide an explanation of how the spatial memory of users may be influenced not only by what is available from a virtual environment, but also by individual differences in terms of their cognitive abilities and task-related strategies.

Categorization and abstraction

The categorization and abstraction task was designed to help us understand the nature of clusters of articles as perceived by individuals through the spatial model. Some subjects wanted to check at each cluster again before they could provide a name. Some named a cluster on something that they are familiar with or something that is easy to memorize, for example, a comet, the head of a dolphin, and the western frontier. Some subjects actually identified topical themes, including visualization, user interfaces, and interaction techniques. Various names were given to the central circular structure: the mothership's orbit, the universe, and the main ring.

User satisfaction

A general usability questionnaire was used to assess the usability of the spatial user interface and user satisfaction. The questionnaire has three parts concerning the overall satisfaction, subjective usability ratings, and design preferences (Table 2).

Most of the subjects though that the user interface was original, intuitive, imaginative and fun. Some found it lacked predictability. Few found it was confusing and boring (Table 3).

Many subjects agreed that the purpose of the software was clear. However, the scores to the other three usability questions were slightly below the average (see Table 4). These results suggest that subjects might need to be more familiar with manipulating a virtual world. The last statement, "each area was clearly marked to indicate my location," has the lowest mean. Subjects in study II also identified this problem. Users need to know their location in the virtual world.

TABLE 3. Design satisfaction ratings for the user interface.

Design satisfaction	Mean	SD
Original	4.00	1.07
Intuitive	3.50	1.35
Imaginative	3.40	0.84
Fun	3.20	1.55
Predictable	2.80	1.55
Confusing	2.20	1.62
Not my type of program	2.00	1.83
Boring	1.40	1.17

TABLE 4. Usability satisfaction ratings for the user interface.

Usability	Mean	SD
Right when I start, the purpose of the software was clear.	3.80	1.03
Right when I started, I knew what I could do.	2.90	1.29
It was easy to get where I wanted to go.	2.80	1.03
Each area of the software was clearly marked to indicate my location	2.20	0.79

In essence, subjects thought that the spatial interface was unique, with a sense of sharing, and easy to use. Many subjects liked the unique interface design (mean = 4.20, SD = 0.63). Subjects did not feel familiar with the user interface.

In this study, users searched through a spatial model of a semantic space. With little knowledge about the underlying computational model of the user interface, users adopted a brute-force search strategy. They heavily relied on rolling their mouse over the spheres in the virtual world and bringing up the titles for initial inspection. Subjects commented that the spatial interface should help them to locate where they were or where they have been. As predicted, we found a strong positive correlation between associative memory scores and performance scores for Task 1 (Pearson's $r = 0.855$, $p = 0.006$). In addition, it is clear that if users understand more about how the semantic space is generated, they may develop more effective search strategies (Table 5).

Study II

The second study aims to further explore the relationships between individual differences and search performance. Spatial ability (VZ-2) and associative memory (MA-1) were considered in this study.

TABLE 5. Satisfaction rating for the on-line appeal of the user interface.

On-line appeal	Mean	SD
This software feels unique (or different).	4.20	0.63
This software provides a shared experience (or community).	4.00	0.89
This software is responsive (not too slow).	3.50	1.18
This software is mentally challenging.	3.44	1.01
This software has appealing graphics.	3.33	1.22
This software provides a detailed environment to interact with	3.30	1.49
This software provides valuable information.	3.25	1.39
This software is easy to use.	3.20	1.14
This software feels familiar.	2.20	1.75

TABLE 6. Summary of answers from the pretest questionnaire.

Pretest questions	Mean	SD
Experience with point-and-click user interfaces (five-point scale)	4.83	0.39
Searching on the World Wide Web	4.33	0.98
Searching on electronic library catalogues	3.67	0.98
Using virtual worlds, including VRML	1.58	0.90

Subjects

Twelve subjects participated in the experiment. Among the 12 subjects, 8 were male and 4 were female. Five of them were Ph.D. students or researchers. Five were academic staff in our department, and two were administration staff. The average age was 33. The average experience in on-line search was 5 years. Most subjects had experiences in searching on the WWW. Few people had used VRML-based virtual worlds before the experiment (Table 6).

Procedure

The second study also included a pretest and a posttest. In the pretest, spatial ability scores (VZ-2) and associative memory scores were obtained from standard tests described in (Eckstrom et al., 1976).

This spatial interface used within-subjects design. Subjects were asked to find as many articles as they could in relation to four topics. Two user interfaces were used in each session: one spatial and one textual. Each subject was scheduled according to a Latin-square design. In the spatial version, the search facility was only available within each node content window, whereas in the textual version, one could search keywords in either the table of contents window or the node content window. Each session included a pretest, in which spatial ability scores (VZ-2) and associative memory scores (MA-1) were obtained. Subjects also completed a pretest questionnaire about their experiences in on-line search and VRML-based user interfaces. Subjects were asked to search with one user interface on two topics and then switched over to the other user interface for the remaining two topics.

Ten minutes were allowed for each topic. At the end of each topical search, subjects were asked to complete a brief questionnaire about their knowledge of the topic they just searched. Finally, after subjects completed the search tasks for all the four topics, they filled in a posttest questionnaire regarding the overall experiences of using the two interfaces.

The spatial user interface used in the experiment consisted of a split screen layout. The left-hand side window displays the virtual reality model of the semantic space, whereas the right-hand side window displayed the content of the document that the user selected in the semantic space. As the user's mouse rolled over a sphere in the spatial display, the title of the associated article would be displayed at the bottom line of the browser. Once a sphere was clicked, its content would appear in the right-hand side window. The content of a node included the title of the corresponding article, the authors and their affiliations, the abstract and a list of keywords. Subjects could use these cues to decide whether or not a particular article was relevant.

Subjects were instructed to save relevant articles for each topic into a dedicated file directory on the local computer. Because most of these subjects were not particularly familiar with the four search topics, two sets of relevance rating schemes were used initially in the study.

The first scheme was based on the pooled answers from all the subjects. For a given topic, the relevance of a document was proportional to how many people who have also included this particular document in their answers to the same topic. The more people who selected a document in their answers, the higher the relevance of the document.

The second rating scheme was based on document-query relevance ratings from LSI. For each search topic, a complex query was formed and submitted to LSI. The relevance of a document was determined based on the top 20 documents returned from LSI. If the document was not in the top 20, then its relevance score was set to zero. If the document was in the top 20, then its relevance score from LSI was used as the relevance score. For each subject, the overall relevance score for each topic was the sum of the relevance scores of individual documents saved by this subject. Table 7 illustrates this scoring scheme, which takes into account the ranking order estimated by LSI.

In the data analysis, we particularly concentrated on the relationships between individual differences and the search performance scores, including correlation coefficients between spatial ability and associative memory scores with LSI-based performance scores, including correlation coefficients between spatial ability and associative memory scores with LSI-based performance scores, and pooled recall and precision. The effects of the form of user interfaces, spatial versus textual, on these measures were also analyzed. Correlation relationships between subjective ratings in questionnaires and individual differences were analyzed, including both spatial ability and associative memory. Unless stated otherwise, all the statistical significance was based on the conventional 0.05 level.

In study II, we concentrated on the main effects of on-line experience, spatial ability (VZ-2), and associative memory (MA-1). We were interested in testing our null hypothesis that there are no significant main effects of these variables on individuals' overall search performance. We used General Linear Model (GLM) multivariate tests in SPSS for Windows 8.0 on a set of dependent variables, including recall, precision, and the number of saved articles.

Recall scores for both the spatial and textual interfaces were defined to take into account the semantic structure. Ψ denotes the set of top 20 articles relevant to a search topic according to LSI's document-query relevance scores ω_is. S_m is subject m's search results.

TABLE 7. The LSI-based scoring scheme is designed to take the role of the spatial-semantic model into account.

LSI	Filename	Search results on Topic 4—Information visualization											
0.512	95_jdm_bdy.html	1	1										
0.350	95_mah_bdy.html			1	1	1	1	1					
0.335	95_gwf_bdy.html								1	1			
0.312	95_ppp_bdy.html												
0.294	97_ty.htm			1	1								
0.290	95_sgm_bdy.html												
0.259	95_hl_bdy.html												
0.252	96_cps1txt.htm					1	1				1		
0.241	97_mm1.htm												
0.236	95_il_bdy.html				1	1	1	1	1			1	
0.202	97_lt.htm	1				1							
0.182	96_skc1txt.html			1	1								
0.181	96_paper.html												
0.172	97_rcb-wbi.htm												
0.172	96_si_bdy.htm		1		1	1		1					
0.167	95_sm_bdy.html						1			1	1		1
0.165	96_srp_txt.htm												
0.158	95_mcc_bdy.html	1											
0.158	97_ek.htm												
0.154	96_pp2.html												
	Spatial Recall (LSI)	0.18	0.14	0.17	0.26	0.25	0.21	0.16	0.12	0.10	0.09	0.05	0.04

For the spatial interface, the recall by LSI top 20 and the recall by pooled answers are significantly correlated ($r = 0.589$, $p = 0.022$, one-tailed).

$$\mathrm{LSI\_G\_}R(m) = \left.\frac{\sum_{d_i \in \Psi \cap S_m} \bar{\omega} i}{\sum_{j \in \Psi} \bar{\omega} j}\right|_{spatial}$$

$$\mathrm{LSI\_TXT\_}R(m) = \left.\frac{\sum_{d_i \in \Psi \cap S_m} \bar{\omega}_i}{\sum_{j \in \Psi} \bar{\omega} j}\right|_{textual}$$

The number of articles saved as one's search results was also computed for each interface across topics.

$$\mathrm{SV\ \_}G(m) = \#S_m|_{spatial}$$

$$\mathrm{SV\ \_TXT}(m) = \#S_m|_{textual}$$

Results

The LSI- and pooled-answers–based rating schemes were strongly correlated ($r = 0.765$ and 878, for recall and precision scores, respectively, at the level of 0.01 level, two-tailed). Therefore, we will concentrate on LSI-based scores in the subsequent analysis and discussion (Table 8).

Spatial ability and associative memory were moderately correlated (Pearson $r = 0.581$, $p = 0.024$, one-tailed).

TABLE 8. Two rating schemes are strongly correlated.

		Recall (LSI)	Precision (LSI)
Spatial interface	Variables	LSI_G_R	LSI_G_P
Recall (pooled)	G_R	0.765 ($p = 0.004$)	
Precision (pooled)	G_P		$r = 0.878$ ($p = 0.000$)

Cognitive abilities and search performance

We first examined the recall scores across all the search topics and found that spatial ability and associative memory strongly correlated with the recall scores on one topic—Topic 3 ($r = -0.603$ and -0.619, respectively). Other correlations were not statistically significant at the conventional level of 0.05. No significant correlations were found with on-line experience (Table 9).

In this study, we examined cognitive factors such as spatial ability and associative memory. Search performance was measured in terms of recall, precision, and the number of articles saved during the search. We expected to find significant correlations between both cognitive factors and search performance. The only statistically significant corre-

TABLE 9. Correlations between recall and cognitive factors across topics.

	Spatial ability		Associative memory	
Recall (LSI)	Pearson	Sig. (two-tailed)	Pearson	Sig. (two-tailed)
Topic 1	−0.198	0.537	−0.286	0.367
Topic 2	0.078	0.810	−0.061	0.852
Topic 3	−0.603	0.038	−0.619	0.032
Topic 4	0.102	0.752	0.046	0.888

TABLE 10. Multivariate test of main effects.

Effect	Value (Hotelling's trace)	F	Hypothesis df	Error df	Sig. (two-tailed)
Online (years)	9.319	6.213	6	4	.049
Associative memory	3.104	2.069	6	4	.251
Spatial ability	1.806	1.204	6	4	.448

lation we found was between associative memory and precision with the spatial interface (Pearson $r = -0.600$, $p = 0.039$, two-tailed).

Main effects of cognitive abilities

We tested the main effects of spatial ability, associative memory, and on-line experience using the GLM multivariate procedure provided in SPSS for Windows 8.0. The dependent variables included LSI-based recall and precision scores, and the number of articles saved during the search. Cognitive abilities and on-line experience were used as the covariate variables in the GLM model. No intercept was included in the model.

Separate scores were taken for each interface. The main effect of on-line experience was significant, [$F(6, 4) = 6.213$, $p = 0.049$, two-tailed]. But no statistically significant main effects were found for spatial ability and associative memory (Table 10).

Because on-line experience was the only one with a significant main effect, we examined the results of corresponding univariate test to reveal further information regarding the impact of on-line experience on this set of interrelated dependent variables. As far as on-line experience is concerned, only one significant difference was found. It was with the recall scores with the textual interface, $F(1, 9) = 5.368$, $p = 0.046$, two-tailed. A variance of 83.8% in this dependent variable was explained by this model. An individual who is more experienced in on-line search is more likely to have a higher recall score than an individual with less experience in on-line search (Table 11).

Users' feedback

After the search sessions, subjects were encouraged to comment on design features they liked or disliked most. Users' feedback was also collected from answers to open-end questions. Two major issues emerged from users' comments: the interpretation of the visualization of the semantic space, and difficulties with directly manipulating the unfamiliar VRML world.

Search satisfaction and cognitive abilities. Answers to questions in posttest questionnaires were analyzed in relation to spatial ability and associative memory in an attempt to obtain an overall understanding of individuals' experience. These questions were answered on a five-point scale. Point 5 indicates a positive answer to the question.

When asked about the usefulness of the spatial interface, associative memory was significantly correlated with the answers ($r = 0.577$, $p = 0.025$, one-tailed), but associative memory was negatively correlated with the answers to the question "Did you understand the nature of this search task (with the textual interface)?" ($r = -0.672$, $p = 0.008$, one-tailed). Spatial ability was correlated with self-reported familiarity with the search tasks on the textual interface ($r = 0.671$, $p = 0.008$, one-tailed) (Table 12).

Understanding the semantics of a spatial model. A major difficulty identified by users in their comments was related to the interpretation of the grouping semantics in the spatial interface. The degree of the difficulty experienced by individuals varied. Some understood the grouping structure but indicated that they would have probably organized differently. Some needed more information to understand the grouping mechanisms. Some could not see the significance of connectivity. The recall scores seem to be descending as the understanding of the organizational principle decreases (see Table 13).

A possible line of research is to investigate whether people with certain cognitive abilities tend to impose a premature mental model or take a given semantic model for granted. For example, cognitive abilities such as field-dependent and field-independent abilities may provide further insights. One incident we experienced after the search sessions might also shed light on sources of possible mismatch between a visualization model and a model imposed by individuals. After his search session, subject 8 wanted to find two articles he encountered earlier in his search, but he did not take any note of these articles. He only remembered they were about simulation. So we used the spatial interface and enabled the search facility through LSI. Initially, we queried the spatial model with the word "simulation," but the articles he wanted (highlighted in Fig. 6) were not among the hit nodes.

Eventually, it turned out that these two articles were indexed in such a way that "programming" would be a

TABLE 11. Tests of between-subjects effects.

Dependent variables	$F(1, 9)$	Sig. (two-tailed)
Recall (textual)	5.368	.046
Saved (textual)	1.697	.225
Precision (spatial)	.750	.409
Precision (textual)	.601	.458
Saved (spatial)	.130	.727
Recall (spatial)	.082	.781

TABLE 12. Correlations between answers to posttest questions and cognitive abilities.

Posttest questions	Correlation	r	Sig. (one-tailed)
Did you find the spatial interface useful for the search?	MA-1A	0.577	0.025
Did you find this task similar to other search tasks that you typically perform (with the textual interface)?	VZ-2A	0.671	0.008
Did you understand the nature of this search task (with the textual interface)?	MA-1A	−0.672	0.008

much more useful term to form the query. Programming is, in fact, the theme of articles in neighboring branches as well. Avoiding such conceptual mismatch between individuals' perceived link semantics and the true high-dimensional characterization appeared to be a nontrivial task. This is, in part, due to the high-dimensional nature of the semantic space and higher order patterns identified by LSI. In addition, Pathfinder network scaling, on the one hand, has usefully simplified the structure of the final network. On the other hand, the conceptual gap between the original high-dimensional semantic space and the final Pathfinder associative network seemed to entail an extra cognitive load for users to interpret the semantics of the spatial model, suggesting a smooth transition from one to another might be helpful. We are currently exploring complimentary methods to reduce the ambiguity by incorporating document cocitation and author cocitation mapping (Chen, 1999).

The need to become familiar with the semantic landscape is another topic emerged from users' comments. One subject suggested that more time to familiarize with the semantic landscape would have been helpful: "by 2D or 3D search, (I) was beginning to have a feel for what was there." Another subject attributed the difficulties in understanding the semantics of the spatial model to the lack of familiarity with the subject: *I would have preferred to try these searches on a subject I was more familiar with—thus making the groupings (on the graphic search) easier to understand.*

At the end of each search, subjects completed a miniquestionnaire about the extent to which they were familiar with the search topic and how satisfied they were about their search. A summary of these miniquestionnaires are listed in Table 14, including the mean and standard deviation of the familiarity and satisfaction scores across four topics. Overall, these subjects were unfamiliar with the search topics. Topic 2, *multimodal interfaces,* was the least familiar topic, which was also associated with the least search satisfaction.

Direct manipulation issues. With the spatial user interface, most users had to learn for the first time how to use a 2D mouse to manipulate and move around in a 3D virtual world. Among the 12 subjects, three explicitly mentioned the difficulties they encountered in using various controls in the CosmoPlayer. According to one subject, "most difficult bit was controlling movement (zooming, sliding)". Another subject said he would prefer more familiar zoom and pan tools instead of the ones from the CosmoPlayer viewer.

Four subjects described that the spatial interface should clearly indicate the current node and/or the last node that have been visited. One subject said: *"Selected node was not highlighted, so when returning to the spatial interface after reading the paper, it was hard to remember where you were."*

In the design of later versions of the spatial interface, we have taken this requirement into account. For example, when a node is selected, its color will become brighter. After that, the brightness of the color will be gradually reduced until it returns to the original level.

Users would like to be able to switch between searching and browsing with the spatial interface. One subject mentioned that she frequently wanted to search a particular area in the spatial interface. Local search is not supported in our current prototype, although a global search is available to users at Brunel University. A tighter coupling between the virtual world and the content window for intercommunication has also been recommended by users in various occasions.

TABLE 13. Comments concerning the interpretation of the grouping semantics.

Subject	VZ-2A	Recall (spatial)	Comments made after search sessions
S01	0	0.24	Papers were not necessarily grouped as I may personally have grouped them (which was) making searching more difficult.
S12	0	0.22	I was not confident that the indexing was how I would visualize the proceedings.
S04	0	0.19	(In the graphical interface, it was) not too clear about the relationships of the nodes (articles).
S08	1	0.18	It was not clear to me what the significance of the links was, or the shape of the whole structure. The grouping of articles in the graphical system needs much more explanation.
S05	0	0.14	The groupings appeared to be arbitrary.
S10	1	0.11	The significance of proximity unclear, not knowing why the clusters were there.
S09	1	0.05	The links between different clusters were not obvious to me.

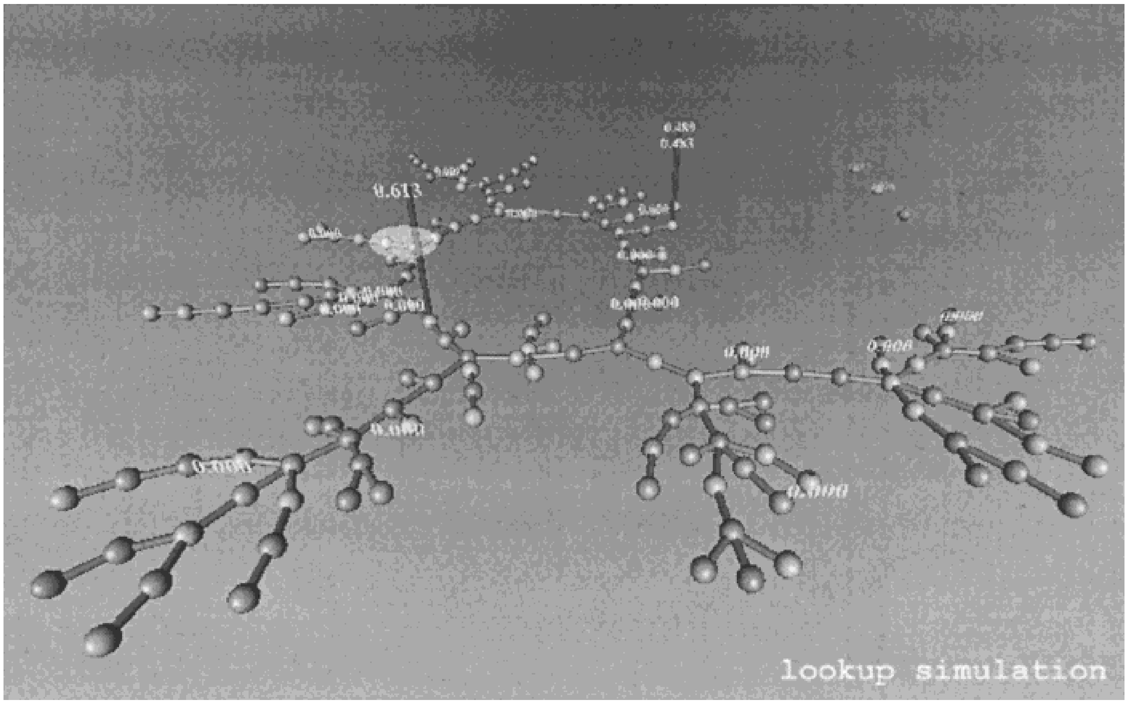

FIG. 6. The initial search results with the word "simulation" did not reveal the two articles wanted, even though the term "simulations" is included in the abstracts and keyword lists of both articles.

Discussions and Conclusions

In Study I, we found a strong, positive correlation between associative memory and the LSI-based recall scores: $r = 0.855$, $p = 0.006$, two-tailed. No significant correlations were found with visual memory.

In Study II, we found our LSI-based recall and precision are equivalent to recall and precision based on the pooled answers ($r = 0.77$ and 0.88, respectively). So we used LSI-based scores in the rest of the analysis. We first analyzed correlation coefficients across the four topics. We expected to find positive correlations, but instead two significant negative correlations were found and both were associated with topic 3: between spatial ability and recall ($r = -0.603$, $p = 0.038$, two-tailed), and between associative memory and recall ($r = -0.619$, $p = 0.032$, two-tailed). Across the interfaces, only one significant correlation was found. It was between associative memory and precision with the spatial interface ($r = -0.600$, $p = 0.039$, two-tailed). There was no simple explanation for these negative correlations, but they were based on a relatively small sample size ($n = 6$).

TABLE 14. Familiarity and satisfaction of subjects across four topics.

	Familiar		Satisfied	
Topic	Mean	SD	Mean	SD
1	2.42	1.44	1.92	1.00
2	1.92	1.31	1.75	0.75
3	2.42	1.38	2.83	0.94
4	2.08	0.90	2.67	0.89

To understand the overall effects of individual differences on search performance, we tested the main effects of cognitive abilities on all the dependent variables using the GLM multivariate test. The multivariate test found a significant main effect of on-line experience, but not for spatial ability and associative memory. In particular, a univariate test suggested that on-line experience made significant difference on the recall scores with the textual interface. Therefore, we were not able to reject the null hypothesis concerning the effects of spatial ability and associative memory.

In addition to quantitative measures, we also examined qualitative information. We examined users' comments and answers to questions in the posttest questionnaires in an attempt to understand what users had experienced in their search. There was a strong correlation between spatial ability and the familiarity with searching the textual interface ($r = 0.671$, $p = 0.008$, one-tailed), which may suggest individuals with high spatial ability in our sample have been mainly using text-based interfaces.

Earlier work, such as Chen and Rada (1996) and Swan and Allan (1998), has indicated that the effect of spatial ability often appears to be low or medium sized, and other factors such as prior experience with computers and the knowledge of a subject domain are likely to be a more predominant predictor. Swan and Allan (1998) reported a study concerning spatial ability, also measured by VZ-2 scores, and the use of a 3D interface of a visualization of interdocument relationships. They expected people with higher spatial ability would use the 3D interface more extensively. But their findings suggest that prior experience with graphical user interfaces is probably a better predictor than spatial ability on using a computer-based 3D interface. Three clusters of people emerged in their study: (A) people with moderately high VZ-2 scores who used the 3D interface very little, (B) people with high VZ-2 scores who used the 3D interface extensively, and (C) people with below average VZ-2 scores but who also used the 3D interface extensively. Their conclusion echoes the main effect of on-line experience found in our study.

Early studies have suggested that the process of constructing a mental model is likely to hinder the performance of low-spatial ability users, and the removal of such demands from the task altogether, therefore, would help users with low spatial ability to improve their performance. For example, Stanney and Salvendy (1995) used a compensatory match strategy to help low-spatial ability users to access a hierarchical structure. The differences between high- and low-spatial ability users virtually disappeared when a hierarchical structure was presented as a completely explicit 2D visual hierarchy with no hidden structural layers. By eliminating the need to mentally visualize the structure of embedded task information, low spatial individuals were able to perform as well as high spatial individuals. Stanney and Salvendy concluded that visualization techniques particularly helped low-spatial individuals in this case.

An important issue highlighted by subjects' comments after their search sessions is concerning the semantics of the spatial model. Understanding the overall semantic structure is likely to help users in their search. Several users found the semantics of the spatial model not obvious to them. As we explained earlier, this is partially due to the high-dimensional nature of the underlying semantic space and the consequence of imposing the triangle inequality condition extensively in the Pathfinder network scaling. For details of the algorithms, see Chen (1998b) and Schvaneveldt et al. (1989). A similar sense-making problem has been reported with approaches using artificial neural networks (e.g., Chen, Houston, Sewell, & Schatz, 1998). A possible solution would be conducting higher order analyses to provide additional cues to the user. Furthermore, because the spatial-semantic model is designed for persistent use instead of one-off access, the spatial-semantic coupling is likely to become increasingly clear to users as they become familiar with the semantic landscape. As commented by a subject, through the search sessions, he was beginning to have a feel for what was there.

Another issue is concerning the ability to control the virtual world, which may also contribute to the sharp learning curve for many subjects who had never used a VRML viewer before the experiment. In such situations, prior experience with graphical user interfaces would probably play a more predominant role than cognitive abilities alone.

In summary, the results have revealed some unexpected correlation coefficients, but the tests of main effects only found on-line experience that matters significantly. It appears that searching in a spatial-semantic environment, especially for first-time users, cannot be simply explained by general cognitive abilities. To fully understand the underlying factors, one will need to examine details of how individuals interact with a wider range of virtual worlds and graphical user interfaces. More qualitative studies will be needed in parallel to quantitative studies.

The design of an information with a strong spatial-semantic coupling should take into account a range of knowledge representation suitable for individuals and specific tasks at various levels. For example, GeoSpace was designed to help people find various resources in the Boston urban area (Lokuge, Gilbert, & Richards, 1996; Lokuge & Ishizaki, 1995). It has a 3D graphical user interface implemented in OpenGL graphical language. An important finding was that users developed different mental maps of an area based on the nature of interrelationships concerned. Two subjects in our study mentioned that they would have organized the virtual world differently, suggesting that an alternative approach is to let individuals to build personalized digital libraries and share with other like-minded people. A good example is *the brain* (see http://www.thebrain.com/), which allows people to organize their own information and publish it on the WWW. Examples of using spatial metaphors for people to organize information according to their own understanding include spatial hypertext systems such as VIKI (Marshall, Shipman, & Coombs, 1994), and more recently Data Mountains (Robertson, Czerwinski, Larson, Robbins, Thiel, & van Dantzich, 1998).

Darken and Sibert (1996) examined individuals' wayfinding strategies in virtual worlds with different environmental cues. They found that landmarks or organizational cues such as borders, boundaries, and gridlines, significantly improved navigation performance in a virtual world. Darken and Sibert (1996) also investigated their subjects' spatial memory in connection with using a virtual environment, by asking their subjects to sketch an overall organization of the virtual environment in which they searched for ships on the sea. They found that different organizational cues resulted in significant differences in terms of the recall accuracy of the spatial layout of the sketch and for individual targets in the environment. Sketches found in our first study turned out to be useful for our analysis. Not only can a sketched spatial layout reflects the spatial attention of individuals, but also reflect the mental map that individuals developed with reference to the shape of the virtual environment.

We briefly discussed three types of metaphors for the design and use of an information space, spatial navigation, semantic navigation, and social navigation. In this article, we have focused on an integration of spatial and semantic models for search and navigation. Social interaction in virtual environments is a topic beyond the scope of this article, but it is an integral part of interacting with a virtual environment. A synergy of cognitive and social dimensions in a virtual environment would be a potentially fruitful line of research to pursue, as social interaction may provide an additional and probably preferred means of accommodating individual differences in virtual environments.

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