

Information Space Representation in Interactive Systems: Relationship to Spatial Abilities

Bryce Allen

School of Information Science and Learning Technologies

University of Missouri

217 Hill Hall

Columbia, MO 65211, USA

Tel: 1-573-882-9545

E-mail: isbryce@showme.missouri.edu

ABSTRACT

Digital libraries, lacking a natural spatial organization, may adopt a variety of mechanisms for visualizing information in two or more dimensions. Understanding the cognitive basis for the use of spatial features in information retrieval, including spatial abilities, is important to the development of interactive information retrieval. This research investigated the interaction of spatial abilities with two-dimensional data representations in an experimental interactive system. The results showed that users with lower levels of spatial abilities were assisted in finding and interpreting digital information when spatial representations of information were employed. These results have implications for the design of digital libraries.

KEYWORDS: Data visualization, cognitive abilities, spatial representations

INTRODUCTION

Digital libraries are composed of documents that have no spatial extension or location in the usual sense. As a result, these documents lack the physical features that would suggest approaches to arranging them in a two- or three-dimensional organizational structure. As digital libraries have developed, interest and research in data visualization has also developed, providing a surrogate for traditional forms of spatial organization for the purposes of navigation and finding. This article discusses some of the cognitive background to data visualization and navigation in digital libraries, and reports research into the effectiveness of two-dimensional representation of information with users who possess different levels of cognitive abilities.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, to republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

Digital Libraries 98 Pittsburgh PA USA

Copyright ACM 1998 0-89791-965--3/98/ 6...\$5.00

Users of traditional analog storage libraries have a range of options for finding items of interest, of which some are dependent on spatial organization. For example, some people arrange their office “libraries” in piles and files. With any luck, I can pull a document out of the pile in which it resides in the apparent confusion of my perennially messy office. When documents are placed into files, these files can be organized in a variety of ways: separating them into different filing cabinets or placing them on shelves with visual cues such as colored tabs to identify them. Analog materials can be further organized into different rooms (or different floors) within a building. A hierarchical classification can place materials in a sequence in such a way that “left” and “right”, “up” and “down” have meaning when it comes to finding documents. In this case, a conceptual organization of information has been reflected in a spatial organization of materials

Users of digital libraries have no particular spatial organization to facilitate their tasks of browsing collections and finding documents. To fill this apparent gap, there are a variety of applications of two-dimensional (or n-dimensional) data representation, primarily in information systems that use data visualization to allow users to navigate through an information space to the information that interests them. Andrews [2], Hearst [5] and Wise et al. [14] present interesting examples of such data visualization, and important research such as the VIBE project at Pittsburgh [9] and the Envision project at Virginia Tech [10] have advanced the technology of data visualization to the point that it can be considered for operational information systems. Perhaps the most important application of spatial organization is in digital libraries that incorporate geospatial information. In this area, the work of the Alexandria Digital Library project is particularly significant [13].

The more elaborate forms of spatial representation of

information are, however, not the only approaches that need to be considered. For example, iconic representation of information, including documents and files, also provides a way of organizing information in two or more dimensions. In web pages that use frames, information is associated with specific screen locations, thus adding a two-dimensional component to the meaning of the information contained. Also in the web-page arena, site maps provide a way of visualizing the content and navigating to desired components. It seems clear that spatial organization of and representation of information is of continued importance in working with digital resources.

BACKGROUND

The idea of cognitive facilities developed by Jackendoff [6] provided a foundation in theory for this research, and allows an understanding of the importance of spatial representation of information in digital libraries. The main point of this body of research in linguistics and cognitive science is that there appear to be two separate cognitive facilities: one that deals with space and the objects that are encountered in space, and one that deals with language and other symbols. These two separate facilities have separate ways of representing knowledge: spatial representation and conceptual representation. Through these separate facilities, people learn, understand, and remember. But they do so in rather different ways. When a person looks around a room, he or she may see a door, and remember where that door is. The spatial representation of the room that is created within the mind is good enough that if the lights go out, the individual may well be able to find his or her way to the door without difficulty. The other type of processing occurs when people perceive language. Typically, what gets created in the mind is a conceptual structure, rather than a spatial structure. One can hear, or read, that a particular room has two exits. This is perfectly clear and understandable, but understanding this statement does not create the same kind of spatial representation in the mind that seeing the room does.

It is possible that there are two different parts of the brain that are responsible for the maintenance of these two cognitive facilities, and there is some evidence from neuropsychology that this is true [12]. It is, however, not necessary to resort to biological reductionism to see that the traditional approaches to information seeking and information retrieval have used primarily the conceptual facility of the mind. The majority of current approaches to information retrieval are linguistic in nature, requiring the use of vocabulary and of syntax. Spatial representations of information, to the extent to which they are presented by information systems, can be used in addition to conceptual representations to provide a basis for finding information.

The idea of using both the conceptual and spatial capabilities of the mind in information retrieval is hardly

revolutionary. In the long history of libraries, browsing through physical artifacts that are organized spatially has been the primary means of access to information. It is only in the past century that the emphasis has shifted to searching using catalogs, indexes, and other conceptual structures. The use of data visualization and similar spatial representations of information in digital libraries is, it seems, an attempt to balance conceptual approaches with spatial approaches to information.

However, balancing conceptual and spatial approaches to information raises questions about the interaction between the two underlying cognitive facilities. There are many examples of this kind of interaction, and all of them point to potential challenges as well as opportunities for enhanced information retrieval. For example, people can talk about space. With care, one can give a detailed description of a physical space or an object that occupies space. But, this is not as simple as it sounds. There are notorious ambiguities in spatial language. Similarly, making sense of language about space requires one to adopt a specific point of view. Suppose I tell John to put an object behind the curtain. There is no ambiguity as long as we are both on the same side of the curtain when I give the instruction. But if we are on opposite sides of the curtain, it is unclear whether I want the object placed behind the curtain from my point of view (i.e., on the same side as John), or behind the curtain from John's point of view (i.e., on the same side as me). If these kinds of ambiguity and confusion can arise in situations where the dimensionality is thoroughly understood, it seems likely to occur as well in situations such as data visualization where the dimensionality is poorly defined and arbitrary. If browsing through an information space and language-based searching are regarded as independent capabilities in information systems, these capabilities will not conflict. But, if system designers wish to allow users to switch from one form of access to another at any time, there may be challenges of matching the spatial information world with the conceptual information world.

Other examples of interactions between conceptual and spatial representations include Paivio's extensive body of research [10], which demonstrates that the ability to encode information presented conceptually as a spatial representation can facilitate learning and memory. The same information is encoded, and accordingly can be remembered, in two different ways: spatially and conceptually. This dual encoding approach provides both opportunities and challenges for enhanced information retrieval. Dual encoding is facilitated by an isomorphism between the dimensions of conceptual and spatial representations. In information spaces, dimensionality may be entirely arbitrary, and certainly may not be clear to a user. If this is the case, the advantages of dual encoding may be lost.

The use of spatial representations as an aid to learning and understanding also applies to the development of mental models [8]. These are spatial representations that allow us to think about the relationships between conceptual structures, to solve problems and make inferences, and to learn. For example, it is frequently easier to understand a topic if we make a diagram of the topic that shows the interrelationships of its component parts. Similarly, students who make conceptual maps of an area of study are better able to grasp the material to be learned. In a somewhat different sense, the importance of mental models to information retrieval performance has been shown [3]. Mental models of the information retrieval process facilitate the movement from one phase of the process to another. The challenge presented to information system designers is to present meaningful and helpful mental models to users, for example, by the use of interface metaphors.

Finally, there is a special challenge that faces information system design, and that serves as the basis for the research reported here. The two cognitive facilities are associated with different cognitive abilities. Some individuals experience difficulty in reading a map to find their way to a nearby town, but can give and follow directions to that town. They are better at conceptual processing than at spatial processing. Similarly, some students learn better than others when they use concept maps to diagram their area of study. Of the many cognitive abilities that have been shown to influence performance in information retrieval, most have been associated with conceptual processing. So, for example, it comes as no surprise that verbal comprehension or logical reasoning would play a role in the quality of information obtained from information systems that rely primarily on conceptual processing and representation. It has always been a bit difficult to explain, on the other hand, why abilities such as spatial scanning and perceptual speed were found to influence performance in information retrieval, or why a cognitive style (field dependence) that appears to have overtones of spatial processing should have a similar influence. It is possible that, even in primarily conceptually-oriented information retrieval, there are some spatial processes such as the building and using of mental models that have been influenced by these spatial cognitive abilities.

The main concern at this point, however, is that approaches to digital libraries that combine spatial and conceptual forms of representation may work well for some users (those who have higher levels of spatial abilities), while more traditional, language-based approaches to subject access may work well for other users (those who have higher levels of conceptual abilities). This research focused on the contribution of spatial (two-dimensional) representation of information to effective use of an information system, and in particular to the interaction

between design features that emphasized different aspects of spatial representation and the cognitive abilities of users.

PURPOSE

The objective of this research was to investigate how users with different levels of certain cognitive abilities would interact with information systems that used different types of two-dimensional information representation. Accordingly, an experiment was designed in which two design features employing different types of spatial information cues were presented to users whose abilities had previously been measured. In this research, the two abilities measured were spatial scanning (a measure of the ability to orient oneself and to locate objects in space) and perceptual scanning (a measure of the ability to scan a visual field for recognition rather than for understanding). These two abilities were selected because it seemed likely that both would be associated with spatial learning and memory, although in different ways. Spatial scanning seems to be a purely spatial ability, related to the ability of people to derive meaning from spatial representations. Perceptual speed, on the other hand, seems to be related to the selection of scanning strategies. Those with higher levels of perceptual speed are more likely to engage in a sequential scan of a visual field, while those with lower levels are more likely to scan selected parts of the field to find information. It is this selection of areas of a display to scan that is associated with two-dimensional displays of information.

In addition to varying the design features and measuring the cognitive abilities, this experiment was designed to provide for a modest level of generalizability across information tasks. To this end, the users were randomly assigned to one of two possible tasks, one requiring a relatively exhaustive search, and one requiring a relatively selective search.

The hypotheses tested in this research focused on the interaction between experimental effects. It was hypothesized that there would be an interaction between cognitive abilities and design features: in other words, that users with different levels of abilities would conduct more effective searches using specific design features. Similar interactions between design features and tasks were sought, as were multiple interactions between cognitive abilities, design features, and task. In order to investigate the possibility that two-dimensional information representation worked equally well for all users, the main effects of the design features were tested. Outcome variables included a wide range of performance measures derived from transaction logs.

METHODS

The Word Map

As a means of providing a spatially-oriented approach to a subject heading index to a database of bibliographic records,

a word map was created. All of the significant words from the subject headings were normalized by stemming (usual morphological analysis), and the 100 most frequently occurring word roots were entered into a word/record matrix in which the cells were frequencies of occurrence of the word stems in the subject headings of the record. This matrix was reduced to a word/word similarity matrix by calculating cosine similarity measures between words. This similarity matrix served as input to multidimensional scaling, which produced a two-dimensional word map.

This word map was presented in a scrollable window on the

left side of the screen, and the list of subject headings in a scrollable window on the right side of the screen. Clicking on any word of the word map caused a box to be drawn around the word, and caused the subject heading list to scroll to a heading associated with that word. The word map provided a way of visualizing the information space in a two-dimensional display. Users could move up and down and left and right, thus revealing additional parts of the information space. This visualization was directly associated with browsing, in which actions in the word map produced direct results for retrieval of further information. Figure 1 illustrates the word map in use.

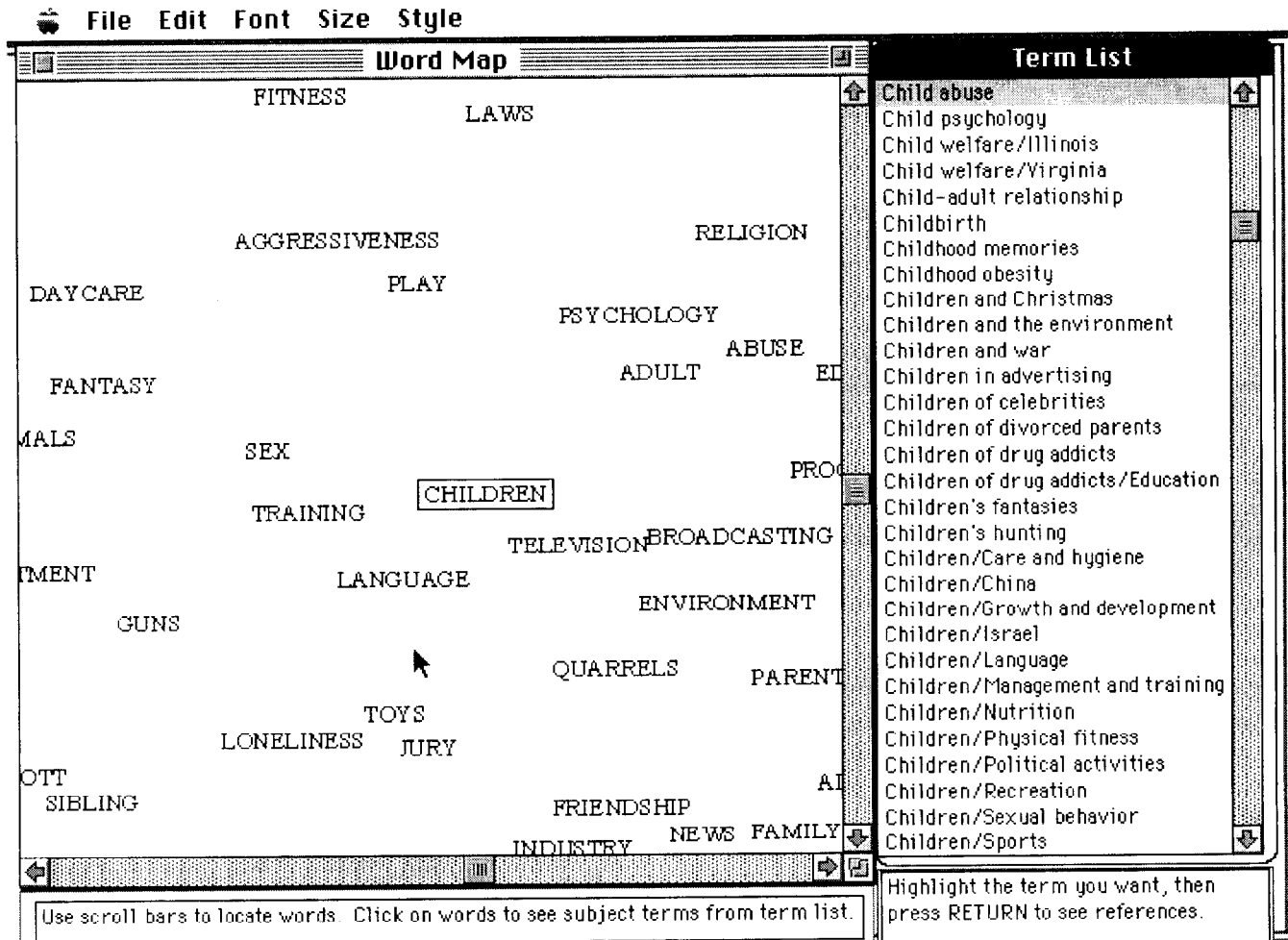


Figure 1. Word Map. The term "CHILDREN" has been clicked in the Word Map, and the Term List has scrolled to the beginning of the corresponding subject headings.

The Multiwindow Display

A multiwindow data presentation screen was developed for the display of the bibliographic records retrieved from the database. On this screen, each element of the bibliographic record appeared in a separate window, all of which were

visible on the screen concurrently. This display provided a somewhat different type of two-dimensional display of information. In making decisions about the usefulness of information presented in a structured display, certain data elements are of greater importance than others. By

providing a consistent location on the screen in which these important data elements were to be found, it was anticipated that users would be able to find their way to the important

data elements more easily, and accordingly to interact with the information more effectively. Figure 2 illustrates the multiwindow display.

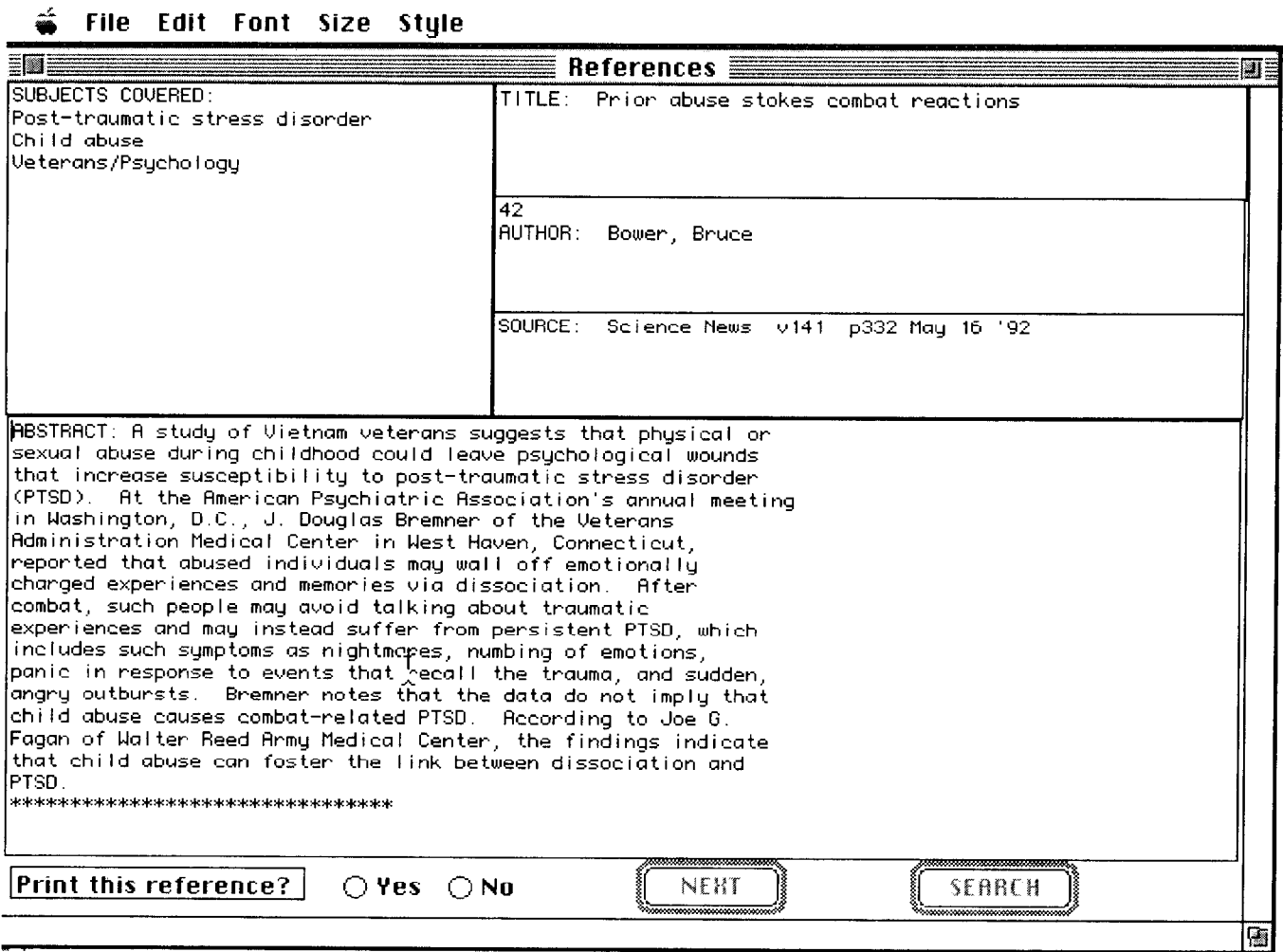


Figure 2: The Multiwindow Display

The Information Systems

To assess the effects of these design features, four variants of an information system were used in this research. System 1 provided the most opportunity for spatial effects on searching. It used the word map, which presented possible search vocabulary in a two-dimensional manner. It also used the multiwindow record display, which associated specific data elements with specific screen locations. System 2 provided the least opportunity for spatial effects on searching. It presented the subject heading list without the word map, allowing users to browse in a linear fashion up and down the alphabetical list. It also presented records in a single window in which data elements appeared in sequence, and accordingly in no fixed location. Systems 3 and 4 provided the basis for separating the effects associated with word maps and multiwindow displays. System 3 used the word map, but the single window display, while System

4 used the multiwindow display, but not the word map.

All of these systems used the same database consisting of 668 bibliographic records on the topic of "Family Issues", accessed via 466 subject headings. An inverted index was used to link the list of subject headings to the database of bibliographic records. Built into each of the systems was an elaborate mechanism that logged the activities of searchers. Each search term that was entered by a participant in the research, each word from the word map that was clicked, each subject heading from the subject heading list that was selected, and each record that was viewed were recorded. In addition, participants' judgments about the usefulness of each record viewed were recorded, as were the scrolling activities in the word map and the subject heading list.

Materials

Cognitive abilities were measured using pencil-and-paper tests derived from the Kit of Factor-Referenced Cognitive Tests [4]. Spatial scanning ability was measured with the Maze Tracing Speed Test and the Map Planning Test, and perceptual speed was tested with the Number Comparison Test and the Identical Pictures Test.

Participants

Eighty volunteer participants from the general student population of the University of Missouri participated in this research. They were paid a sum of \$5 for their participation, which lasted on average about 45 minutes.

Tasks

To prepare for the information search, participants read a short (2-page) document describing some of the main findings of research into the effects of viewing television violence on aggressiveness in children. Users were then given one of two sets of instructions, associated with two separate tasks. The first task condition was presented as follows:

A few minutes ago you read an article on a topic. Now, assume that you are working a term paper assignment for one of your classes, which requires you to complete a 10-page paper on this topic. To do this, you want to find additional information about the topic. You will be searching an experimental information retrieval system to find a few good articles about the topic that you can include in your term paper.

The second task condition was presented as follows:

A few minutes ago you read an article on a topic. Now, assume that you have been asked to write an article in the student newspaper on this topic. To do this, you want to find additional information about the topic. You will be searching an experimental information retrieval system to find as many articles as you can about the topic so that you can write a well-informed article.

Participants were then randomly assigned to one of the four information systems, and were given individualized instruction in the use of that system. This instruction was limited to details of the manipulation of the windows and search features, and did not address questions about the topic being searched.

Participants then searched the information system until they felt they had achieved their objective. Every time they viewed a bibliographic record, the system asked whether the user would like to print the record or not. In the instructional sessions, it was explained to participants that they would normally only print records that they felt to be

useful to them.

Data Extraction and Analysis

Following procedures established in previous research of this nature [1], bibliographic records selected for printing by more than half of the participants who viewed the records were identified as relevant to the topic being searched. From this basis of operational relevance judgments, precision and recall measures for each search were calculated. In addition, the detailed time-stamped logs produced by the experimental information systems formed the basis for the calculation of measures such as the number of relevant records viewed per minute. These measures provided assessments of both quality and efficiency of the searches. The amount of vocabulary learning accomplished during each search was assessed by noting the proportion of subject headings used in searches that had been previously viewed in the bibliographic records.

Analysis of the data was accomplished by Analysis of Variance, in which there were four independent variables: Task (2 levels, comprised of the term paper and the newspaper article tasks), Word map used (2 levels, Yes and No), Display used (2 levels, comprised of single window and multiwindow), and Cognitive ability (2 levels, low and high). The cognitive ability variables were dichotomized using a median split to provide for more detailed interpretation of results, and were tested independently in separate ANOVA models for each dependent variable. Because task was designed as a random factor, error terms were selected to provide correct statistical tests for a mixed model design [6].

FINDINGS

Main Effects: Design Features

Design features had a moderate impact on search outcomes, independent of cognitive abilities or task. Table 1 illustrates these outcomes. The word map facilitated learning of search vocabulary, while reducing the amount of scrolling required in the term list.

Table 1: Search outcomes influenced by design features

	Learning of vocabulary	List scrolls
No word map	.1453	408.63
Word map	.1988	119.28
	F(1,1)=336.73, p<.04	F(1,1)=78842.4, p<.01

The fact that use of the word map decreased the amount of scrolling of the list of subject headings may be regarded as a simple replacement of one type of browsing with another. The increase in learning of subject terms occasioned by the use of a word map deserves additional comment. It seems that additional attention was focused on the subject headings by their association with word map elements. This attention to subject headings could have transferred to the viewing of

records, thus giving rise to the additional learning of vocabulary. If this somewhat circuitous chain of effects is correct, it presents another example of the unintended outcomes attendant upon system design decisions. One would have expected the multiwindow display, with its consistent and prominent display of subject headings, to produce an overall effect on vocabulary learning. No such effect was observed, while the other two-dimensional design feature, the word map, produced the increase in learning.

Interactions between Design Features and Cognitive Abilities

Learning of search vocabulary was influenced by design features. The influence of information system design on learning was, however, different depending on the cognitive abilities of the users. This interaction is illustrated in the following tables.

Table 2: Vocabulary learning as influenced by type of display and perceptual speed

		Perceptual Speed	
		Low	High
Display	Single Window	.13	.23
	Multiwindow	.16	.17

F (1,1)= 647.42, p<.03.

Use of a multiwindow display by users with lower levels of perceptual speed produced an increased amount of learning. A partial scan strategy likely to be employed by users with lower levels of perceptual speed would be facilitated by the clear separation of data elements in the multiwindow display. Use of the multiwindow display by users with higher levels of perceptual speed seems to impair the amount of learning. A top-down, sequential scanning strategy likely to be used by individuals with higher levels of perceptual speed would be impeded by the breaking up of the display into separate windows. The improvement brought about by adding spatial meaning to a (primarily) conceptual display occurred among those users with lower levels of abilities.

Table 3: Vocabulary learning as influenced by type of display and spatial scanning

		Spatial Scanning	
		Low	High
Display	Single Window	.16	.22
	Multiwindow	.17	.17

F (1,1)= 649.48, p<.03.

Individuals with higher levels of spatial scanning showed larger amounts of learning when they used the single window display, but there was no difference between the learning displayed by users with lower levels of spatial scanning. This result shows that design features can act to deteriorate performance if there is not a good match between the design feature and the abilities of the users.

Table 4: Vocabulary learning as influenced by word map and spatial scanning

		Spatial Scanning	
		Low	High
Word map used	No	.15	.22
	Yes	.29	.24

F (1,1)= 1495.87, p<.02.

Users with lower levels of spatial scanning who searched for information using systems that employed the word map exhibited higher amounts of vocabulary learning than those who used systems that did not have a word map. It appears that these users cannot visualize an information space with the same facility as users with higher levels of spatial abilities. Accordingly, the word map presented a novel approach to information that focused additional attention on subject headings, leading to higher levels of learning.

Parsimony in search activities and selectivity in completing search tasks were influenced by the interaction of these effects, as illustrated in the following Tables.

Table 5: Number of headings selected from browse list, as influenced by type of display and spatial scanning

		Spatial scanning	
		Low	High
Display	Single window	12.38	6.46
	Multiwindow	5.63	8.67

F (1,1)= 2420.16, p<.02.

Participants with lower levels of spatial scanning adopted a more selective and strategic approach to searching when they used the multiwindow display, as compared to those who used the single window display, who seemed to take a trial and error approach, selecting over a dozen different subject headings on average. It seems likely that the prominence given to subject headings in the multiwindow display, and the fact that the multiwindow display provided an excellent match with scanning strategies employed by users with lower levels of scanning abilities, emphasized the importance of subject headings to users. This emphasis on the importance of subject headings in turn produced the selective and strategic approach to selecting headings from the term list.

Table 6: Number of references viewed, as influenced by word map use and perceptual speed

		Perceptual Speed	
		Low	High
Word map used	No	38.84	63.43
	Yes	45.81	55.47

F (1,1)= 20825.48, p<.01.

People with higher levels of perceptual speed viewed more records than those with lower levels of this ability. This finding is consistent with previous research that shows that perceptual speed has an impact on search activities [1]. But the use of a system that included a word map reduced the number of references viewed by high speed users, while

increasing the number of references viewed by low speed users. The reduction in search activity on the part of high-speed users suggests that the word map provided a distraction for them that reduced their activity level.

Table 7: Records printed, as influenced by type of display and perceptual speed

Display		Perceptual Speed	
		Low	High
Single window		14.7	15.95
	Multiwindow	13.5	21.2

$F(1,1)=1410.23, p<.02.$

As with records viewed, there was an effect of perceptual speed on records printed. Users with higher levels of perceptual speed tended to print more records. The use of a multiwindow display increased the number of references printed by high-speed users, while having no significant impact on number of references printed by low-speed users. The multiwindow display impeded the process of viewing and understanding the references in high-speed users, leading them to accept more records as potentially useful.

Interactions between Design Features and Task

It was hypothesized that there would be significant interactions between information system design features and task accomplished in determining search characteristics. This result would indicate that certain design features led to better performance in accomplishing specific tasks than in accomplishing other tasks. Several such interactions were found.

Table 8: Proportion of references printed, as influenced by display type and task

Display		Task	
		Term Paper	Newspaper Article
Single window		.41	.32
	Multiwindow	.32	.41

$F(1,64)= 8.02, p<.01.$

The term paper task placed a premium on selectivity, while the newspaper article task placed a premium on exhaustivity. Using a multiwindow display enhanced selectivity in the term paper task, while at the same time enhancing exhaustivity in the newspaper article task. The multiwindow display, which displayed search vocabulary prominently and in a consistent location, allowed users to apply an appropriate level of selectivity to the task in hand.

Table 9: Relevant references printed, as influenced by word map and task

Word map used		Task	
		Term Paper	Newspaper Article
No		11.5	9.3
	Yes	8.0	9.15

$F(1,64)= 4.41, p<.05.$

Table 9 presents the only significant interaction between the use of the word map and task. Participants who used the word map while completing the term paper task selected fewer relevant references to be printed. The word map apparently enhanced selectivity in this task, while having minimal effect on selectivity in the newspaper article task. This effect may be another example of the phenomenon noted above: the word map seems to have drawn additional attention to search vocabulary, and so to have led users to consider this vocabulary more carefully when viewing records.

Interactions between Cognitive Abilities, Design Features, and Task

There was a significant three-way interaction between task, display type, and perceptual speed ($F(1,64)= 4.94, p<.03$) in predicting the proportion of records printed by users. This measure is essentially one of selectivity: if a higher proportion of records viewed were selected for printing, a user was taking a less selective approach to the search. Tables 10 and 11 illustrate this interaction.

Table 10: Proportion of records printed, as influenced by type of display and perceptual speed (term paper task only)

Display		Perceptual Speed	
		Low	High
Single window		.44	.38
	Multiwindow	.27	.37

In this task, users were asked to find a few good articles on the topic, placing an emphasis on higher levels of selectivity. The use of a multiwindow display by individuals with lower levels of perceptual speed increased selectivity. Again, there was a good match between the abilities of the users and the design feature, apparently resulting in an increased focus on the data that allowed users to select some records over others.

Table 11: Proportion of records printed, as influenced by type of display and perceptual speed (newspaper task only)

Display		Perceptual Speed	
		Low	High
Single window		.32	.31
	Multiwindow	.49	.32

In this task, users were asked to find as many articles as they could on the topic, placing an emphasis on lower levels of selectivity. The use of a multiwindow display by individuals with lower levels of perceptual speed significantly reduced selectivity. The fit between the users' abilities and the design feature again allowed the users to accomplish the task assigned.

There was a significant three-way interaction between task, use of the word map, and spatial scanning ($F(1,55)=4.77, p<.04$) in predicting the number of relevant records printed. This measure combines features of recall, the number of relevant records viewed, and selectivity. Tables 12 and 13

present the results.

Table 12: Relevant records printed, as influenced by word map and spatial scanning (term paper task only).

		Spatial Scanning	
		Low	High
Word map present	No	9.4	15.43
	Yes	9.14	7.5

Participants with higher levels of spatial scanning ability printed far fewer relevant records in this task that required selectivity when using the word map than when using a simple list of headings. Without a word map, relying on their own visualization of the information space, high-ability users were less selective. When their own visualization was replaced by that of the word map, selectivity increased. This may be an instance in which the two-dimensional representation of information gave a more realistic overview of the information space than the users' own mental models, and thus enabled them to complete the assigned task more effectively.

Table 13: Relevant records printed, as influenced by word map and spatial scanning (newspaper article task only).

		Spatial Scanning	
		Low	High
Word map present	No	9.2	9.57
	Yes	7	10.31

The users who had lower levels of spatial scanning ability and who used the word map produced the most selective outcome in this task that emphasized exhaustivity. It seems likely that the negative impact of the word map in this situation presents a serious limitation on the effectiveness of two-dimensional presentations of information: word maps work better for some tasks than for others.

DISCUSSION

Taken as a whole, these findings demonstrate the complexity of the interactions between individual characteristics, tasks, and design features that can influence the effectiveness and usability of interactive systems. This complexity has clear implications for the design of digital library systems, particularly those that employ visualization and navigation features to supplement language-based searching. It is likely that implementation of design features that emphasize spatial organization of information will allow some users to perform better searches, while hindering the performance of others.

It was expected that certain cognitive abilities would be associated with processing of spatial representations of information. The findings supported this idea, but in an unexpected manner. One might have expected that users with higher levels of spatial abilities would have been most able to make use of spatial representations of information, and so to derive the most benefit from these representations.

In fact, the opposite occurred. Users with lower levels of spatial abilities benefited most from the design features that made use of two-dimensional information representation.

The results presented in Table 4 provide one example of this effect. It seems likely that users with higher levels of spatial scanning are able to visualize information spaces on their own, without system-provided aids. It was those who had lower levels of spatial scanning, and who were presumably less likely to form their own mental image of the information space, who benefited from the provision of a visual representation of that space. A different explanation accounts for the results involving the multiwindow display and perceptual speed (Tables 2 and 7, for example). Here, the lack of perceptual speed influenced users to adopt a selective, strategic mode of scanning of displayed data. Having the display organized into chunks that were displayed in consistent screen locations fitted directly into that scanning strategy, and led to improved performance. The corollary of these points, confirmed in the results, is that a mismatch between the abilities of users and the design features implemented can deteriorate performance.

The interactions between design features and tasks are less definitive from a design viewpoint. The multiwindow display affected selectivity in the direction desired for each task. At the same time, it was associated with higher levels of recall in the term paper task: a task in which low recall and high precision would be optimal. The single interaction between the use of the word map and success in a specific task is difficult to interpret and inconclusive. An examination of the three-way interactions adds no additional evidence that might be used to design information systems, since these interactions simply replicate results obtained from the two-way interactions. A comparison of the results for interactions of design features with cognitive abilities and with task leads to the conclusion that personal characteristics provide a stronger basis for the design of usable systems than tasks. The findings clearly showed the nature of the fit between design features and user abilities in ways that can guide the provision of spatial representations in digital libraries.

CONCLUSIONS

The conjunction of spatial and conceptual approaches to information in digital libraries is a logical outcome of the fact that while storage media have changed, users have not. Digital libraries may employ a revolutionary storage technique, but their users are every bit as analog as they have been for the past four millennia. Since library users have traditionally used a combination of conceptual and spatial approaches to information, it is entirely appropriate that users of digital libraries should employ both types of approach in combination. When this happens, however, important issues of effectiveness and usability are raised.

These issues are particularly important when the different cognitive abilities of users are considered. In some cases, spatial representations of information can produce significant improvements in performance in searching for information. In other cases, the same design features can deteriorate performance. There must be a match between the abilities of the user and the design configuration of the information system. This research pointed out that a positive match frequently occurs with users who have lower levels of abilities, and for whom system features such as spatial representations of information can augment their abilities. It also found that the contributions to performance made by design features may not be easily predictable. The ability of a word map (a data visualization device) to influence the learning of vocabulary (a conceptual task) in users who have lower levels of spatial scanning ability is one example of the unpredictability and complexity of the interactions between abilities and design features.

It seems superfluous to point out that additional research into these issues is necessary. The design of fully usable systems can come about only through such continued investigations. The crucial point is that digital libraries provide an incredibly fruitful testbed for conducting this research. Because digital materials and collections can be organized and represented spatially in so many different ways, and because the ongoing research on data visualization is so productive of design alternatives, researchers have a rich environment in which to continue to analyze the effects of spatial representations of information on the effectiveness and usability of information systems.

REFERENCES

1. Allen, B.L. "Perceptual Speed, Learning and Information Retrieval Performance". In SIGIR '94. Proceedings of the Seventeenth International Conference on Research and Development in Information Retrieval (1994). Springer-Verlag, pp. 71-80.
2. Andrews, K. "Visualising Cyberspace: Information Visualisation in the Harmony Internet Browser." In Information Visualization Proceedings (1985) IEEE, pp. 97-104.
3. Borgman, C.L. "The User's Mental Model of an Information Retrieval System: Effects on Performance." Unpublished doctoral dissertation, Stanford University, 1984.
4. Ekstrom, R.B., French, J.W., Harman, H.H., and Dermen, D. *Manual for Kit of Factor-Referenced Cognitive Tests*. Educational Testing Service, Princeton, NJ, 1976.
5. Hearst, M.A. "TileBars: Visualization of Term Distribution Information in Full Text Information Access." In CHI '95 (1995), ACM, pp. 59-66.
6. Jackendoff, R. *Languages of the Mind*. MIT Press, Cambridge, MA, 1992.
7. Jackson, S. and Brashers, D.E. *Random Factors in ANOVA*. Sage, Thousand Oaks, CA, 1994.
8. Johnson-Laird, P.N. *Mental Models: Toward a Cognitive Science of Language, Inference, and Consciousness*. Harvard University Press, Cambridge, MA, 1983.
9. Korfhage, R.R. and Olsen, K.A. "Image Organization Using VIBE, a Visual Information Browsing Environment." Proc. SPIE. 2606 (1995), 380-388.
10. Nowell, L. T. "Visualizing Search Results: Some Alternatives to Query-Document Similarity." SIGIR Forum (1996), 67-75.
11. Paivio, A. *Mental Representations: A Dual Coding Approach*. Oxford University Press, New York, 1990.
12. Shallice, T. "The Language-To-Object Perception Interface: Evidence from Neuropsychology." In *Language and Space*. MIT Press, Cambridge, MA, 1996, pp. 531-552.
13. Smith, T.R. "Digital Library for Geographically Referenced Materials." *Computer* 29, 5 (May, 1996), 54-60.
14. Wise, J. A., Thomas, J. J., Pennock, K., Lantrip, D., Pottier, M., Schur, A., & Crow, V. "Visualizing the Non-visual: Spatial Analysis and Interaction with Information from Text Documents." In *Information Visualization Proceedings (1995) IEEE*, pp. 51-58.