Spatial Ability and Information Shape: When Do Individual Differences Matter

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Abstract

Psychologists have long known that cognitive differences between individuals can significantly affect performance on a variety of tasks. Several recent studies have shown that so-called spatial reasoning ability has a significant effect on users success with (spatial and non-spatial) hypertexts. If we understood why spatial ability has such a strong effect on success with hypertext then we could adapt hypertext for use by different types of people, and explore new types of presentation.

It is clear that the different success rates are not solely due to the hypertext systems and the need to integrate two-dimensional spatial data (as with spatial HT systems like VKB) but rather the need to make sense of, and navigate in, multi-dimensional structures of meaning. A. Dillon and D. Schaap refer to some of these issues as 'information shape'.

Despite clear evidence that spatial reasoning ability affects success with hypertext, studies of the effect are remarkably vague about what subfactors were assessed. We have made a preliminary analysis of these studies to determine their common components. We present both a survey of studies of hypertext that have found such effects, and an investigation into the underlying causes.

Contents

1 Introduction

The past few years have seen a massive increase in the amount of information available online, and the apparent ease with which it can be accessed. This wealth of information comprises a large information space, often referred to as Hyperspace, and is organized in hypertext and hypermedia form on the World Wide Web (WWW). *Hypertext* is generally conceived as a collection of non-linear, text-based nodes that are linked together to give structure to the information space, providing users with increased navigational flexibility (Benyon and Höök, 1997).

Any substantial, structured collection of information comprises an *information space*. Hyperspace is not the only important large information space. Information spaces include many other large information retrieval systems, such as spreadsheets, databases, CD-ROMs, help systems, file systems, and even three-dimensional virtual worlds (Benyon and Höök, 1997). Furthermore, information spaces are not necessarily virtual environments. A library in the physical world, for example, can be considered an information space (Benyon and Höök, 1997).

The remainder of this paper presents an overview of research investigating how individual differences in spatial ability affect navigational tasks in information spaces. A number of terms that are important to understand in this area of research are now presented, but will be expanded upon in Section 2. The *usability* of computer systems is a measure of how easily users can perform tasks when using the system. Navigation refers to a person's ability to remain unconfused when perusing an environment. *Information shape* is a technique that provides structure to an information space. *Cognitive style*s are stable patterns of thinking that people use. *Spatial ability* refers to cognitive abilities that deal with objects in space.

Once these terms have been fully explained, the paper explains that the study of how cognitive abilities affect performance can be enhanced through the use of techniques from the field of differential psychology. Next, the paper presents an extensive review of the literature investigating how individual differences in spatial ability affect navigational tasks in information spaces. A summary of this research can also be found in the charts presented in Appendix A. Finally, a discussion of the significance of this research is presented, along with ideas and directions for further studies.

2 Background

This section describes a range of terms that are important to the investigation of individual differences in the field of human-computer interaction.

2.1 Usability

Much research today investigates how different hypertext systems can be evaluated in terms of efficiency, effectiveness, and affectiveness. *Efficiency* refers to the speed with which a user can access the information they are interested in. *Effectiveness* refers to how accurate the information actually is once it has been accessed. *Affectiveness* refers to how satisfied a user is with the system (Jordan, 1998).

A major difficulty in this area stems from the fact that individual differences such as spatial ability, cognitive style, field independence, online experience, reasoning ability, memory, domain knowledge, gender, and age can all strongly affect performance in information systems. Exactly how these individual differences affect a person's ability to navigate through information spaces is still unclear. These issues must be addressed before accurate usability assessments of information systems can be performed.

2.2 Navigation

Whether navigation through virtual information spaces uses the same cognitive resources as navigation in the physical world is an often debated issue. Traditionally, navigation has been defined as the act of remaining unconfused while traversing an uncharted area, whether in Euclidian or cognitive space (Kolb and Wishaw, 1996). It is still unclear, however, whether navigation through cognitive space really utilizes the same underlying abilities as real world navigation (Spence, 1999). Recent research into this topic has studied how people naturally think of large information spaces, such as the WWW (Maglio and Barrett, 1998; Maglio and Matlock, 1998). Their results indicate that people think of the WWW's information space in the same way that they think about physical information spaces (Maglio and Barrett, 1998; Maglio and Matlock, 1998). For example, when talking about downloading a web page, people tend to say things such as "I'm going to the web page." This suggests that navigation through virtual information spaces can be conceived of in terms of cognitive maps similar to cognitive maps that are created when navigating physical environments (Maglio and Matlock, 1998).

It is generally believed that cognitive maps of Euclidean space incorporate landmark knowledge, route knowledge, and survey knowledge (Maglio and Barrett, 1998). *Landmark knowledge* is the use of conspicuous objects to mark locality. *Route knowledge* represents procedures for how to get from one landmark to another. *Survey knowledge* is the use of map-like representations (Maglio and Barrett, 1998). Interestingly, research has shown that users searching for information on the WWW follow familiar routes to anchor points (landmarks) close to the desired information (Maglio and Barrett, 1998). Designers could possibly exploit this knowledge when designing large information spaces by including explicit route and landmark information.

Traditionally, studies of navigation have been primarily concerned with wayfinding, which refers to how individuals figure out how to reach their destinations (Benyon and Höök, 1997). There are considerable individual differences in wayfinding strategies, primarily between three broad strategies, namely, the use of landmark knowledge, route knowledge, or survey knowledge (Kolb and Wishaw, 1996). Different individuals rely primarily on one of these three strategies to find their way to a destination (Kolb and Wishaw, 1996). Navigation through information spaces, however, is more concerned with learning about an information space than finding a specific destination (Benyon and Höök, 1997; Spence, 1999).

Spence (1999, p. 920) defines *navigation* as "the creation and interpretation of an internal (mental) model, and its component activities are browsing, modelling, interpretation and the formulation of browsing strategy." As will be discussed later, the creation of internal models, such as cognitive maps of an information space, is related to an individual's spatial ability, more specifically, to the visualization factor of spatial ability (Carroll, 1993). Furthermore, the spatial relations factor of an individual's spatial ability is concerned with an individual's ability to maintain orientation with respect to objects in space (Carroll, 1993), and as such is related to navigational ability. An individual's navigational ability affects their information retrieval and problem solving skills in the context of human-computer interaction (Spence, 1999). For example, users often become disoriented while following hypertext links (Hofman and van Oostendorp, 1999; Kim and Hirtle, 1995; McDonald and Stevenson, 1996). Before hypertext systems that are usable for all individuals can be designed, research must identify exactly what underlying abilities affect this disorientation.

2.3 Information Shape and Scent

Two methods that seem to enhance the usability of information systems are the use of information shape and scent. Using information shape when designing an information system means taking advantage of "spatial-semantic properties that convey coherence that users can exploit both semantically and physically to gather meaning," (Dillon and Watson, 1996, p. 522). This technique provides structure to the information space, and is important because a user's ability to perceive structure or shape when navigating an information space is important to the usability of an information system (Dillon, 2000). Users with poor spatial ability seem to have problems creating and maintaining an internal mental model of information spaces. The point of information shape is to give structure to the information, which will provide a more explicit presentation that compensates for their lack of an accurate internal model of the information.

Another technique that can enhance the usability of information systems is taking advantage of scent. Larson and Czerwinski describe scent as "conveying distal target information via category labelling" (Larson and Czerwinski, 1998, p. 26). This refers to how easily users can figure out where to go for the information they need just by reading the category labels presented to them.

2.4 Differential psychology

Differential psychology looks at how individual differences between participants can affect their performance on the tasks being analyzed. Studies in differential psychology are typically characterized by large sample sizes, and the rigorous use of multivariate or factor-analytic techniques to try and find patterns in the differences between participants (Dillon and Watson, 1996). Psychologists assume that variations from the mean actually reflect latent mental abilities that are required to perform the tasks (Dillon and Watson, 1996). In contrast, experimental psychologists typically assumes that whatever ability is required to perform a task is relatively homogenous across participants, and is less concerned with sample sizes (Dillon and Watson, 1996).

To date, the field of human-computer interaction has adopted the experimental perspective almost exclusively. Many researchers believe, however, that the field of human-computer interaction could greatly benefit from a differential perspective (Chen et al., 2000; Dillon and Watson, 1996).

Egan (Egan, 1998) reported that many common computer tasks show individual differences on the order of 20:1. This ratio implies that many users are not able to perform these tasks effectively. Egan (Egan, 1998) went on to say that by understanding and being able to predict these individual differences, systems could be designed to reduce or even eliminate them. More and more researchers are beginning to realizing that individual differences in cognitive ability can significantly influence task performance in predictable ways (Chen et al., 2000; Dillon and Watson, 1996). It is widely believed that 25% of the variance in performance can be attributed to individual differences in ability alone (Dillon and Watson, 1996).

The majority of user interfaces designed today are designed with only a generic, ideal user in mind (Chen et al., 2000). It is possible, however, to design information systems that accommodate individual differences (Chen et al., 2000). Dillon and Watson (1996) suggest that explicit mapping of individual differences to interface characteristics can reduce the variance due to individual differences in cognitive ability. Furthermore, understanding which individual differences significantly affect performance on a task can help to constrain the number of design solutions (Dillon and Watson, 1996).

Designing information systems to accommodate individual differences is a difficult task, which researchers have only recently begun. There are three steps that must be performed in succession before this goal can be attained (Cribbin and Chen, 2001). First, the specific individual differences that influence task performance must be discovered. Secondly, the tasks themselves must be analyzed to determine the task components that actually account for the variability. Finally, the design components must be modified in some manner that reduces the differences in performance (Chen et al., 2000; Cribbin and Chen, 2001; Egan and Gomez, 1985).

It is known that spatial ability is an important source of individual differences in the field human-computer interaction, but the specific factors of spatial ability that influence performance of various tasks have yet to be determined. It is important to understand what the different factors of spatial ability are before determining their effects on performance. The following section will describe the factors of spatial ability in detail, and explain how to perform psychometric assessments of these factors.

2.5 Spatial Ability

Spatial ability is a term often used to describe a myriad of different cognitive abilities within the broader domain of visual-perceptual abilities. These abilities are considered spatial because most are related to how people deal with objects presented in space, or with how people orient themselves in space (Carroll, 1993).

Kritchevsky (Kritchevsky, 1988, p. 111) defines *spatial cognition* as "any aspect of an organism's behavior which involves space and is mediated by cerebral activity." Nearly every researcher has a different definition of spatial ability, however, making it difficult to interpret and compare the results of different studies (Caplan and Romans, 1998).

The absence of an agreed upon definition of spatial ability leads to the fact that there is not an adequate scheme of spatial functions and skills as there is in the language domain (Caplan and Romans, 1998). This is unfortunate, especially considering the fact that spatial abilities have been studied for so long. Over 130 years ago, Quaglino and Borelli (Quaglino and Borelli, 1867) reported on the link between visual-spatial impairment and right cerebral hemisphere lesions. It is notable that the right cerebral hemisphere was long referred to as the 'non-dominant' hemisphere. Consequently, research emphasis was placed on the left hemisphere until recently, most likely due to its control of language (Caplan and Romans, 1998).

There have been many efforts made to subdivide spatial ability into various factors that can each be more easily tested. As with definitions of spatial ability, however, these factors vary from study to study. Carroll (1993) performed an extensive survey and analysis of factor analytic studies that yielded five factors of spatial ability belonging in the visual-perceptual domain. These five factors are called visualization (VZ), spatial relations (SR), closure speed (CS), closure flexibility (CF), and perceptual speed (P). As well, Spatial scanning (SS) and visual memory (MV) are factors that may also be related to spatial ability. Each of these seven factors are important components of spatial ability that can be measured using various psychometric tests (Carroll, 1993). The psychometric test battery most often used for assessing the components of spatial ability is the Kit of Factor-Referenced Cognitive Tests, developed at the Educational Testing Service (ETS) (Ekstrom et al., 1976).

2.5.1 Visualization

Visualization is the most often studied factor of spatial ability, and is often considered the most important factor to performance with computer systems. Carroll (1993, p. 362) defines *visualization* as "ability in manipulating visual patterns, as indicated by level of difficulty and complexity in visual stimulus material that can be handled successfully, without regard to the speed of task solution." In tasks that assess visualization ability, the person being tested must recognize a spatial object in order to match it with another spatial object, often having to rotate it in two or three dimensions, one or more times (Carroll, 1993).

Most of these tasks involve spatial thinking in three dimensions, but it is thought that performance in three dimensions is correlated with spatial thinking in two dimensions. Hence, there is good reason to expect that people who perform well on a three-dimensional visualization task will also perform well in two dimensions (Carroll, 1993). Another important point about tests of visualization is that they are administered under liberal time limits, unlike tests of the other factors of spatial ability (Carroll, 1993).

The ETS Kit of Factor-Referenced Cognitive Tests (FRC Tests) defines *visualization* as "the ability to manipulate or transform the image of spatial patterns into other arrangements" (Ekstrom et al., 1976, p. 173). That Kit includes three tests that assess visualization. These tests are the Form Board Test (VZ-1), the Paper Folding Test (VZ-2), and the Surface Development Test (VZ-3) (Ekstrom et al., 1976).

2.5.2 Spatial Relations

Another often studied factor of spatial ability is that of spatial relations, or spatial orientation. Carroll (1993, p. 363) defines spatial relations as "speed in manipulating relatively simple visual patterns, by whatever means (mental rotation, transformation, or otherwise)." Tests that assess spatial orientation require the person being tested to compare multiple stimuli in order to determine whether one is a rotated or reflected version of another (Carroll, 1993). These tests are relatively simple, speeded tests (Carroll, 1993).

The FRC Tests defines *spatial orientation* as how well people perceive spatial patterns and maintain their orientation with respect to objects in space (Ekstrom et al., 1976). The ETS Kit of Factor-Referenced Cognitive Tests includes two tests that assess spatial orientation. These tests are the Card Rotations Task (S-1), and the Cube Comparisons Test (S-2) (Ekstrom et al., 1976). Other often used tests of spatial orientation include Thurstone's Cards Flags and Figures Test, and tests of left-right handedness (Carroll, 1993).

2.5.3 Closure Speed

Carroll (1993, p. 363) defines closure speed as "speed in apprehending and identifying a visual pattern, without knowing in advance what the pattern is, when the pattern is disguised or obscured in some way." The objects must be known to the individual, as an individual will not recognize an object the individual has never seen before (Carroll, 1993). The main concern when evaluating tests of closure speed is the speed with which the recognition occurs (Carroll, 1993).

The FRC Tests includes two tests that assess closure speed. These tests are the Gestalt Completion Test (CS-1), and the Concealed Words Test (CS-2) (Ekstrom et al., 1976).

2.5.4 Closure Flexibility

Closure flexibility is "speed in finding, apprehending, and identifying a visual pattern, knowing in advance what is to be apprehended, when the pattern is disguised or obscured in some way," (Carroll, 1993, p. 363). However, Carroll (1993, p. 341) suggests that a more accurate name and interpretation of closure flexibility would be the "speed of detecting and disembedding a known stimulus array from a more complex array." This factor is related to the cognitive style referred to as field independence (Carroll, 1993). The FTC Test includes three tests that assess closure flexibility. These tests are the Hidden Figures Test (CF-1), the Hidden Patterns Test (CF-2), and the Copying Test (CF-3) (Ekstrom et al., 1976).

2.5.5 Perceptual Speed

Carroll (1993, p. 363) defines *perceptual speed* as "speed in finding a known visual pattern, or in accurately comparing one or more patterns, in a visual field such that the patterns are not disguised or obscured." Tests of perceptual speed measure the speed at which an individual locates, or compares symbols (Carroll, 1993). These tests necessarily involve some peripheral motor behaviour, such as eye movements or finger movements (Carroll, 1993).

According to the FRC Tests, perceptual speed is "speed in finding figures, making comparisons, and carrying out other very simple tasks involving visual perception," (Ekstrom et al., 1976, p. 123). The ETS Kit of Factor-Referenced Cognitive Tests includes three tests that assess perceptual speed. These tests are the Finding A's Test (P-1), the Number

Comparison Test (P-2), and the Identical Pictures Test (P-3) (Ekstrom et al., 1976).

2.5.6 Spatial Scanning

According to Carroll (1993, p. 363), spatial scanning is defined as "speed in accurately following an indicated route or path through a visual pattern." Carroll (1993), however, determined that spatial scanning may not be a true factor of spatial ability. It is included here only because many studies in the field of human-computer interaction have used spatial scanning tests as assessments of spatial ability (Allen, 1998, 2000).

According to FRC Tests, spatial scanning is "speed in exploring visually a wide or complicated spatial field," (Ekstrom et al., 1976, p. 155). The ETS Kit of Factor-Referenced Cognitive Tests includes three tests that assess perceptual speed. These tests are the Maze Tracing Speed Test (SS-1), the Choosing a Path Test (SS-2), and the Map Planning Test (SS-3) (Ekstrom et al., 1976).

2.5.7 Visual Memory

Carroll (1993, p. 282) defines visual memory as the "ability to form and remember over at least a few seconds a mental image or representation of a visual shape or configuration that does not represent some easily recognized object." Technically, visual memory is a factor of Carroll's (1993) learning and memory ability, not spatial ability, but other researchers have named it a factor of spatial ability (Cribbin and Chen, 2001). Visual memory intuitively seems related to spatial ability, and so is included here for completeness.

The FRC Tests includes three tests that assess visual memory. These tests are the Shape Memory Test (MV-1), the Building Memory Test (MV-2), and the Map Memory Test (MV-3) (Ekstrom et al., 1976).

2.6 Cognitive Style

Cognitive style refers to the way people think; their manner of cognition.

Dillon and Watson (1996, p. 626) define cognitive styles as "relatively stable patterns of information processing that are displayed by an individual." Most cognitive styles are bipolar, and value differentiated, meaning neither pole is better than the other. In contrast with cognitive abilities, which are normally specific to one particular domain, cognitive styles apply to all domains. They are variables that organize and control cognitive processes (Sjölinder, 1996). Research has shown that cognitive style is an important determinant of computer anxiety (Sjölinder, 1996). A related concept, learning style, is involved in the organization and control of strategies for learning and knowledge acquisition (Sjölinder, 1996).

Messick (Messick, 1988) identifies nine examples of cognitive styles: field independence versus field dependence, scanning, breadth of categorizing, conceptualizing styles, cognitive complexity versus simplicity, reflectiveness versus impulsivity, levelling versus sharpening, constricted versus flexible control, and tolerance for incongruous or unrealistic experiences.

Field independence refers to a value-directional cognitive style, with independence at the more adaptive pole (Sjölinder, 1996). Field independence is the ability to correctly orient an object while ignoring its surroundings (Sjölinder, 1996). Dillon and Gabbard (1998, p. 341) define this cognitive style as "differences in preference to attend to specific issues or to rely on context." According to Sjolinder (Sjölinder, 1996), people who are field independent tend to be more analytic, impersonal, and flexible than those who are field dependent.

One way to measure cognitive field independence is to use an embedded figure test, such as Witkin's Embedded Figure Test (Witkin et al., 1971). According to Castelli, et al. (Castelli et al., 1998, p. 181), this test measures "the degree of perceptive 'disembedding' ability." However, it also assesses the broader cognitive style, field independence, "as the characteristic and coherent functioning displayed by people in their perceptive and intellectual activities," (Castelli et al., 1998, p. 181).

Many studies have investigated the effects of cognitive styles, particularly field independence, on navigational performance in information spaces (Castelli et al., 1998; Dillon and Watson, 2000; Liu and Reed, 1994; Palmquist and Kim, 2000). However, it has yet to be shown that cognitive styles can actually predict performance (Dillon and Gabbard, 1998; Dillon and Watson, 1996). Dillon and Watson (Dillon and Watson, 1996) explain that the reasons cognitive styles have not shown predictive power may be due to any number of factors. They state that it is possible that the dimensions studied thus far are superficial and may need further refining before they can be useful (Dillon and Watson, 1996). Carroll (1993, p. 555) stated that "differential dimensions of cognitive style have not as yet been well established." Another possibility is that individuals may use multiple styles, depending on the task and circumstances (Dillon and Watson, 1996). Furthermore, specific styles may be correlated with specific tasks (Dillon and Watson, 1996).

Some studies show moderate predictive power of cognitive field independence, while others have determined that cognitive field independence has no predictive power. In a 1998 literature review, Dillon and Gabbard (1998, p. 344) state that cognitive field independence "has failed to demonstrate much in the way of predictive or explanatory power and perhaps should be replaced with style dimensions that show greater potential for predicting behavior and performance." However, the relation of cognitive field independence to spatial is clear, so more studies should include measures of cognitive field independence along with measures of cognitive abilities.

3 Studies

The following section describes a selection of experiments that have investigated how individual differences in spatial ability affect performance on navigational tasks in information spaces. The studies were performed on disparate user groups, but most often using university students. The cognitive tests used on the participants varied considerably, but all measured some aspect of spatial ability.

3.1 Spatial Relations and Visualization I

The three experiments described in this section used the Kit of Factor-Referenced Cognitive Tests (Ekstrom et al., 1976) to measure the visualization and spatial relations factors of spatial ability. Both Vicente & Williges (1988) and Stanney & Salvendy (1995) used two-dimensional hierarchical file systems as information spaces, while Curl, Olfman, and Satzinger (1998) used a database as an information space. Note also that Curl et al. (1998) measured only visualization ability.

3.1.1 Vicente and Williges (1988)

Vicente and Williges (1988) performed one of the first experiments which attempted to accommodate individual differences in spatial ability. Psychometric tests measured individual differences in spatial ability, and then the participants performed navigational tasks using both a verbal and a visual hierarchical file system. The researchers employed the theory of momentum, which refers to how easily individuals can integrate and extract information from different user interfaces (Vicente and Williges, 1988). By including a visual hierarchy in their study, they hoped to improve visual momentum in file selection (Vicente and Williges, 1988). They predicted that this improved visual momentum would compensate users with low spatial abilities. Although their results were in the predicted direction, it was found that users did not perform significantly better when using the graphical interface (Vicente and Williges, 1988).

3.1.2 Stanney and Salvendy (1995)

In an extension of the Vicente and Williges (1988), Stanney and Salvendy (1995) attempted to compare the use of a two-dimensional visual hierarchy to that of a linear structure as methods of accommodating individual differences in spatial ability (Stanney and Salvendy, 1995). More traditional file system hierarchies have information embedded at different levels. The researchers predicted that both the two-dimensional visual hierarchy and the linear hierarchy would improve performance of low spatial individuals, by compensating for their deficiencies in ability (Stanney and Salvendy, 1995).

Stanney and Salvendy (1995) had 74 university students perform three psychometric tests in order to assess cognitive abilities. All three tests were taken from the Kit of Factor-Referenced Cognitive Tests (Ekstrom et al., 1976). Spatial ability was measured using the Cube Comparison Test and the Surface Development Test, which, respectively, measure the spatial relations and visualization factors of spatial ability. As a measure of verbal ability, all participants also performed the Extended Range Vocabulary Test. Two groups of 12 individuals were chosen from the results of these tests to represent individuals with high and low spatial ability. The groups were controlled for verbal ability by having the same number of individuals in each group who performed above or below the group mean on the verbal ability test (Stanney and Salvendy, 1995).

Results of the experiment performed by Stanney and Salvendy (1995) confirmed their predictions that the two-dimensional visual hierarchy and the linear hierarchy would improve performance of individuals with low spatial ability. It was determined that the individual differences in performance found when using traditional hierarchies were eliminated when a two-dimensional visual hierarchy or a linear hierarchy was used (Stanney and Salvendy, 1995). These researchers suggest that significant results were not found by Vicente and Williges (1988) because those researchers left embedded information in the graphical hierarchy they used (Stanney and Salvendy, 1995). Stanney and Salvendy (1995) believe that it is the embedded information in traditional hierarchies which causes difficulty for individuals with low spatial ability.

3.1.3 Curl, Olfman, and Satzinger (1998)

Curl et al. (1998) investigated the relationship between users' spatial visualization ability and their ability to write effective database queries. The Paper Folding Test from the Kit of Factor-Referenced Cognitive Tests (Ekstrom et al., 1976) was used to measure participants spatial visualization ability. Users performed tasks that involved making queries based on a view of the database that was either spatially or non-spatially represented (Curl et al., 1998). Users were separated into two groups based on their scores on the Paper Folding Test, high and low spatial ability groups. All users were then randomly assigned to one or the interface (Curl et al., 1998).

The researchers predicted that the spatial visualization interface would enhance performance for both groups, as well as reducing the differences between the two groups (Curl et al., 1998). Furthermore, they predicted that individuals with high visualization ability would perform better than those with low visualization ability (Curl et al., 1998).

Surprisingly, results did not show a significant relationship between visualization ability and performance (Curl et al., 1998). However, the results were in the expected direction. The researchers suggest that a lack of statistical power may be the cause of the insignificant results. This means that it is possible an effect is present, even though it was not detected by the researchers (Curl et al., 1998).

3.2 Spatial Relations and Visualization II

The two experiments described in this section used the Duremann-Salde test battery (Psykologiforlaget, 1971) to measure the visualization and spatial relations factors of spatial ability. Both experiments measured performance of Swedish participants in two-dimensional information spaces.

3.2.1 Dählback, Höök, and Sjölinder (1996)

Dählback, Höök, and Sjölinder (1996) investigated the relationship between spatial ability and ability to navigate through hypermedia. The information space they used was an on-line, hypermedia based help system for a software development method, SDP (Dählback et al., 1996). Twenty-three participants performed a variety of information seeking tasks, and measures of efficiency, effectiveness, and satisfaction were taken (Dählback et al., 1996).

To measure spatial ability, four tests were taken from the Duremann-Salde test battery (Psykologiforlaget, 1971): two tests of the visualization factor(namely, the figure rotation and block tests), a test of spatial relations factors of spatial ability, a test of perceptual analysis ability, and some tests of verbal and logical-inductive abilities.

The Figure Rotation Test (Dählback et al., 1996, p. 3) had individuals perform "rotation of images where the subject should choose, by turning the images in their head, the images that were identical with the image in the task." During the Block Test (Kohs' Block Test) (Dählback et al., 1996, p. 3), "the subject should make a pattern with blocks, which should be identical with a pattern on a card that the subjects were shown." As a test of the spatial relations factor of spatial ability, participants performed the Hand Test, described (Dählback et al., 1996, p. 3) as "left or right hand identification in pictures of hands that were turned different ways." A test of perceptual analysis ability, the Figure Drawing Test, had individuals draw imitations of images (Dählback et al., 1996).

Dählback et al. (1996) found that only the Hand Test and the Figure Rotation Test were significantly correlated with ability to use the information space. They suggest that these two tests assess internal spatial ability, in contrast with the Block Test and Figure Drawing Test, which include external manipulation of physical objects and thus provide visual feedback (Dählback et al., 1996). Furthermore, they found a significant difference in the speed at which users performed the tasks between those with low internal spatial ability and those with high internal spatial ability (Dählback et al., 1996).

3.2.2 Dählback and Lönnqvist (2000)

Another study that attempted to analyze the relationship between spatial ability and navigation through an information space was performed by Dählback and Lönnqvist (2000). This study had 21 participants perform hypermedia navigation tasks using an encyclopedia CD-ROM information space (Dählback and Lönnqvist, 2000). Psychometric tests assessed the spatial ability of participants using a mental rotation test and a spatial visualization test. Both of these tests measure the visualization factor of spatial ability, and were taken from the Duremann-Salde test battery (Psykologiforlaget, 1971). Additionally, spatially loaded logic reasoning, classic logic reasoning, and learning style were measured (Dählback and Lönnqvist, 2000).

The main purpose of this study was to figure out which cognitive abilities were especially important for the performance of different types of navigational tasks (Dählback and Lönnqvist, 2000). Results showed that different tasks seemed to be correlated with specific cognitive abilities (Dählback and Lönnqvist, 2000). They suggested that finding the connections between different cognitive abilities and specific tasks is an important step toward accommodating individual differences in these cognitive abilities.

3.3 Spatial Scanning and Perceptual Speed

In contrast with most other researchers, Allen (1998; 2000) measured the spatial scanning and perceptual speed factors of spatial ability. Visualization and spatial relations ability were not measured in these experiments.

3.3.1 Allen (1998; 2000)

Using a bibliographic management system as an information space, Allen (1998; 2000) investigated how different levels of spatial ability can be capitalized on or compensated for by providing different interfaces to the user. Participants in these experiments had to retrieve references relevant to a previously chosen subject, for a number of different tasks. Subjects used either a simple term index or a word map layout, which is a more spatially oriented interface. Also, subjects used either a single window display for the information, or a multi-windowed display (Allen, 1998, 2000).

In order to assess spatial ability, four tests were used from the Kit of Factor-Referenced Cognitive Tests (Ekstrom et al., 1976): The Maze Tracing Speed Test and the Map Planning Test were used to measure spatial scanning ability, while the Number Comparison Test and the Identical Pictures Test were used to measure perceptual speed (Allen, 1998, 2000).

The experimental results showed that the spatially oriented word map compensated for low spatial ability, providing users with low spatial ability with greater recall (Allen, 1998, 2000). So, the word map helped those with poor spatial abilities to better visualize the information space. The multi-windowed display capitalized on high spatial ability, providing those individuals with greater recall (Allen, 1998, 2000). Furthermore, the multi-windowed display compensated low spatial ability, providing those individuals with greater precision (Allen, 1998, 2000). So, the multi-windowed display allowed all users to use better scanning strategies.

3.4 Three-Dimensional Information Spaces

This section will describe two experiments which looked at the effects of spatial ability when navigating through three-dimensional information spaces. Chen (2000) measured the visualization factor of spatial ability, while Cribbin and Chen (2001) measured both the visualization and spatial relations factors of spatial ability.

3.4.1 Chen (2000)

Recently, techniques in virtual reality and information visualization have been employed in an attempt at reducing individual differences in the performance of information retrieval tasks when navigating through information spaces (Chen et al., 2000). One experiment in this area was performed by Chen (2000) using a collection of journal articles represented in a three-dimensional, spatial-semantic, VRML-based information space. This study actually consisted of two experiments, the first looking at the effects of associational and visual memory on navigational performance, and the second looking at the effects of associational memory and visualization ability on navigational performance (Chen, 2000). To assess the visualization factor of spatial ability, the Paper Folding Test from the Kit of Factor-Referenced Cognitive Tests was used (Ekstrom et al., 1976).

Both experiments found a significant correlation between associational memory and performance, but the effects of visual memory and visualization ability were not significant (Chen, 2000). Interestingly, it was found that online experience was the most important predictor of performance (Chen, 2000). An important factor to consider in this experiment is that a relatively small sample size was used in this study. Only 10 people participated in the first experiment, and only 12 people participated in the second experiment (Chen, 2000).

3.4.2 Cribbin and Chen (2001)

Another study that attempted to figure out which user characteristics can predict differences in performance when using three-dimensional, graphical interfaces is that of Cribbin and Chen (2001). This study used psychometric testing to measure a variety of the participants cognitive abilities, and then had them perform information retrieval tasks to assess their performance (Cribbin and Chen, 2001). All psychometric tests were taken from the Kit of Factor-Referenced Cognitive Tests (Ekstrom et al., 1976). Visualization ability was measured using the Paper Folding Test and spatial orientation was measured using the Card Rotations Task. Perceptual speed, visual memory, associative memory, associational fluency, and ideational fluency were also measured (Cribbin and Chen, 2001).

Although 21 individuals participated in psychometric testing, only 13 returned for the actual experiment (Cribbin and Chen, 2001). The information space consisted of 200 newspaper articles chosen by keywords (alcohol, endangered, storm, and gambling), all between 250 and 750 words to control for reading speed (Cribbin and Chen, 2001). All users were tested with a traditional text interface as well as a spatial interface which was created using the Minimum Spanning Tree Algorithm (MST). The MST algorithm takes advantage of the semantic properties of information to impose a logical, graphical structure on the information (Cribbin and Chen, 2001).

As predicted, it was found that certain cognitive abilities can consistently predict performance on different information retrieval tasks. For example, spatial orientation ability dominated on simple, structured tasks where the ability to maintain orientation and reorient oneself to different perspectives was important (Cribbin and Chen, 2001). More complex tasks showed interactions of different abilities. Unexpectedly, perceptual speed was negatively correlated with performance on certain tasks, suggesting that a simple, fast strategy is sometimes important to performance (Cribbin and Chen, 2001).

4 Discussion

User interface designers should strive to accommodate as many users as possible. One important way of achieving this goal is to design user interfaces that minimize the effects of cognitive factors. A balance should be struck between compensation for individuals with low spatial ability, and capitalization of the strong spatial ability of other users (Allen, 2000; Cribbin and Chen, 2001). Interfaces must be designed to be robust, rather than just expecting the users to be trained to use the interfaces, as in more traditional design paradigms (Cribbin and Chen, 2001).

The rest of this discussion will cover numerous issues that are important to this area of research. These issues will be summarized here and then discussed more extensively. Studies have shown that there is a correlation between specific tasks and specific cognitive abilities. Researchers have conflicting definitions of these cognitive abilities, however, especially spatial ability. There are also extensive discrepancies between the tests researchers have used to assess spatial ability, making it difficult to compare results. Most studies thus far have used very small sample sizes, calling their results into question. Furthermore, there seems to be many individual differences other than spatial ability that interact to provide predictive power when performing navigational tasks in virtual information spaces. Many researchers have already attempted to accommodate individual differences by redesigning the interfaces of information spaces. Once these issues have been discussed, suggestions for future investigations will presented.

Dählback and Lönnqvist (2000) determined that there is a correlation between specific tasks and identifiable cognitive abilities. Future studies should attempt to determine which cognitive abilities are important to which tasks. User interfaces then need to be modified to provide additional support for user goals, taking into account the cognitive abilities that are most important to the tasks. Cribbin and Chen (2001) found even more complex interactions between tasks and cognitive abilities. Thus, when attempting to determine which cognitive abilities have predictive power, it is important to keep in mind that there may be subtle differences between tasks that must be accounted for.

It is clear that individual differences in spatial ability have a significant effect on task performance when navigating through information spaces. Exactly which aspects of spatial ability are involved, however, is much less clear. The main problem is that different researchers have different ideas about what spatial ability is, and use different tests to measure it. Carroll (1993) describes five different factors of spatial ability, whereas most studies consider only one or two of these factors. Furthermore, even within each factor of spatial ability, different researchers use different psychometric tests for measurement, making it difficult to compare them.

Keeping these caveats in mind, there do seem to be some fruitful avenues for investigation. For example, research by Dählback et al. (1996) demonstrates that there may be a difference between external and internal spatial ability. This means that a figure rotation test and a paper folding test, both measures of the visualization factor of spatial ability, may actually be assessing different abilities.

Dählback et al. (1996) suggest that internal spatial ability is much more important to navigational tasks in virtual information spaces, calling into question the results of studies that use only tests of external spatial ability. For example, studies by Curl et al. (1998), and Chen (2000) both found that spatial ability did not have significant predictive power using only a paper folding test. More research must be performed to determine which psychometric tests of spatial ability should be used in studies of human-computer interaction. Once chosen, the tests should be used consistently across studies.

The use of small sample sizes is yet another significant problem in this area of research. Differential psychology has shown that large sample sizes should be used when investigating the effects of individual differences on performance (Dillon and Watson, 1996). However, the field of human-computer interaction has traditionally drawn on experimental psychology, which places less emphasis on sample sizes, which has most likely led to this deficiency. It is clear that further investigations into the accommodation of individual differences need to consider this factor more seriously.

A further complication is the wide range of individual differences that seem to have an effect on performance of navigational tasks in virtual information spaces. The concentration of this paper has been on differences in spatial ability, but it is not yet clear that spatial ability is the most important factor. For instance, in an extensive review and meta-analysis, Chen and Rada (1996) determined that the effects of spatial ability are often very small, with other factors, such as computer or domain expertise being more effective predictors. Chen (2000) also found that online experience was the most important predictor of performance. It is clear that studying spatial ability alone will not provide all the answers. Studies have shown that computer and online experience (Lazonder et al., 2000; Palmquist and Kim, 2000), domain expertise (Dee-Lucas, 1999; Hofman and van Oostendorp, 1999), reasoning and memory ability (Chen, 2000; Cribbin and Chen, 2001), and even gender (Burin et al., 2000; Czerwinski et al., 2002) can all have effects on performance. Further investigations must consider all these factors, as well as the complex interactions between them.

Although the specific user characteristics that affect performance have yet to be determined, many researchers have gone ahead and attempted to redesign interfaces to accommodate individual differences. Although perhaps somewhat premature, these investigations spur innovations that may help with the ultimate goal of designing interfaces that enhance performance for all users. For example, it is thought that part of the reason there are such large individual differences in performance is that individuals with poor visualization ability have trouble creating mental models of information spaces. Various methods have been attempted to try and compensate for these users' low visualization ability by providing more explicit visual models. Using the concept of information shape when designing information spaces is one way to try and compensate for users' difficulties creating mental models.

Early work in this area (Stanney and Salvendy, 1995; Vicente and Williges, 1988) found that embedded levels in file system hierarchies caused difficulties for low spatial individuals. To compensate, these researchers determined that designers should eliminate deep hierarchies from user interfaces. More recently, researchers have created graphical overviews of information spaces by imposing a logical, semantic structure on the information spaces (Chen et al., 2000; Chen, 2000; Cribbin and Chen, 2001). Results with these visual information retrieval interfaces (VIRIs) have not been very favourable, however, as their use seems to raise more human factors issues than they solve (Cribbin and Chen, 2001)).

A novel approach tried by Allen (2000) provided users with a variety of user interfaces to an information space in an attempt to determine whether users would choose the interfaces that allowed them to perform optimally without any direction. It turned out that they did not; users tended to stick with whichever interface was the first one shown to them (Allen, 2000). An alternative approach would be to let the system somehow match the user with an appropriate user model, thereby deciding for the user which interface would be best. How to approach this, however, is another important question that needs further investigation.

So where do we go from here? Further investigations must perform more extensive psychometric testing. To determine how spatial ability affects performance, all five of Carroll's (1993) factors of spatial ability should be accounted for. Researchers need to be aware of the differences between tests of internal and external spatial ability, using a range of tests from each area. Tests of cognitive field independence should also be included. As a control, tests of reasoning and memory abilities should also be included. People with stronger abilities in these areas tend to perform better on all tasks, making it difficult to interpret the predictive power of spatial ability. The degree of online and computer expertise also needs to be considered in future studies.

Studies that use a range of information spaces must be performed, to ensure that the predictive power of abilities found can be generalized across domains. The level of domain knowledge of participants should also be controlled. A wide range of tasks also need to be assessed, as it is obvious that different tasks require the use of different abilities. One fruitful avenue for investigation would be to replicate studies that have already been performed using more extensive psychometric testing and larger numbers of participants.

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A Summary Chart of Studies

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Stanney & Salvendy (1995)	Hierarchical File System	Spatial orientation	How well people perceive spatial patterns and maintain their orientation with respect to objects in space.	Cube Comparison*
		Visualization	“the ability to manipulate or transform the image of spatial patterns into other arrangements” (Ekstrom et al., 1976, p.173)	Surface Development*

chart continues...

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Dahlback et al. (1996)	On-line hypermedia help manual	Perceptual analysis ability	"tested through drawing imitation of images" (Dählback et al., 1996, p. 3)	Figure Drawing[†]
		"Spatial ability"	"rotation of images where the subject should choose, by turning the images in their head, the images that were identical with the image in the task." (Dählback et al., 1996, p. 3)	Figure Rotation[†]
		"Spatial ability"	"Left or right hand identification in pictures of hands that were turned different ways" (Dählback et al., 1996, p. 3)	Hand Test[†]
		"Spatial ability"	"the subject should make a pattern with blocks, which should be identical with a pattern on a card that the subjects were shown." (Dählback et al., 1996, p. 3)	Block Test (Kohs' Block Test)[†]

chart continues. . .

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Dahlback & Lonnqvist (1998) ⋮	Hypermedia based encyclopedia CD-ROM ⋮	Spatial visualization	• Represents Carroll's Carroll (1993) visualization factor of spatial ability. • Similar to Ekstrom et al.'s Paper Folding Test Ekstrom et al. (1976).	Platmodeller (paper folding test)[†]

chart continues...

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Dahlback & Lonnqvist (1998)	Hypermedia based encyclopedia CD-ROM	Mental rotation	• Probably represents a test similar to the Figure Rotation Test used by Dahlback et al. Dählback et al. (1996). • Similar to work by Ekstrom et al. Ekstrom et al. (1976)	Mentala rotationer (mental rotation test)†

chart continues...

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Curl et al. (1998)	Visual database query system	Visualization	"the ability to manipulate or transform the image of spatial patterns into other arrangements" (Ekstrom et al., 1976, p. 123)	Paper Folding Test (VZ-2)*

chart continues...

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Allen (1998)	Database of bibliographic references	Spatial scanning	"speed in exploring visually a wide or complicated spatial field" (Ekstrom et al., 1976, p. 155)	• Maze Tracing Speed Test* • Map Planning Test*
		Perceptual speed	"speed in comparing figures or symbols, scanning to find figures or symbols, or carrying out other very simple tasks involving visual perception" (Ekstrom et al., 1976, p. 123)	• Number Comparison Test* • Identical Pictures Test*

chart continues...

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Allen (2000)	Database of bibliographic references	Spatial scanning	"speed in exploring visually a wide or complicated spatial field" (Ekstrom et al., 1976, p. 155)	• Maze Tracing Speed Test* • Map Planning Test*
		Perceptual speed	"speed in comparing figures or symbols, scanning to find figures or symbols, or carrying out other very simple tasks involving visual perception" (Ekstrom et al., 1976, p. 123)	• Number Comparison Test* • Identical Pictures Test*

chart continues...

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Chen (2000)	Three-dimensional, spatial-semantic, VRML-based, virtual environment	Visualization	"the ability to manipulate or transform the image of spatial patterns into other arrangements" (Ekstrom et al., 1976, p. 173)	Paper Folding Test (VZ-2)*

chart continues...

Study	Information Space	Factor Measured	Definition of Factor	Tests Used
Cribbin & Chen (2001)	Three-dimensional, spatial-semantic, VRML-based, virtual environment	Visualization	"the ability to manipulate or transform the image of spatial patterns into other arrangements" (Ekstrom et al., 1976, p. 173)	Paper Folding Test (VZ-2)*
		Spatial orientation	How well people can perceive spatial patterns and maintain their orientation with respect to objects in space.	The Card Rotations Task (S-1)*
		Perceptual speed	"speed in comparing figures or symbols, scanning to find figures or symbols, or carrying out other very simple tasks involving visual perception" (Ekstrom et al., 1976, p. 123)	Not mentioned

*From the Kit of Factor-Referenced Cognitive Tests Ekstrom et al. (1976)
†From the Duremann-Salde test battery Psykologiforlaget (1971)