JYVÄSKYLÄ STUDIES IN COMPUTING 34

Marketta Niemelä

Visual Search in Graphical Interfaces

A User Psychological Approach

Esitetään Jyväskylän yliopiston informaatioteknologian tiedekunnan suostumuksella
julkisesti tarkastettavaksi yliopiston Agora rakennuksessa (Ag Aud. 2)
joulukuun 20. päivänä 2003 kello 12.

Academic dissertation to be publicly discussed, by permission of
the the Faculty of Information Technology of the University of Jyväskylä,
in the Building Agora, (Ag Aud. 2), on December 20, 2003 at 12 o'clock noon.

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2003

Visual Search in Graphical Interfaces

A User Psychological Approach

JYVÄSKYLÄ STUDIES IN COMPUTING 34

Marketta Niemelä

Visual Search in Graphical Interfaces

A User Psychological Approach

UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2003

Editors
Seppo Puuronen
Department of Computer Science and Information Systems, University of Jyväskylä
Pekka Olsbo, Marja-Leena Tynkkynen
Publishing Unit, University Library of Jyväskylä

URN:ISBN 9513917088
ISBN 951-39-1708-8 (PDF)

ISBN 951-39-1638-3 (nid.)
ISSN 1456-5390

Jyväskylä University Printing House, Jyväskylä
and ER-Paino Ky, Lievestuore 2003

ABSTRACT

Niemelä, Marketta
Visual Search in Graphical Interfaces: a User Psychological Approach
Jyväskylä: University of Jyväskylä, 2003, 61 p. (+ included articles)
(Jyväskylä Studies in Computing
ISSN 1456-5390; 34)
ISBN 951-39-1708-8
Finnish summary
Diss.

This dissertation applies and develops a user psychological approach to the research of human-computer interaction (HCI). The motivation behind the approach is to derive scientific psychological knowledge to explain and solve practical problems in HCI. Psychology provides data and theories to build explanatory frameworks, within which the user behavior during interaction tasks can be described and analyzed. In this dissertation, the particular explanatory framework is derived from cognitive psychology. Understanding of cognitive functions of the user is used to explain certain phenomena when the user interacts with a computer. A specific problem, to which the user cognitive psychology approach is applied, is the spatial arrangement of interface objects in graphical interfaces. Spatial arrangement of objects has been suggested to have substantial consequences on user behavior, but empirically the issue is understudied. To assess the problem of spatial arrangement, a cognitive model of visual search is constructed on the basis of cognitive psychology theories and findings. Four experimental studies assess the influences of spatial arrangement on visual search. The results of the studies show that the cognitive model explains the effects of spatial arrangement on visual search at the level of underlying cognitive functions. The results are also used to revise the model. It is argued that the model provides useful information for graphical interface designers in respect to visual search. The dissertation also evaluates the feasibility of the user cognitive psychology approach. It is shown that it is possible to apply psychological knowledge to profoundly explain practical problems within human-computer interaction. This is increasingly important as the computerized environments, and consequently, interaction problems, are becoming more and more complex in everyday life. The dissertation suggests, however, that more integrative research approaches motivated by real-world problems is needed to be carried out in cognitive psychology to increase its feasibility for HCI research.

Keywords: human-computer interaction, graphical user interfaces, screen design, spatial arrangement, human information processing, visual search

ACM Computing Review Categories

H.5.2 Information Systems: Information Interfaces and Presentation: User Interfaces
Graphical user interfaces
Screen design

H.1.2 Information Systems: Models and Principles: User/Machine Systems
Human factors
Human information processing

Author's address Marketta Niemelä
University of Jyväskylä
Dept. of Computer Science and Information Systems
P.O. BOX 35 (Ag C 514.2), 40014 Jyväskylä, Finland
E-mail: niemark@cc.jyu.fi

Supervisor Professor, Ph.D., Pertti Saariluoma
Dept. of Computer Science and Information Systems
University of Jyväskylä, Finland
E-mail: psa@cs.jyu.fi

Reviewers Professor, Ph.D., Hannakaisa Isomäki
Dept. of Research Methodology
University of Lapland, Finland

Professor, Ph.D., Jorma Sajaniemi
Dept. of Computer Science
University of Joensuu, Finland

Opponents Professor, Ph.D., Jose J. Cañas
Dept. of Experimental Psychology
University of Granada, Spain

Professor, Ph.D., Jorma Sajaniemi
Dept. of Computer Science
University of Joensuu, Finland

ACKNOWLEDGEMENTS

I did it, and it certainly would have not been possible without support and encouragement from so many people. First of all, I would like to thank my supervisor, prof. Pertti Saariluoma, who has the ability to understand a confused mind and clarify obscured thoughts. He also knows how to make people try their best. His expertise and support was indispensable during the writing of this dissertation.

I am also very grateful to the reviewers of this work, prof. Hannakaisa Isomäki from the University of Lapland in Finland and prof. Jorma Sajaniemi from the University of Joensuu in Finland, whose insightful comments improved this work in various ways. Prof. Sajaniemi also acted as the other opponent of this dissertation along with prof. Jose J. Cañas from the University of Granada in Spain, and special thanks belong to them both.

I very much appreciate that I have been able to work with these people, with whom the joint articles were written, in addition to prof. Saariluoma. Dr. Jukka (Jussi) Saarinen guided me to this field of research and helped me with the start of my postgraduate time. Working with prof. Kalle Lyytinen taught me that persistence will be rewarded in article writing. Jouni Huotari gave me enthusiasm for this work and this research field in general, and what I value the most is that he is a person, who can be relied on.

Many people at the department of Computer Science and Information Systems at the University of Jyväskylä deserve my compliments. I am especially indebted to Dr. Anne Honkaranta, who offered me a supporting shoulder during the last hectic weeks of writing, not to mention her numerous practical advice and ways of helping. Words of thanks also belong to Dr. Samuli Pekkola for his support and preparation for the exciting days of doctoral defense. I am grateful to Riitta Kuisma, prof. Airi Salminen, and prof. Minna Koskinen for enjoyable discussions about research, academic life, and everything. For the most pleasant atmosphere at the department, I further thank Virpi, Eleni, Janne, Mikko, Pasi Tiitinen, Pasi Tyrväinen, Antti Lehtinen, Antti Pirhonen, Tero, Zheying, and Jarmo. From the department of mathematical information technology, I want to thank Janne and Tuomas, with whom I have had the pleasure to co-operate and join in intellectual discussions.

This dissertation work was funded by COMAS graduate school and Agora Center of the University of Jyväskylä. I want to thank prof. Pekka Neittaanmäki, who made this dissertation possible, especially for his support during the last steps of the work.

I very much value the work of Gary Littler, who improved the English language of my writing. All remaining errors and obscurities are my mistakes.

My family has, of course, been the most important tower of strength to me. I am totally out of words when it comes to thanking my mother and father. They are gorgeous people. They have always believed in me, during good days and bad days. My home will always be there with you. My brother Hannu has been the most supporting brother, and although I do not at all times agree with you, our controversies have been stimulating! I also want to thank Johanna and Maarit, whose friendships I highly value. You remind me that there is an exciting world outside of the university, and I hope that we can enjoy it together for still a long time.

The most sincere thanks are dedicated to my fiancé, Jani. We have done this journey together. *You are the best*.

Jyväskylä
December 2003

CONTENTS

LIST OF INCLUDED ARTICLES

1 Niemelä, M. & Saarinen, J. 2000. Visual Search for Grouped Versus Ungrouped Icons in a Computer Interface. Human Factors 42 (4), 630-635.

2 Huotari, J., Lyytinen, K. & Niemelä, M. Improving Graphical Information System Model Use with Elision and Connecting Lines. ACM Transactions on Computer-Human Interaction. Accepted to be published.

3 Niemelä, M. Layout Arrangement and Pop-up Labels: Effects on Search. Scandinavian Journal of Psychology. To be resubmitted.

4 Niemelä, M. & Saariluoma, P. 2003. Layout Attributes and Recall. Behaviour & Information Technology 22 (5), 353-363.

1 INTRODUCTION

Computers are everywhere. At least, that is what a citizen of a modern day society may feel nowadays. The development of the computer from a simple calculator to an indispensable aid in everyday miscellaneous tasks has been incredibly rapid, taking only a few decades. Concurrently, typical computer users have changed from specially educated researchers and engineers to people of all ages who may not even be interested in computers and technology in general. To make computers accessible and their use profitable for all kinds of users is one major reason for research of human-computer interaction (HCI). The main goal of HCI research is to improve the usability and usefulness of computers (Landauer, 1997; Nickerson & Landauer, 1997). Usability and usefulness are closely related: more often a usable system is also more useful, at least by reducing the time needed to learn about the system.

HCI research has a practical value, which is shown by its wide distribution and good resources it receives (Preece, Rogers, Sharp & al., 1994; Nickerson & Landauer, 1997). The importance of HCI research is still growing as computers continue to permeate through human life. Pervasive and ubiquitous computing will pose new challenges to HCI as computers are brought into new life domains, entailing different forms of interaction. In particular, human-computer visual interaction, in which simple tasks in the interface are performed by merely ones moving eyes, will probably be in an increasingly important role in the future HCI (Tanriverdi & Jacob, 2000; Hornof & Halverson, 2003). Another exciting research direction is attentive user interfaces, which are able to adapt their behavior according to the user's current interests, measured as an engagement of attention mediated by eye fixations and movements (Baudisch, DeCarlo, Duchowski & al., 2003; Vertegaal, 2003; Zhai, 2003).

To respond to these challenges, HCI research integrates knowledge from different fields of science. "Diverse" would be the only word to describe HCI research. HCI research employs such methods as task analysis, user consultation, formative design evaluation, user testing, performance analysis, and scientific methods derived from fundamental research in psychology (Nickerson & Landauer, 1997). Accordingly, a theory of HCI can rather be conceived as a collection of theories and methodologies from different research fields, than an independent research domain.

In search of usability and usefulness, one subgoal of HCI is to gain a general understanding of the determinants of human behavior (Landauer, 1997). Psychological issues is one way to explain these determinants. By examining psychological functions of a user, it is possible to construct explanatory frameworks, within which HCI tasks and problems can be analyzed and solved. This approach is called *user psychology* (Oulasvirta & Saariluoma, in press; Saariluoma, in press). The importance of this kind of approach to HCI, although without using the specific term, has also been emphasized by others (Green, Davies & Gilmore, 1996; Scaife & Rogers, 1996; Landauer, 1997; Nickerson & Landauer, 1997). Cognitive psychology forms one explanatory framework, within which human-computer interaction tasks can be explicated. Other psychological frameworks can also be constructed, for instance, from social psychology to explain the social aspects of HCI tasks, and from personality psychology to explain the roles of individual characteristics, traits, and motivational issues in HCI. Figure 1 illustrates the relationship between some fields of psychology, the user psychological approach, and HCI research.

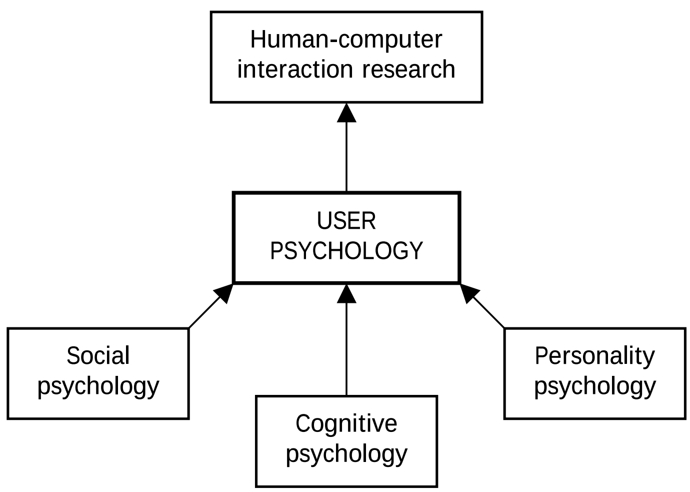

FIGURE 1 Within the user psychological approach, explanatory frameworks for human-computer interaction can be constructed. These frameworks can be derived from different fields of psychology.

1.1 Cognitive psychology in human-computer interaction research

Cognitive psychology is a field of research in psychology, which pursues the understanding of the mental structures and processes of a human, for instance, attention, memory, and the language process. In general, within the contemporary paradigm of cognitive psychology research, human cognition is analyzed in terms of different subsystems that are able to form, maintain, and convey internal representations of the world (Pashler, 1998). This paradigm is called the information processing approach.

Cognitive theory accounts have raised interest in the HCI research field since the first cognitive model, the model human processor, was developed in 1983 by Card and colleagues (Card, Moran & Newell, 1983). Cognitive explanations are still increasing in value for HCI and can be considered as vital in current HCI research (Gopher & Koriat, 1999). In HCI research, the role of cognitive psychology can be seen as two-fold, either studying the computer, or studying the user (Preece, Rogers, Sharp & al., 1994). First, cognitive researchers study and evaluate existing interaction systems and their design in such measures as efficiency and effectiveness in accomplishing tasks, and satisfaction of a user. This approach is called usability psychology, within which known psychological principles are used to solve practical problems (Oulasvirta & Saariluoma, in press; Saariluoma, in press). Usability psychological research has a practical value for designers, but has been criticized for often being obsolete because of the rapid change of systems (Landauer, 1997; Gopher & Koriat, 1999) and even useless, because the useful knowledge is common-sense knowledge (Green, Davies & Gilmore, 1996).

Second, cognitive researchers study the user, that is, the conditions and constraints set to computer design by human cognition (Preece, Rogers, Sharp & al., 1994). This approach aims to define psychological principles for HCI by providing the designers with design guidelines, empirical methods for testing the interface, and cognitive models to explain and predict user behavior with the interface. Within the user psychological approach, knowledge of human cognition is used to build theories and models of cognitive processes underlying human-computer interaction tasks.

The study of the user has several advantages for HCI research. First, the information about user behavior is probably tenable by nature. For instance, the basic visual cognitive structures and processes of a modern human being have been unaltered for approximately 4000 years (Donald, 1991). The basic cognitive system forms the fundamentals, in which all human cognitive behavior is based. This is not to say that understanding the cognitive fundamentals would explain all human behavior, however complex it would be, but to emphasize that user cognition is not a moving target in HCI research the way computer systems may be. The study of the user is likely to produce knowledge, or at least data, that will preserve its value. Second, cognitive psychology brings important theoretical constructions and methods for HCI research. Problems of interaction can be expressed as problems of information processing (Pollitzer & Edmonds, 1996; Proctor & Vu, 2002), and use established theories and methods to solve them.

Other advantages are more practical. The third benefit is that by applying useful theories of user cognitive processing, risks for arbitrariness in design decisions or slow design development by trial-and-error means can be reduced

(Lansdale, Scrivener & Woodcock, 1996). The fourth gain is that insight into the underlying cognitive system of the user may bring forth such innovations that are otherwise difficult to discover (Lewis, 1990; Lansdale, Scrivener & Woodcock, 1996). For instance, development of virtual environments, in which the user is able to see three-dimensional objects and space that do not exist in reality, are based on the knowledge of human visual processing (Wann & Mon-Williams, 1996).

The cognitive approach has been criticized for dislocating cognition from its context, and thus accomplishing data, which is not ecologically valid (Suchman, 1987). Specifically, basic cognitive psychology research has tended to be limited to narrow problems, taken from a few specific domains, and brought to the laboratory (Nickerson & Landauer, 1997). These arguments cannot be denied. However, cognitive theoretical research is continuously becoming more involved with real world-problems. This is due to such reasons as the shortage of funds for basic research, which makes re-orientation to more applied problems necessary, and indeed, the introduction of computers, with which many real-life tasks start to remind us of those examined in the laboratory (Gopher & Koriat, 1999). Cognitive psychology research may still not be able to extend to study cognition during highly complex tasks, such as social communication, emphasized by researchers of distributed cognition (Hutchins, 1995; Hollan, Hutchins & Kirsh, 2000). These two approaches can be seen operating at different levels in the continuum from an individual to social environments (Olson & Olson, 2003).

This dissertation applies the user psychological approach (Figure 2). Psychological functions underlying human-computer interaction tasks are studied in order to find such knowledge about the user that is robust to fast changes in computer systems and their interfaces. The specific problem issue to which the approach is applied is the spatial arrangement of objects in graphical interfaces. Spatial arrangement is an inherent part of a visual interface, and it is suggested to have important consequences on the cognitive behavior of a user, but research is limited in this area (Gittins, 1986; Halgren & Cooke, 1993; Tullis, 1997). In particular, the spatial arrangement has been shown to influence vision-based search (visual search) for menu items (Card, 1982; McDonald, Stone & Liebelt, 1983; Halgren & Cooke, 1993) and for information in more complex graphical interfaces, so called semantic spaces (Westerman & Cribbin, 2000). Therefore, user performance in visual search tasks is proposed to be an indicator of the quality of the spatial arrangement of interface objects. Furthermore, visual search is a task, which has been a subject of much cognitive psychological research (Neisser, 1967; Shiffrin & Schneider, 1977; Treisman & Gelade, 1980; Rayner, 1983; Treisman, 1988). Visual search thus appears to provide a safe and fruitful ground on which to construct a cognitive framework to explain the effects of spatial arrangement in graphical interfaces. Figure 2 illustrates how cognitive psychology provides explanatory frameworks to explain HCI tasks, and more specifically, visual search tasks in an interface (the large arrows). Explanations of these tasks help to analyze and understand practical problems in regards to the interface (the small downward arrow). Practical problems and their solutions, on their behalf, may feed the understanding of the interaction tasks (the small upward arrow).

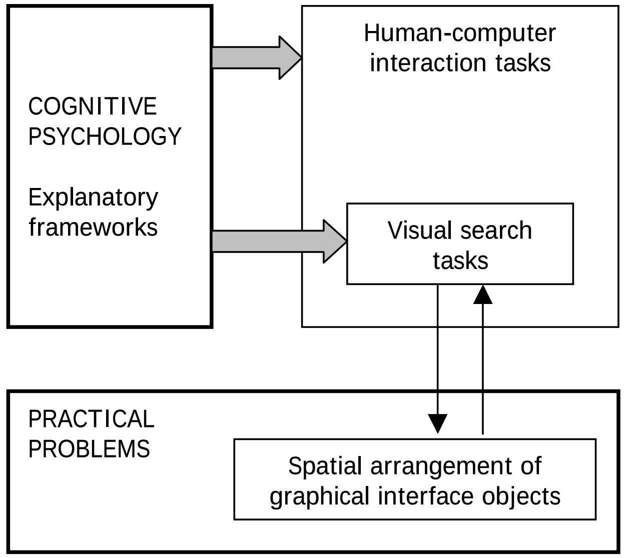

FIGURE 2 The research approach to HCI problems employed in this dissertation. The large arrows show how explanatory frameworks derived from cognitive psychology can be used to explain HCI tasks. In this dissertation, a visual search task is used to assess a specific problem in HCI, the spatial arrangement of interface objects. The small arrows show how understanding of an interaction task can be used to explain practical problems, which on their behalf may increase the understanding of the task.

1.2 Visual search in graphical user interfaces

In graphical interfaces, visual interface objects are spatially distributed on the screen. To locate a particular object, the user performs a visual search. Properties of an interface, such as the spatial arrangement of interface objects, influence the speed and accuracy of the search process. Thereby, the performance of users in visual search tasks can be used to indicate the quality of the interface in regards to visual usability, which is a part of the usability of the whole system.

Earlier research using visual search tasks to evaluate properties of graphical interfaces can be found in the domain of computational cognitive modeling. These cognitive models are computer programs that are built to cover specific aspects of human-computer interaction and thereby predict user behavior, especially timing, in regard to these aspects (Howes & Young, 1997; Ritter, Baxter, Jones & al., 2000). Computational cognitive models present one endeavor to integrate pieces of knowledge from narrow-focused basic psychological research to explain broader sets of phenomena (Lohse, 1991), in addition to the user psychological approach. Several cognitive models on visual search have been developed, with menus (Hornof & Kieras, 1997; 1999; Byrne, 2001) and with icons (Fleetwood & Byrne, 2001; Ehret, 2002).

The most essential difference between computational cognitive models and the user psychology approach presented in this dissertation is that computational cognitive models are built so that they simulate the user as well as possible at the level of overt behavior, so that the model could replace the user, for instance, during test situations (Ritter, Baxter, Jones & al., 2000). Therefore, only those aspects of the behavior can be modeled that are enough for the model to mimic the user. The models are thus cognitively incomplete. In addition, some cognitive aspects of behavior are difficult to formalize within a computer program. For instance, perception of empty space, that is, the space between the object is a problem for current models (Ritter & Young, 2001). Empty space and meaning devoted to it, however, play an important role in spatial arrangement of interface objects.

The user cognitive psychology approach seeks rather to increase understanding of the covert cognitive functions underlying the overt behavior, than to build computational models to replace the user. In particular, the effects of a spatial arrangement of interface objects on visual search are of interest in this dissertation. None of the cognitive models listed above is able to account for arrangemental aspects in interfaces and their effects on the user's search behavior. Some related studies have been carried by Hornof (Hornof, 2001; Hornof & Halverson, 2003), who has modeled visual search among grouped objects with and without category labels. Hornof's work emphasizes the importance of relevant spatial arrangement in graphical interfaces, but does not directly test the effects of grouping on search. Other important work has been done by Ehret (2002), who has proposed a computational cognitive model of location learning in an interface due to repeated interactions (search tasks) with the interface objects. This model takes no spatial arrangement of objects into account either. In this dissertation, more profound understanding of the cognitive processes underlying visual search task is developed, especially to explain spatial arrangemental influences on search. Location learning is included as a vital cognitive component process in the search behavior of a user.

1.3 Graphical user interface

Visual displays are and probably will be, for some time, the predominant means to communicate from a computer to a user (Preece, Rogers, Sharp & al., 1994; Nickerson & Landauer, 1997), thus making the interaction between the user and the display an essential object of study in HCI. The interaction is accomplished via a computer hardware interface (e.g., the keyboard and the mouse) and the computer software interface (e.g., graphics, windows, and icons) (Chalmers, 2003). The focus here is on the software interface, specifically, on graphical user interfaces. In the first place, graphical interface refers to so called WIMP interfaces, WIMP being an abbreviation for Windows, Icons, Menus, and Pointing devices. Graphical interfaces also refer to more generic graphical displays, for instance, web pages, graphical overviews of hypertext, and information visualizations, all in which pieces of information are spatially distributed on the screen.

In graphical interfaces, much information is "in the world" (Larkin & Simon, 1987; Norman, 1988; Gray & Fu, 2001), in the form of visual interface objects such as windows, icons, and menus. Information or knowledge in the world refers to that the user does not need to recall some information (e.g. a command name) by rote, but can rely on recognition of the external representations of that information (e.g. a menu label). Humans have great recognition memory for visually presented objects (Shepard, 1967; Standing, Conezio & Haber, 1970). The difference in the ease of use is significant compared to command-based interfaces, with which recall of textual commands by rote is required to perform even the simplest tasks.

An essential attribute of a graphical interface is the layout, or the spatial arrangement of interface objects. The visual features in graphical displays encourage the user to explore the visual relationships and organization, which in turn influences the retention of information, and thus learning during interaction with the system (Gittins, 1986). Interface design guidelines (Marcus, 1995; Galitz, 1997; Tullis, 1997) commonly recommend such an arrangement in which semantically (or logically or functionally) related interface objects are grouped, in order to facilitate the user's interaction with the interface. Suggested influences of this kind of semantic organization in spatial terms on user behavior seems to be vital. The arrangement affects how easily the user is able to extract information and even how the user semantically interprets the information on the display (Tullis, 1997). An appropriate layout of menu objects can help the user to develop a more appropriate conceptual model of the system (Halgren & Cooke, 1993). First and foremost, the arrangement affects how well the user is able to visually locate currently needed information in the interface, which on its behalf influences other interactions that visual search is part of (Card, 1982; Parush, Nadir & Shtub, 1998; Hornof, 2001).

Tullis (1997) argues, however, that the spatial arrangement of graphical interface elements is empirically understudied. There is no general technique in wide use for measuring grouping, and consequently, grouping is often confounded with other variables, such as the amount of information on the screen. Some models or programs for evaluating screen layouts exist, validated by data collected from real users (Tullis, 1997; Parush, Nadir & Shtub, 1998). The models have demonstrated that the grouping of objects in the interface is one of the best predictors of search time in the interface. A critical fault in these models is that they only assess visual grouping and ignore semantics of the screen elements.

Many earlier studies considering arrangemental aspects in computer interfaces have been carried out on character-based screens and read-only screens (Parush, Nadir & Shtub, 1998). Therefore, their relevance to graphical interfaces in which objects may distribute across the screen in a misaligned manner can be questioned. The development of three-dimensional interfaces may also bring such arrangemental issues that cannot be directly resolved by results from two-dimensional, character-based screens. For these reasons as well, the study of spatial arrangement of interface objects has importance in modern graphical interfaces.

In conclusion, there seems to be a lack of study considering the arrangement of information in graphical interfaces. This dissertation provides an attempt to study the arrangemental effects from the viewpoint of user psychology. The goals if this dissertation are two-fold: (1) to analyze the effects of spatial arrangement of interface objects on a user's visual search, and (2) to seek understanding of the cognitive functions underlying these effects. The first goal is practical by nature, providing information that can be applied to interface design. The latter goal is more theoretical, as it involves explaining the effects spatial arrangement on visual search on the basis of what is known about the user. Knowledge about the relevant cognitive functions is presented in the form of a (non-computational) cognitive model of visual search.

1.4 Structure of the thesis

The thesis starts with a review of relevant theoretical literature about human cognition in the second chapter. A visual search task is defined in terms of visual attentional and perceptual processes, and related memory processes. A cognitive model of visual search is built in which the success of a visual search task is determined by two factors, the visual environment and the observer's search schema. The search schema holds search-relevant information about the target of search as well as learned aspects of the display. Here the learning of locations is of interest. The cognitive model of visual search is put into context of graphical interfaces and used as a framework to explain findings of earlier studies concerning the effects of spatial arrangement on search in graphical interfaces. It is shown that there is a need for more detailed analysis of the effects of spatial arrangement in visual search. In particular, semantic organization needs to be unconfounded from perceptual grouping by spatial proximity to deeply understand the attention process as well as the related memory processes underlying the visual search task.

In the third chapter of the thesis, research questions considering the independent and interactive effects of semantic organization and spatial grouping on search and location memory are formulated.

The summaries of four experimental study papers form the fourth chapter of the thesis. The results demonstrate that both semantic organization and spatial grouping play a role in facilitating visual search. The findings are discussed in regards to the cognitive model of visual search, and the model is revised.

In the fifth chapter of the thesis, the model of visual search is discussed. It is argued that the model provides the first such cognitive approach to visual search that is also able to explain semantic aspects of a graphical interface. It is also argued that the model has the potential to explain visual search in more complex, innovative interfaces, such as used in the domain of information visualization. The contributions and limitations of the user cognitive psychology approach are also discussed.

The sixth and final chapter of the thesis presents the conclusions.

2 A COGNITIVE MODEL OF VISUAL SEARCH

This dissertation seeks to establish some psychological issues that determine user behavior in human-computer interaction, in particular, in tasks that employ visual search. The practical problem motivating this approach is the spatial arrangement of interface objects in graphical user interfaces, and how the arrangement affects a user's visual search. The problem sets constrains for the cognitive issues that must be considered. In attempts to use science to explain practical problems, theoretical issues should be chosen so that they are useful for solving the problem (Lansdale, Scrivener & Woodcock, 1996). This means that only those cognitive aspects are included that are necessary for the explanation. With this in mind, a theoretical model of cognitive functions underlying a visual search task is provided, within which the effects of spatial arrangement of interface objects on visual search can be explained. To start working towards that purpose, the explanatory cognitive functions as well as the constrains set by the problem are first defined.

The critical cognitive function behind the visual search task is visual attention (Neisser, 1967; Shiffrin & Schneider, 1977; Treisman & Gelade, 1980; Rayner, 1983; Treisman, 1988). Therefore, visual search must be approached by studying the visual attention process, and related cognitive processes. The most relevant function of attention in regard to visual search is attentional selection of part of the visual information in the environment for further processing, whilst rejecting other information from access to that process.

Two important issues that influence attentional selection is the visual environment, and the observer's knowledge (Neisser, 1967; Johnston & Dark, 1986; Egeth & Yantis, 1997; Chun & Jiang, 1998; Shinoda, Hayhoe & Shrivastava, 2001; Wolfe, Butcher, Lee & al., 2003). With the observer's knowledge, it is referred to those mental representations of the observer that are directly related to a search task, or more specifically, to attentional scanning in the visual environment. Search-related knowledge forms a search schema. A schema is a general cognitive structure that organizes information based on past experiences, and guides attentional scanning in the environment (Neisser, 1964; 1967). A search schema, as it is defined here, contains information about the target of a search and a search strategy to specifically guide attention.

The visual environment in the graphical interface domain is the display. The display may refer to an "individual frame of information" (Tullis, 1997, p. 503), such as a window or dialog box. Here the display mostly equates to the screen, and these terms are used as synonyms. The display consists of visual interface objects, such as icons, labels, and buttons, distributed in the display space. The objects have attributes, for example, color, form, location, and meaning that the observer is able to extract by means of a visual perception. The object attributes function as the basis of selection, and their value for ease of search may differ (Rayner, 1983). However, in this dissertation the interest is not in object characteristics, but in the attributes of the display at the level of groups of objects. For instance, different groupings of objects may have implications on visual search (Treisman & Gelade, 1980; Treisman, 1982; Duncan & Humphreys, 1989).

The specific display attribute of interest here is the spatial arrangement of interface objects. Spatial arrangement includes such issues as alignment and indentation (Tullis, 1997). Here spatial arrangement is defined as semantic organization of interface objects, which is commonly recommended in interface design guidelines (Marcus, 1995; Galitz, 1997; Tullis, 1997). Semantic organization means that semantically related objects (for instance, members of the same semantic category) are placed spatially close to each other. In a semantically disorganized display, there is no immediate spatial relationship between related objects. What is often ignored, but what is important from the viewpoint of the cognitive explanation, is that semantic organization is usually accompanied with perceptual grouping by the proximity of objects (spatial grouping). The user should be able to assume that the elements within a group relate to each other semantically (Tullis, 1997). However, it will be shown that there are reasons to keep these two arrangemental aspects as separate factors affecting search, at least in regard to the cognitive explanation of the search.

The problem of semantic organization poses constrains on what the target of the search is. The main goal of a search is to locate the desired information, a predetermined target. The properties of the target that make it possible to discriminate the target from irrelevant background objects, form the selection criteria. All attributes in the display can function as selection criteria: visual, semantic, locational, to name but a few. The interest here is in semantic attributes as selection criteria, more specifically, textual names or labels of interface objects. The reason for this is simple: only semantic interface objects allow semantic organization to be implemented in the interface.

Visual attributes, such as color and form, are also of importance in graphical interfaces, as seen in the popularity of icons. Users may even find icons more useful in interface than labels (Wiedenbeck, 1999). Search for semantic labels is still of significance. Even graphical user interfaces contain lots of labels, which are especially important for inexperienced users to learn from (Wiedenbeck, 1999). Icons can be similar, but the label of an object usually makes it unique. Icons without labels rarely exist, often they are accompanied with at least pop-up labels, visible only when the user makes some specific action. Furthermore, it has been shown that icons do not necessarily improve task performance compared to a text-based interface (Benbasat & Todd, 1993). In addition, label search is necessary in web pages, where links are mainly in a textual form. Graphical elements can be used, but there is no standard for how they should be applied, therefore their use may not be without problems.

In order to explain the effects of semantic organization on visual search, a point that must be taken into account is a user's learning. More specifically, when a user performs several searches in the interface, the locations of objects are gradually learnt, which makes the search more efficient (Card, 1982; McDonald, Stone & Liebelt, 1983; Green & Barnard, 1990; Halgren & Cooke, 1993; Ehret, 2002). This requires, of course, that the objects are positionally constant. Positional constancy means permanency of locations of objects over time and across multiple parallel displays or successive displays, for instance, in hyperlinked web pages (Woods, 1984; Norman, Weldon & Shneiderman, 1986; Ozok & Salvendy, 2000). In addition to semantic organization, positional constancy of interface objects is commonly recommended in many design guidelines relating to screen real estate (Marcus, 1995; Galitz, 1997; Tullis, 1997).

The general constraints for constructing a cognitive model for a visual search task have now been defined. The constraints include the following points:

- Visual search is analyzed as a visual attention process.
- The visual environment on which attention operates is defined as the computer display (screen).
  - The specific interface objects of search are semantic objects (labels).
  - The specific display attributes of interest are semantic organization and spatial grouping of objects.
- Location memory process is included in explaining visual search.

A user's visual search in a graphical interface is thus modeled as a visual attention process scanning the display and selecting interface objects defined by semantic target criteria. The attentional scanning process is guided by a search schema, which represents the user's search-related knowledge, target information and a search strategy. The visual search is influenced by the user's learning of the locations of objects, therefore, location memory processes must be included in the search model. These aspects of the visual search process are reviewed next in more detail. The review is divided into three parts, of which the first reviews some empirical and theoretical aspects of visual attention that clarify the characteristic of this basic cognitive function. The second part considers the attentional selection process and how it is guided by the search schema, and how spatial arrangement of interface objects might influence selection and guidance. The third part deals with the learning of object locations and how this affects the search schema. In addition, the effects of spatial arrangement on location learning are considered. The final part proposes a cognitive model of visual search, added with a discussion about the spatial arrangemental effects on search.

2.1 Visual attention

Attention is a complex cognitive function, or perhaps functions, that is not completely understood, but a few disagree with that selection of information received by our senses is an attentional process (Neisser, 1967; Johnston & Dark, 1986; Allport, 1992; Schneider, 1993; Pashler, 1998). Visual attention selects task-relevant information from the input of the eyes, and is thus closely interlinked with visual information processing.

Visual information processing proceeds from extracting simple features to the construction of complex objects and grouping, and meaning (Neisser, 1967; Pomerantz, 1981; Duncan, 1984; Treisman, 1988). During initial processing, discrimination between gross physical features, such as color, location, and orientation, is made. Extracted features are perceptually segmented into groups, objects, and words, which can be further processed to meaning and identity. In regards to visual attention, this processing of visual input takes place at two levels. Initially, information across the entire visual field is processed in parallel, without the involvement of attention; attending to a part of the visual information makes the information to be selected for more detailed, attentive processing (Broadbent, 1958; Neisser, 1967; Treisman, 1988; Theeuwes, 1993).

In one's own experience, focusing of the visual attention and the fixation of the eyes appear to go hand in hand. However, it is possible to attend to an object or location that is not fixated (Helmholtz, 1866/1925, cited in Humphreys & Bruce, 1989; Posner, 1980). Attentional orienting can be divided into overt actions, such as head and eye movements, and covert orienting, available to the attending person only (Posner, 1980). In studies of attentional scanning behavior in real visual scenes and user interfaces, eye movement can be tracked to indicate attentional shifts and selection (Melcher & Kowler, 2001; Shinoda, Hayhoe & Shrivastava, 2001; Hornof & Halverson, 2003). The main point that must be made is that eye movement and fixation is the outcome of attentional orienting processes, not the opposite (Humphreys & Bruce, 1989; Theeuwes, 1993; Pashler, 1998). The visual attention process, not eye movements as such, provides the primary explanation for visual search.

In some conditions, functioning of visual attention can be conceived best in spatial terms, for instance, with a spotlight or zoomlens metaphor (Posner, 1980; Posner, Snyder & Davidson, 1980; LaBerge, 1983; Eriksen & Yeh, 1985; Eriksen & St James, 1986; Treisman, 1988). When the observer focuses attention on a spatial location in advance, following visual information at that location is processed more efficiently than if the attention was focused elsewhere (Posner, Snyder & Davidson, 1980; Awh, Jonides & Reuter-Lorenz, 1998). Focusing on a visual object in mind does not seem to facilitate the processing of information at the location of the object when it appears. It is also difficult to attentionally focus between two spatially separate locations (Posner, Snyder & Davidson, 1980). Spatial division of attention is possible, however, if the scattered objects group by a salient visual feature, such as color (Friedman-Hill & Wolfe, 1995) or common movements (Driver & Baylis, 1989).

The observer is able to attend to spatial regions of different size, from small to large, but this seems to influence the resolution of visual details that can be extracted from the attended region (Eriksen & Yeh, 1985; Eriksen & St James, 1986). From a large spatial field, only gross physical differences can be discriminated. For fine discriminations and identification of individual objects, high resolution is required, and the attended field becomes small. There is some evidence that attentional focusing proceeds from a global level to local details for new visual input (Navon, 1977).

An observer can focus visual attention on a location, but also attending to objects or groups of objects appears to be possible (Neisser & Becklen, 1975; Rock & Gutman, 1981; Duncan, 1984; Duncan & Humphreys, 1989; Egly, Driver & Rafal, 1994). For instance, Neisser and Becklen (1975) showed that observers, who monitored one of two superimposed videos presenting different episodes, had difficulties in monitoring the two videos simultaneously. The observers were able to attend to one of the videos but could not recall unexpected events from the other video. Furthermore, simultaneous processing of two visual attributes is easier when the attributes belong to the same object compared to that they belong to two different objects, independent of the spatial distance between the attributes (Duncan, 1984). These findings indicate that visual selection is not defined merely in spatial terms. The observer is also able to control the level at which attention is focused, to an individual object or groups of objects at different levels of grouping (Pomerantz, 1981).

Visual selective attention thus seems to function in a two-fold manner, sometimes best explained within spatial models, sometimes within object-based models. It seems plausible that these views are not exclusive. In the early processing of visual input, spatial direction would dominate attention, whilst in the later process when the scene segmentation is proceeded to object construction, the observer would be able to select among the objects (Humphreys & Bruce, 1989; Awh, Dhaliwal, Christensen & al., 2001). This also indicates that different perceptual groupings take place at different levels of perceptual and attentional processing. For instance, spatial grouping may influence distribution of attention at an early perceptual phase, whilst more complex groupings, such as grouping by common movement of objects would occur after the objects have been constructed in the perceptual process (Treisman, 1982; Driver & Baylis, 1989). This two-fold view underlies the current model of visual search.

2.2 Visual search for a semantic target

In visual search, the main goal of the observer is to select the target, that is, to discriminate the target from background objects. The discrimination is done on the basis of some selection criterion or criteria that define the target properties in the internal search schema of the observer. The criteria can include any attribute that the observer can extract from the visual input, such as color, form, or size, but also meaning or identity. As the perceptual analysis of visual input goes along, extracted information is used to distinguish and reject background objects by comparing it to the selection criteria, and to pick up the target (Neisser, 1964).

Consequently, the more attributes the target and background objects share, the more difficult it is to discriminate between them (Duncan & Humphreys, 1989). If the selection criteria consists of gross physical features such as color or object size, target discrimination can be done at an early level of visual processing, in some cases even preattentively, parallel across the visual display (Neisser, 1967; Treisman & Gelade, 1980; Treisman, 1982; Lamy & Tsal, 2001). This is one of the reasons why icons are expected to be easier to search than words. Words are more similar to each other at the level of physical features than icons, which usually employ different colors and forms.

When the target of visual search is semantic, that is, the display consists of written words, attention may need to be involved. At least word recognition so that the meaning of a word can be determined appears to require that attention be focused on the word (Stolz & McCann, 2000; Brown, Gore & Carr, 2002). However, when looking for a given target word, search can proceed at the level of visual features. Irrelevant words can be rejected by their clearly distinguishing features, such as word length and initial letters (Neisser & Beller, 1965; Bruce, 1981). Depending on the spatial distance between words, the observer can examine one or more words at one fixation.

A target defined by semantic criteria allows selection at two levels (at least), selection by the identity and selection by the higher-level semantic category of the object. For instance, a word 'thesis.doc' can be selected on the basis that it refers to a thesis writing, or on the basis that it belongs to the class of documents. Extraction of semantic category information from familiar written words appears to occur quite early, either in parallel or before the identity process (Neisser, 1964; Jonides & Gleitman, 1972; 1976). When the observer searches at the semantic level, words are not necessarily fully read or processed to the meaning, but only enough to be rejected. Accordingly, in some conditions, category information can be a very efficient cue in discriminating a semantic target from background objects that belong to other semantic categories (Jonides & Gleitman, 1972; 1976; Henderson & Chard, 1978; Saariluoma & Kujala, 1996). This "category effect" is, however, quite subtle, and easily obscured by gross visual features, such as differences in word length (Bruce, 1981).

Furthermore, selection on the basis of a semantic category is not as efficient as selection by color or other physical criteria that is extracted early in the visual process (Sperling, 1960; von Wright, 1970). Some evidence exists that through prolonged practice, selection by semantic category can be enhanced, as well as selection at the level of a visual identity (Shiffrin & Schneider, 1977; Fisk & Schneider, 1983). This automatization of selection requires conditions that keep the selection criteria and the background constant for hundreds of repeated searches.

It seems that semantic organization does not directly influence the attentional selection process. However, it may influence the search strategy guiding the attentional scanning in the display. If the objects group to semantic categories, they can be spatially organized accordingly, so that members of the same category are placed close to each other. When visually similar objects are spatially grouped, search can be performed at the level of groups, selecting and rejecting all objects in a group together until the target group is found (Treisman, 1982; Duncan & Humphreys, 1989). It seems plausible that this principle applies to semantic groups as well, so that the observer is able to scan groups of semantically related objects, and either reject or accept the groups on the basis of the semantic category the group represents. Then the observer can limit further search to the objects within the accepted group. Semantic organization thus allows the observer to use a more efficient search strategy that guides attentional scanning in the display. Supporting this, it has been shown that users make less eye fixations when objects are organized in a useful hierarchy (e.g., semantically organized), than if the arrangement is random (Hornof & Halverson, 2003).

Semantic organization of objects often go along with spatial grouping, that is, perceptual grouping by spatial proximity (Tullis, 1997; Parush, Nadir & Shtub, 1998). Spatial grouping is a basic means by which the perceptual system organizes incoming visual information into units on which visual attention may operate (Neisser, 1967). Grouping by proximity is not the strongest of the perceptual grouping principles (Palmer, 1992), but it is among the fastest. For example, it can be perceived faster than grouping by the similarity of objects (Ben-Av & Sagi, 1995; Han, Humphreys & Chen, 1999). Spatial grouping is thus supposed to have an important role in visual search. For instance, a target letter was detected faster if homogenous letter-like background elements were grouped by proximity than if they were not grouped, even if there was a smaller number of them (Banks & Prinzmetal, 1976). Furthermore, in a spatially grouped display, observers are able to fixate from group to group, traversing white space within single eye movement (Hornof & Halverson, 2003). It may be that without spatial grouping, semantic groups are difficult to scan at group level, because semantic category information does not allow perceptual grouping, similarly to physical features such as color or size (von Wright, 1970), that would help to direct attention between groups.

Spatial grouping is non-semantic in nature. It does not depend on the meaning of objects in the way a semantic organization does, but any kind of objects can be spatially grouped. This also suggests that semantic organization and spatial grouping might have independent influences on visual search. When implemented in parallel, they work in concert to facilitate discrimination of object groups so that a search can proceed at the level of groups instead of individual objects, until the target group is found and the search must continue from object to object. To fully explain the effect of semantic organization on visual search, the role of spatial grouping must be taken as an independent factor. Earlier studies that would unconfound semantic organization and spatial grouping in a search could not be found. Therefore, a need for empirical research is posed.

2.3 Memory for locations and visual search

During interaction with an visual interface, the user learns the location of the interface objects, and can capitalize the memory for locations in generating a search strategy. For instance, if an experienced Windows user wants to accept some action in the interface by mouse-clicking the "OK" button, the search strategy might be constructed on a memory that the target is located at the bottom of the current frame. Empirical evidence for the learning of object locations facilitates search in graphical interfaces can be found for menu objects and icons (Card, 1982; McDonald, Stone & Liebelt, 1983; Green & Barnard, 1990; Halgren & Cooke, 1993; Ehret, 2002).

Location memory is clearly useful in guiding visual attention. On the basis of location memory, attention can be shifted efficiently to the target location instead of scanning groups or objects until the target is found (Shaw & Shaw, 1977; Shaw, 1978; Posner, Snyder & Davidson, 1980; Miller, 1988). Furthermore, experienced interface users tend to anticipate object locations and can fixate even before the objects to be searched have appeared (Hornof & Halverson, 2003). Anticipating the location of the target enhances perceptual processing of the target that follows at that location (Posner, Snyder & Davidson, 1980; Awh, Jonides & Reuter-Lorenz, 1998). The way the memory for locations guides visual attention may also be quite complex in nature. People are able to learn how a certain target is located within a certain spatial configuration, and use this knowledge to search for the target more efficiently, even if they are not aware of their knowledge (Chun & Jiang, 1998; Jiang & Chun, 2001; Peterson & Kramer, 2001; Chua & Chun, 2003).

The influence of the attention process in location learning is less clear. It has been shown that it is possible to recall the location of objects although there has been no intention to learn or even awareness of the locations at the time of attending to the objects (Mandler, Seefmiller & Day, 1977). There is also evidence that locations of non-attended objects can be remembered (Hasher & Zacks, 1979; Ellis, 1990; Andrade & Meudell, 1993). However, focusing attention on objects improves memory for their locations (Naveh-Benjamin, 1987; 1988; Newby & Rock, 1998; Tsal & Bareket, 1999). Also non-conscious learning of a spatial configuration seems to be modulated by attending to the configuration, as the arrangement of non-attended objects has no effect on a search (Jiang & Chun, 2001). In line with these results, Ehret (2002) has proposed that location learning takes place as a by-product during the user's interactions with interface objects, and is thus a gradual process. Learning does not need to be intentional. This indicates that repeated visual searches in the same display would cause the learning of the location of the attended objects, even if users would not pursue it.

Location learning is not, however, a necessary outcome of positional constancy of interface objects. According to Ehret (2002), users learn object locations when it is the least-effortful interaction strategy in the interface to do so. There is a trade-off between cost of perceptual-motor operations (search) and memory operations (learning and recalling locations) (Gray & Fu, 2001; Melcher & Kowler, 2001). If objects are very representative, a search is easy on the basis of appearance, and location learning takes place to a lesser degree. The more visually complex, abstract, or non-meaningful the appearances of the objects to be searched are, the more the user tends to rely on memory for the locations of the objects than on recognition of their appearances during search (Blankenberger & Hahn, 1991; Moyes, 1994; Ehret, 2002). Semantic labels can be considered as representative, but not visually representative as shown by Ehret (2002), and therefore location learning is expected to occur due to repeated searches in the display.

In regard to the aim to explain the effects of semantic organization on visual search, particularly interesting in location learning is that it interacts with the organization in the display. The results of menu studies comparing semantic and random organization showed that after an extensive number of search trials with constantly positioned menu objects, the differences in search speed between the organizations disappeared (Card, 1982; McDonald, Stone & Liebelt, 1983; Halgren & Cooke, 1993). This indicates that as location memory for a certain display develops, a more detailed search strategy can be built to guide attentional scanning in the display, instead of studying objects or groups of objects in a random order. However, it takes extensive practice – hundreds of searches in the menu studies – to learn locations so well that the effect of spatial arrangement on the search disappears. Real users do not normally receive that extensive training (Paap & Cooke, 1997).

Investigating the nature of location memory, in addition to the visual attention process, is thought to be useful in trying to understand the role of semantic organization in the visual search. In particular, the separation of semantic organization from spatial grouping is interesting in regards to the interaction between location memory and visual attention. It has been suggested that object location memory can be distinguished to spatial memory for mere locations, and memory for associations between objects and locations (Postma & De Haan, 1996). Furthermore, it has been proposed that the attentional guidance by location expectations includes two component processes, identity-independent spatial location component and identity-specific location component (Miller, 1988). The identity-independent component guides the attention towards a probable location of the target and is supposed to facilitate the processing of any object at that location. This process is the basis for the "spotlight" characteristics of visual attention (e.g. Posner, 1980). The identity-specific component of spatial attentional guidance would show increased sensitivity to a particular target at that location.

It seems natural that the two location memory components (Postma & De Haan, 1996) and the spatial attentional guiding components (Miller, 1988) would be integrated within the search schema to explain location learning effects on a search. Memory for mere location would guide the attention towards the probable location of the target, and associative memory for a certain object in the location would bias the attentional selection towards that object. This idea may help to explain the separate effects of semantic organization and spatial grouping on a search when the location memory is also involved.

2.4 Summary

A cognitive model of visual search, constructed on the basis of the literature review, is illustrated in Figure 3. Within this cognitive model, visual search for a semantic interface object (label) is explained in terms of the visual attention process, guided by the visual information extracted from the environment (the display) and the observer's search schema. One component of the search schema is the target information, required to discriminate and pick up the target among background objects. During a search, attended objects are compared to target information, and the result of this matching process (the two-head arrow) makes the search stop or continue. Another component of the search schema is a search strategy guiding visual attention. The search strategy can be based on memory for locations acquired during earlier searches or other experience. In addition, the semantic organization of objects in the display influences the search strategy.

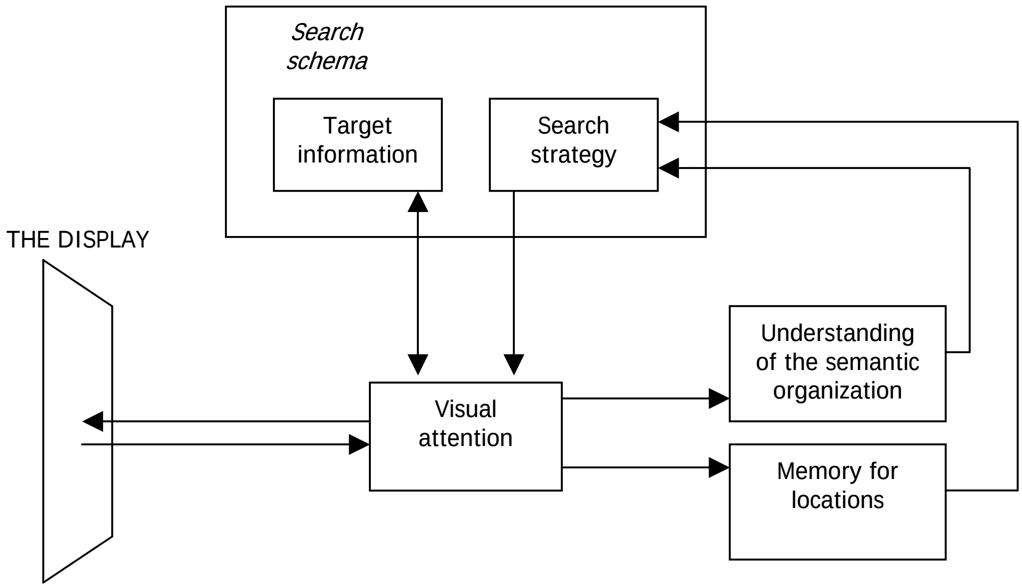

FIGURE 3 A cognitive model of visual search. The visual attention process scans visual information in the display. The attention is guided by a search schema, containing information about target and a search strategy. During the search, the observer learns aspects of the display that can be used to modify the search strategy for a more efficient search. These aspects include the understanding of semantic organization and locations of the objects in the display.

It has been shown that semantic organization of interface objects affects visual search (Card, 1982; McDonald, Stone & Liebelt, 1983; Halgren & Cooke, 1993), and one purpose of this dissertation is to clarify how this happens at the level of cognitive processes. On the basis of the literature review, the effects of semantic organization on visual search are explained by showing that semantic organization allows visual attention to scan the display at the level of object groups, rejecting whole groups until the target group is found; from there on, a search proceeds from object to object. In a disorganized display, attention scans objects one by one as no useful groups are available. These effects are mediated by the search strategy of the observer.

It is noted, however, that semantic organization and spatial grouping of objects have often been confounded in search studies. Spatial grouping is shown to be independent from semantic organization, and so far it is not clear how it affects visual search for semantic objects without semantic organization. This poses a need to empirically study the unconfounded influences of spatial grouping and semantic organization on visual search for a semantic target.

An experienced observer's search strategy may also be based on memory for object locations. This requires that the objects in the display are positionally constant across time, that the observer interacts with the objects, and that the search process is not too easy, for instance, because of very representative objects. The search strategy constructed in the location memory will gradually overrun attentional scanning between groups or objects so that attention can be efficiently guided towards the target object. Therefore, after practice, search in a randomly organized display will be as efficient as in a semantically organized display.

Due to that the location memory may need extensive practice to develop, it can be asked whether a semantic organization on its behalf is able to facilitate location learning. Furthermore, because semantic organization and spatial grouping must be separated, there is a need to study their independent effects on location learning as well as on visual search.

3 RESEARCH METHOD AND QUESTIONS

This dissertation endeavors to explain the effects of semantic organization of interface objects on visual search within the theoretical framework delivered from cognitive psychology. The review in the previous chapter revealed that in order to understand the cognitive functions underlying the effects of semantic organization, spatial grouping must be separated from semantic organization. For that purpose, two rigorous experimental studies were designed to assess these factors, one focusing on search and the other on location learning. Before that, however, the influences of semantic organization on visual search were investigated in two other studies, in which the visual search process, as well as the semantic organization effects on it, were attempted to capture in more applied research settings. The results of these first studies raised the importance of semantic organization as well as the role of location learning in visual search, which were then assessed in the latter studies.

To acquire reliable information about the effects of semantic organization on visual search, the research method used in all four studies follows the experimental paradigm of cognitive psychology. Within the experimental paradigm, the purpose is to abstract cause-and-effect relationships by systematically varying some variables and observing the changes in other variables in controlled settings (Christensen, 1997). Well-controlled conditions allow for the making of strong and reliable inferences of the relationship between manipulated and observed variables. The main problem of an experimental paradigm concerns artificiality and simplicity of issues that can be properly experimentally tested because of the need for rigid control. Thus, extra care must be taken in generalizing the results acquired in controlled experimental settings. In the applied study, the requirement of strict control was sacrificed to some extent to better ecological validity in study conditions.

In cognitive psychology experiments, researchers make inferences of human cognition by systematically manipulating some variables (while keeping irrelevant variables constant) and measuring or observing resulting behavioral changes. The measures concern more often than not speed of performance (reaction time) and accuracy of performance (errors), which are also the main measures used in the experiments of this dissertation. An inevitable problem here is the indirectness of measuring the internal processes, as there is no way to directly assess the cognitive processes ongoing in the human mind. In spite of these difficulties, an experimental approach has proved to be useful also in cognitive research, providing reliable results over time and solutions to practical problems (Eysenck & Keane, 1995; Christensen, 1997).

The studies in this dissertation consist of visual search tasks performed during different visual displays. In the tasks, individually tested participants searched and recalled locations of different interface objects. The search was always based on a semantic attribute of the target (the textual label). The manipulated display attributes included semantic organization, spatial grouping by proximity, and positional constancy of objects. The measures consisted of search time, search accuracy, location learning time, location recall time and location recall accuracy. Not all factors and measures were included in all studies.

Within the four experimental studies, reported in four articles, two specific research questions are assessed as follows:

1 How do semantic organization and spatial grouping of objects influence the user's visual search?
   - Article I
   - Article II
   - Article III

2 In the case of positional constancy, how do semantic organization and spatial grouping influence the user's memory for the locations of objects?
   - Article II
   - Article III
   - Article IV

The four studies are described separately, presenting their empirical setting, main results, and their relationship to the research questions as well as their limitations in this function. At the end of this chapter, the integrated results are discussed in regards to the cognitive model of visual search.

The contributions to writing the four articles divide in the following way. In the first article, the author was the main writer and Jukka Saarinen contributed by partly writing the theoretical background section of the article, and by giving advice on the design of the experiments.

There is equal contribution from all three authors in the second article. The author's responsibility was to write the psychological background section for the article, to design and carry out the experiments together with Jouni Huotari, to analyze and write about the results of the experiments, and to partly write the discussion section.

In the third article, the author was the only writer.

In the fourth article, the author was the main writer and Pertti Saariluoma contributed by giving advice in the design of the experiments and by writing parts of the introduction and discussion sections.

4 OVERVIEW OF ARTICLES

The effects of semantic organization on visual search are examined in four experimental studies, which are reported in four articles. The overviews of the articles consist of summaries of the experimental designs, the main findings, and short discussions of the findings in regards to the research questions. In addition, the limitations and validity issues of the studies are discussed. The findings are summarized at the end of the chapter and discussed in the context of the cognitive model of visual search.

4.1 Article 1: "Visual Search for Grouped Versus Ungrouped Icons in a Computer Interface"

Niemelä, M. & Saarinen, J. 2000. Visual Search for Grouped Versus Ungrouped Icons in a Computer Interface. Human Factors 42 (4), 630-635.

In this study, an investigation on whether the spatial arrangement of icons has influence on icon search was carried out. In particular, semantic organization of icons was compared to random arrangement of the icons. The semantic category of icons was determined by their visual appearance (similarity), differently from menu studies in which categorization depends on the user's knowledge. In addition, the semantically organized icons were compared to similarly arranged textual labels. In this condition a category name replaced the icon picture.

The experimental task was to search a target icon among distractor icons. Search time and accuracy were measured. The number of distractor icons on the display varied, thus making it possible to inspect search speed as a function of the number of distractors. The steepness of this slope can be used to depict the difficulty of visual search (Wolfe, 1998). A total of 14 participants were tested, and all of them attended to all three conditions (within-subjects design).

The main finding was that the semantic organization of icons significantly reduced the search time compared to the random organization. In addition, the increasing number of background objects slowed the search less with semantically organized icons. This study thus confirms and extends the results of earlier studies concerning semantic organization in menu search (Card, 1982; McDonald, Stone & Liebelt, 1983; Halgren & Cooke, 1993) to an essential element of graphical interfaces, icons. This has not been experimentally shown before. Another finding was that semantically organized labels without icons were significantly slower to search than semantically organized icons, especially when the number of distractors increased.

One limitation of this study is that the labels were not systematically varied but were the same in all icon type groups. The target was one of two labels. Thereby it was more difficult for the participants to search on the basis of mere labels (of course, it is uncertain whether they would have done that anyway). The participants were pushed to search first between groups at the category or icon level, and then within the target group, looking for the predetermined label. This may have distorted the results. It is not clear whether the observer uses category information available in the search if it is not useful, that is, with randomly organized objects. Another limitation considers labels without icons. Only semantically organized labels were used, without comparison with random organization. As the main focus of the study was on grouping, only a grouped label condition was used to examine the effects of icons in a grouped display.

The results of this study show that semantic organization (with spatial grouping) also improves visual search with icons, which is an important contribution to the understanding of visual search in graphical interfaces. However, the study did not unconfound semantic organization and spatial grouping, and it also left open questions about the search of mere labels and the role of discriminability between groups in the search. Furthermore, it did not take learning into account. Although the experimental material was realistic (real interface icons), the experimental design followed the well-defined paradigm of visual search (e.g. Treisman & Gelade, 1980). In this paradigm, search performance is analyzed as a function of changes in the display, not the learning of the observer. This kind of visual search does not correspond to visual search tasks in realistic interface use situations, in which a user can learn aspects of the interface and use this knowledge to perform search more efficiently. The next study included visual search tasks in a more realistic situation.

4.2 Article 2: "Improving Graphical Information System Model Use with Elision and Connecting Lines"

Huotari, J., Lyytinen, K. & Niemelä, M. Improving Graphical Information System Model Use with Elision and Connecting Lines. ACM Transactions on Computer-Human Interaction. Accepted to be published.

This study was a step to more applied research, with more realistic materials (information system design diagrams) and tasks. In the study, the possibilities that some new visualization techniques provide for information system (IS) designers in regard to graphical design, especially integration of information from different diagrams, were examined. Visualization aids create new ways to spatially organize objects: in this study, the particular technique was "elision", in which hierarchical organization between objects is expressed by the hiding of those levels that are not currently of interest (Schaffer, Zao, Greenberg & al., 1996; Parker, Franck & Ware, 1998).

This study thus compared two ways to visualize hierarchical relationships between diagrams, which are here interpreted as semantic relationships. In the first visualization, semantic organization was expressed in spatial terms (the "default" meaning of semantic organization in this dissertation), by placing the diagrams side by side in the display, in the approximate order of hierarchy. In the other visualization, semantic organization was expressed with the elision technique, by only showing related diagrams in demand and spatially embedded to the diagram of the higher hierarchical level. In addition, connecting lines were added between some diagrams to facilitate integration between those diagrams, but these lines were not used with the same diagrams that were organized with the elision technique. The study was conducted with 84 participants. The study tasks consisted of different search tasks, a location memory task (the diagrams stayed positionally constant throughout the test), and a test of spatial visualization ability. The main measured variable was the accuracy of the search. The search time was also recorded but not used since different interfaces the participants used in the study influenced the search time and thus confounded the effect of organization.

The results showed that both search and memory for locations were improved when semantic organization was expressed with the elision technique, compared to semantic organization in spatial terms. Another finding was that search accuracy correlated positively with memory performance. The study thus confirms the role of location memory in search, and that spatial arrangement can influence both. The results also demonstrate that semantic organization does not need to be limited to the arrangement of objects in spatial (Euclidean) terms, but advanced computer graphics provide new ways for this purpose, such as elision. The elision technique made the shifting of attention towards the target object(s) and location learning easier by reducing the amount of information on the screen. This is important because it implies that although computer systems and interfaces change and develop fast, they can be reliably evaluated in regards to the human cognitive functions instead of the surface features of the systems. This is one of the fundamental assumptions underlying this dissertation.

One limitation of this study is that the two ways to express semantic organization was not compared to random organization. This is forgivable considering the applied nature of the study. There is not much use in the collection of hierarchically organized diagrams, which are placed so that objects within a diagram are not spatially close to each other. However, this study leaves us short of understanding the role of semantic organization in visual search or in location memory. In addition, the semantic organization by using virtual space was confounded with perceptual grouping by connecting lines, which is a strong grouping factor (Palmer & Rock, 1994). The independent influences of connecting lines and elision were attempted to isolate by analyzing different search tasks, employing one integration factor but not the other, but no significant differences between the conditions were found. Therefore, it is not exactly clear how and to what extent these factors, elision and connecting lines, independently caused the decrease in search accuracy and improvement in location memory. In statistical analysis, it was shown that using elision decreased the amount of error approximately 50 % and using connecting lines approximately 30 %, but this result is just an indicator, since the effects were not tested separately for the two factors.

Another concern of validity is the different user interfaces employed in the different conditions of the study. The way a participant was able to control the diagram presentation during the tasks varied across conditions, and greatly influenced search time. However, this confounding factor cannot be ruled out, as the interface is at least partly inherent to the selected visualization technique (separate diagrams or elision). This fault is argued not to be critical, because results of an earlier study indicate that search accuracy is not necessarily affected by different user interfaces, even if search time is (Benbasat & Todd, 1993).

The main concern of this study is that its contribution to the research questions of the role of semantic organization or spatial grouping in visual search or location memory can be criticized to be small. The study is still argued to be relevant for understanding visual search in graphical interfaces. It employs realistic visual search tasks, and emphasizes the connection between visual search and location learning during interaction. It was shown that the recall of locations positively correlates with search performance, and that the spatial arrangement of the objects in the display influences both search and memory. Therefore, the study helped to clarify the components of visual search that must be examined in order to study the effects of spatial arrangement. Furthermore, the study dealt with the question of the spatial visualization ability and its role in perceiving relationships between objects, depending on the spatial arrangement. It was shown that the elision technique improved search and memory for locations especially for those individuals who had lower spatial abilities. Spatial visualization ability has a close relationship to spatial memory (Miyake, Friedman, Rettinger & al., 2001), and therefore this finding supports the view that location memory has an important role in visual search.

In order to clarify the independent roles of semantic organization and spatial grouping on visual search and location memory, two studies were carried out with more rigorous research settings. The first of them, Study III, investigates the separate roles of semantic organization and spatial grouping in search. In addition, positional constancy of objects is manipulated to investigate the interaction between the three factors. The second study, Study IV, focuses on the location memory, and seeks to elucidate the effects of semantic organization and spatial grouping in location learning, which may further influence the visual search.

4.3 Article 3: “Layout Arrangement and Pop-Up Labels: Effects on Search"

Niemelä, M. Layout Arrangement and Pop-up Labels: Effects on Search. Scandinavian Journal of Psychology. To be resubmitted.

This study was designed to examine the arrangemental effects of textual labels on search in a more systematic way. The two aspects of spatial arrangement, spatial grouping and semantic organization, and positional constancy were included. The experimental design consisted of four conditions, in which two arrangemental factors, spatial grouping and semantic organization, were varied. In the first condition, the objects were totally randomly laid out. In the second condition, the objects formed spatial groups by proximity, but the groups did not express semantic categories. In the third condition, the objects were arranged so that the objects from the same semantic category were positioned close to each other but without forming perceptual groups by spatial proximity. In the fourth condition, the objects were arranged into spatial groups according to their category.

The study consisted of three experiments, in which the four arrangements were tested with (1) a random positioning across trials, (2) a rule-based positioning across trials, or (3) a constant positioning. In this design it was possible to study the learning of object locations and its relationship to the spatial arrangements. In addition, the study compared normal, continuously visible labels to so-called pop-up labels. These labels are invisible until the user makes a certain action, for instance, takes the mouse cursor over an object. All three experiments were conducted with both continuously visible labels and pop-up labels. The study was run with 38 participants with a mixed design (within-subjects with spatial arrangement factors, and between-subjects with positional constancy). The task in all experiments was to search for a target object among distractor objects.

Semantic organization (independent of spatial grouping) was clearly the dominating layout factor in search. The semantic organization improved search even when the positioning of objects across trials is constant and the participant has thus a possibility to learn the object locations. Spatial grouping improved search significantly, but mostly when only implemented with semantic organization. This results support the view that semantic organization facilitates attentional scanning between groups, and spatial grouping supports this effects by making these groups more perceivable. The effects were similar with both continuously visible labels and pop-up labels.

A significant improvement in search due to location learning could be shown only with pop-up labels and random positioning of objects. This was a disappointment because the relationship between search improvement and learning of locations was not confirmed. The interpretation of the result is that only that particular condition was difficult enough to search to accomplish location learning during the limited number of trials (25), which the participants had per condition. This finding is in line with the argument that location learning occurs when it is the least-effortful strategy to do so (Gray & Fu, 2001; Melcher & Kowler, 2001; Ehret, 2002). However, spatial grouping had an independent effect on search with pop-up labels, which were difficult to search due to that they were hidden until pointed with the mouse. This may indicate that when locations are learnt, spatial grouping improves the learning process, which implication would specify the role of spatial grouping in the model of search. To ascertain this, the learning issues were studied in more detail in Study IV.

The internal validity of this study can be claimed to be high due to the strict control of variables in the experiments. The external validity, however, can be questioned: how well do the result apply to and across different settings? In the design of the experiment, ecological validity was aspired in material (the labels reminded icons, only without different pictures), and in the distribution of the labels on the screen (as icons and other interface objects often are). Therefore, the results should be easily applicable to graphical interfaces.

4.4 Article 4: "Layout Attributes and Recall"

Niemelä, M. & Saariluoma, P. 2003. Layout Attributes and Recall. Behaviour & Information Technology 22 (5), 353-363.

In this final study, the focus was turned from search to recall. Otherwise the two arrangemental conditions, spatial grouping and semantic organization, were the same as in Study III. This study consisted of three experiments with three different tasks. In the first experiment, the participants recalled the labels of the objects. In the second experiment, the task was to recall the locations of the objects. In the third experiment, these two tasks were combined and the participants recalled both the labels and the locations of the objects. Also accuracy of object-to-location assignment was measured in this task. The learning tasks proceeded as a series of study-and-recall trials. A total of 30 participants attended the study, ten participants in each experiment (within-subject design).

The results show that the best spatial arrangement is dependent on the task demands. Semantic organization without spatial grouping did not affect recall of locations, but was helpful when the task was to recall labels. Spatial grouping facilitated the recall of locations, but did not influence label recall. However, when both the labels and locations were to be recalled, the effects were more complex. Neither spatial grouping nor semantic organization had any significant influence on recall of the locations, but semantic organization improved the memory for labels and also label-location assignment. These results indicate that spatial grouping and semantic organization both influence location learning, but at different levels: spatial grouping at the level of mere location memory and semantic organization at the level of association between semantic objects and locations. Interestingly, a spatially grouped but semantically disorganized display resulted in the worst recall performance, whilst when objects were both semantically organized and spatially grouped, memory for locations was consistently the best. This effect has not been shown before in experimental studies.

The same validity issues concern this study as Study III. In this study, the variables were also strictly controlled, and it can be stated that the internal validity of the experiments is high. Furthermore, the experimental "interface" was designed to remind a real graphical user interface, within the constraints set by the desire for the control of variables. Therefore, it can be claimed that the results apply well to graphical interfaces.

4.5 Summary and discussion

In four experimental studies, the cognitive processes underlying the effects of semantic organization and positional constancy during visual search were examined. The research questions addressed in the four experiments were:

1 How do semantic organization and spatial grouping of objects influence the user's visual search?

2 In the case of positional constancy, how do semantic organization and spatial grouping influence the user's memory for the locations of objects?

Table 1 summarizes the main outcome of the studies in regards to the research questions. The results of the first study show that semantic organization improves visual search for icons. Arrangemental effects on search have been studied earlier in menu layouts (Card, 1982; McDonald, Stone & Liebelt, 1983; Halgren & Cooke, 1993). The results of the second study demonstrate the role of location memory in search and also that spatial arrangement influences both components. The third and fourth study assess the research questions by systematically analyzing the unconfounded effects of spatial grouping and semantic organization on visual search and location memory. This has not been done before.

In regards to the cognitive model of visual search in graphical interface, the results of Study I show that semantic organization, facilitating attentional scanning at the level of groups, applies to icons as well as semantic labels. A difference between icons and labels is that organized labels are slower to search than organized icons. This supports the model in that semantically organized objects are more efficient to search for if object groups are easier to perceive. In

TABLE 1 Summary of the results of the four studies

STUDIES	ASPECTS OF SPATIAL ARRANGEMENT			MAIN RESULTS The number of the assessed research question in brackets
	Semantic organization	Spatial grouping	Positional constancy	
STUDY I (labeled icons, search)	X (confounded)			Semantic organization (confounded with spatial grouping) improved search with icons (1)
STUDY II (labeled objects in IS diagrams, search, recall)	X (confounded)		(X)*	The way the semantic organization is expressed influenced visual search (1) and memory for locations (2)
STUDY III (labels, search)	X	X	X	Semantic organization improved search. With visible labels, spatial grouping improved search only when implemented with semantic grouping. With pop-up labels, spatial grouping improved search independently (1) The influence of location learning on search was not confirmed (2)
STUDY IV (labels, recall)	X	X	(X)*	Semantic organization did not affect memory for mere locations, but enhanced memory when object-to-location assignment had to be recalled (2) Spatial grouping improved memory for mere locations, but not when object-to-location assignment had to be recalled (2)

* Positional constancy was not a manipulated factor

this study, perceptual groups were formed by visual similarity and spatial grouping.

The contribution of Study II to the cognitive model is in confirming the role of location memory in improving the attentional scanning, and in showing that the effects of spatial arrangement extend to the both components of search. Furthermore, the study points out an interesting relationship between the spatial visualization ability of a user and the spatial arrangement in the display. Although this connection is not included in the recent cognitive model, it underlines on its behalf the importance of visual memory components in search in complex graphical interfaces. This is one promising direction to which the model of search could be developed.

Study III contributes to the model of visual search by demonstrating the separate roles of both semantic organization and spatial grouping. Semantic organization of objects allows a more efficient search strategy, in which search proceeds at the level of groups. Without semantic organization, objects must be scanned one by one. Spatial grouping supports the discrimination between groups so that they are easier to scan, but grouping without semantic organization is quite useless to visual search, unless the search is very difficult. For instance, search among spatially grouped pop-up labels was easier compared to random organization.

One major problem in the results of this study is that the relationship between location learning due to positional constancy of the display and improvement in the search could not be properly confirmed in Study III. Semantic organization and spatial grouping facilitated the search similarly regardless of whether the object location was constant across trials or not. This does not mean that there would not be a relationship between location learning and an improvement of search. This relationship is well established in earlier research (Card, 1982; McDonald, Stone & Liebelt, 1983; Green & Barnard, 1990; Halgren & Cooke, 1993; Ehret, 2002). The unexpected result is probably due to a relatively small number of trials (25), compared to even hundreds of trials in these earlier studies. In fact, it has been shown that even during repeated visual searches in the same display, rejected objects are not necessarily attended intensively enough to create memory representation (Horowitz & Wolfe, 1998; Woodman, Vogel & Luck, 2001). This emphasizes the importance of semantic organization of interface objects in supporting the location memory for enhancing visual search.

The idea that there are separate roles for spatial grouping and semantic organization in the location memory is confirmed by the results of Study IV. Spatial grouping appears to support memory for mere locations, whilst semantic organization seems to facilitate the coupling of objects to position. The division of the location memory to the spatial component and object-to-location component has been presented before (Postma & De Haan, 1996), but the independent effects of semantic organization and spatial grouping on the location memory have not been shown. These results help to construct a more detailed cognitive model of visual search; especially the location memory component of the model can now be revised.

4.6 The revised cognitive model of visual search

A visual search task in graphical interfaces, in which semantic interface objects are spatially distributed on the screen, is suggested to be based on two cognitive processes: the visual attention process, and the location memory process that interacts with visual attention. The visual attention process is based on the visual information extracted from the environment (the display) and the observer's search schema. The schema contains and mediates search-relevant knowledge of the observer, information about the search target and a search strategy. Effects of location learning and spatial arrangement of objects in a display are proposed to be mediated by the search strategy. This model of visual search is specified by the experimental study results in regard to the effects of semantic organization on search and location memory. The model, illustrated in Figure 4, is specified by showing where the independent effects of semantic organization and spatial grouping takes place in the model. In addition, a relationship between semantic organization and location memory is added to the model.

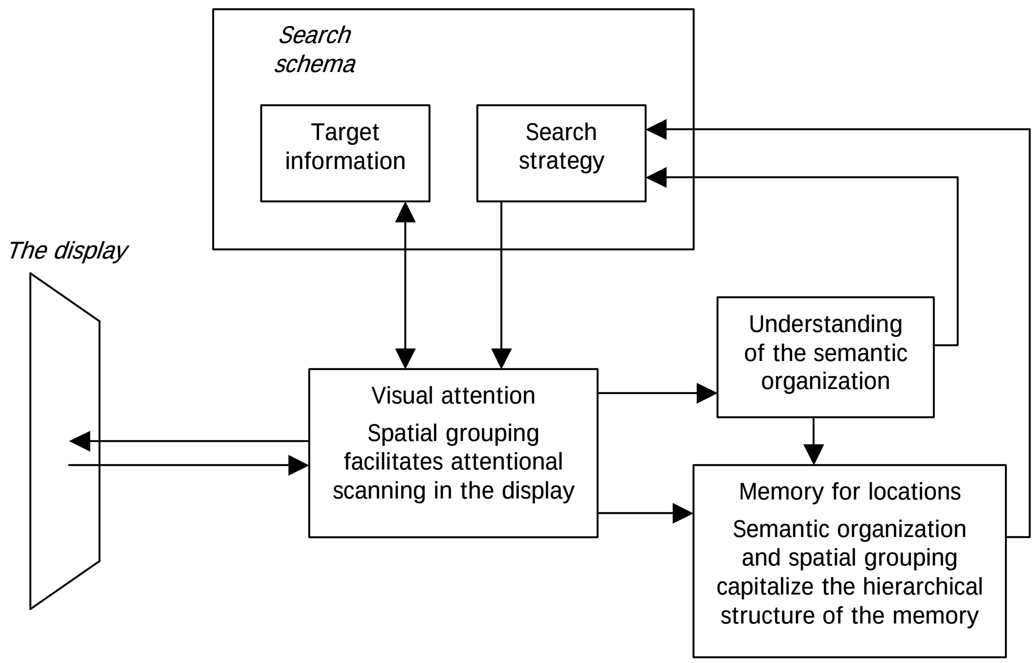

FIGURE 4 The revised model of visual search. Compared to the model presented in Figure 3, this model specifies the separate effects of spatial grouping and semantic organization on visual attention and location memory. In addition, the location memory is proposed to be hierarchically structured to explain the arrangemental effects in the memory.

It has been shown that semantic organization needs to be separated from spatial grouping, and these factors have independent effects on the search. Semantic organization allows for attentional scanning (and thus eye movement) to proceed at the level of groups, that is, a more efficient search strategy. Spatial grouping makes the groups more perceivable and thus improves attentional scanning between groups. If the display is positionally constant, the observer has the possibility to learn the locations of objects. Spatial grouping appears to support memory for mere locations, whilst semantic organization has influences on associating objects to locations. Semantic organization and spatial grouping is also suggested to facilitate search mediated by spatial memory. Both factors are proposed to encourage hierarchical clustering in spatial memory, and those clusters can be used to guide attention at group level.

The effects of spatial grouping facilitating both the location memory and semantic organization facilitating the object-to-location associations, and the effects of both spatial grouping and semantic organization facilitating attentional scanning, can be integrated within a hierarchical view of memory for the locations. This view is of course speculative because it has not been subjected to experimental testing.

It has been shown in earlier research that spatial memory is hierarchically structured. When forming spatial memories of spatially distributed objects, people tend to cluster the objects in memory according to some categorization (Hirtle & Jonides, 1985; Hirtle & Mascolo, 1986; Hirtle & Kallman, 1988; McNamara, Hardy & Hirtle, 1989; Hommel, Gehrke & Knuf, 2000). It can be hypothezised that spatial grouping would provide the basis for the spatial clustering of locations, and semantic organization for the semantic clustering of objects in the spatial memory. In addition, there are indications that both location memory components, non-semantic and semantic, participate in guiding visual attention (Miller, 1988). Therefore, it can be proposed that on the basis of semantic organization in the display, the observer is able to create object clusters in a spatial memory. These clusters, instead of locations of individual objects, would function as the basis of guiding attention towards the target group in the display. Spatial grouping also provides clustering in the spatial memory, but these clusters do not contain useful category information to guide attention. However, when spatial grouping and semantic organization are implemented in parallel in the display, the formed clusters in spatial memory support each other, and search is facilitated the most.

Similar ideas in regard to the influence of semantic organization in spatial memory has been proposed by Axia and Caravaggi (1987), who also showed that it is easier to remember locations of semantically arranged objects than of randomly arranged objects. They argue that with semantic organization, both object locations and understanding of the semantics expressed in the spatial arrangement can be integrated in the memory (this is interpreted to refer to semantic clustering). The resulting memory representation is stronger and richer than acquired with random organization, when only the location memory can be utilized.

Hierarchically structured spatial memory may also explain the unexpected results of spatial grouping effects on memory obtained in Study IV. Spatial grouping in a semantically disorganized display entailed worse recall than a semantically disorganized display without spatial grouping. However, recall was the best for a spatially grouped and semantically organized display. Perhaps spatial grouping, creating location-based clusters, interferes with the location memory process for semantically related objects (when their relationship is not mapped to locations). Spatial grouping alone provides clustering, which is useless. In fact, some supporting evidence for this can be found in Study III, especially in the results of Experiment 3. In this experiment, positions were constant and location learning thus possible. In part of the search trials, search was slower when there was spatial grouping without semantic organization, compared to a totally random organization. This indicates that the idea that there are two kinds of clustering in spatial memory that also mediate the effects of spatial arrangement on visual search is well possible, and certainly worth further investigation.

5 DISCUSSION

The presented model of visual search is built for the purpose of explaining the effects of spatial arrangement of objects in graphical interfaces. The model widely integrates psychological findings and theoretical constructions, as well as applied study results, to explain these effects. It is argued that the model is the first cognitive approach to visual search that is also able to explain the semantic and spatial organization aspects of the interface. Furthermore, the model takes learning of the user into account, and is able to explain influences of spatial arrangement in an interface also in this regard. The domain of computational cognitive modeling provides some models, within which visual search can be explained (Hornof & Kieras, 1997; 1999; Byrne, 2001; Fleetwood & Byrne, 2001; Ehret, 2002), but the current models do not include spatial arrangemental aspects of the interface. In addition, to understand the underlying cognitive processes of the user is not the primary function of computational cognitive modeling, but to be able to replace the user in the development and testing phases of interface design (Ritter, Baxter, Jones & al., 2000; Ritter & Young, 2001). Therefore, it can be argued that computational cognitive models do not seek to profound the understanding of user behavior to the extent that the cognitive model of this dissertation does.

The model provides an explanation of how search takes place in differently organized interfaces. Ideally, interface objects are arranged according to their semantic relationships and also grouped, as recommended by the design guidelines (Marcus, 1995; Galitz, 1997; Tullis, 1997). However, more often it may be that there is no obvious spatial arrangement in the interface that the user could capitalize in search. If the semantic contents in the interface is unfamiliar to the user, the search strategy cannot be based on semantic organization, but the search is explained either as search in a randomly arranged display or spatially grouped display without semantic organization. Especially in the latter case, the spatial grouping may interfere with search. Futhermore, in some applications, information may be semantically organized but the organization does not directly support distinctive groups. For instance, visualizations of information retrieval results (represented as so called information nodes in two-or three-dimensional space) can be semantically organized in relation to the retrieval terms. The search model also explains search in these situations. On the basis of the model, it can be suggested that spatial grouping helps search even if there is not clear categorization in the material, to the extent that semantic organization does not contradict the grouping.

The model is limited in explaining the effects of spatial arrangement as it only takes two arrangemental aspects, semantic organization and spatial grouping, into account. Interfaces can also employ such spatial organizations as ordering and alignment of objects (Tullis, 1997). Their influence on visual search or location memory cannot be directly explained within the present model. However, it is believed that concentrating specifically on semantic organization and spatial grouping is valuable because it makes the model more applicable to modern complex graphical interfaces such as semantic information spaces (Westerman, 1998; Chen, 1999; Westerman & Cribbin, 2000), in which ordering and alignment may not be relevant ways of spatial arrangement at all. Another, maybe more crucial limitation of the model is that it does not specify the role of eye movements in search. Visual attention is the cognitive process underlying eye movements (Humphreys & Bruce, 1989; Theeuwes, 1993; Pashler, 1998) and thus emphasizing the attention process in the model of visual search is justified. However, attention is a complex function not well understood even by cognitive psychologists. Psychological research on attention is theoretically oriented and thus not easy to apply to real-world tasks. The model could perhaps better attain interface designers, if the relationship between eye movements and attentional scanning was described more throroughly in the model. This complement to the search model would also better associate the model to studies on graphical interfaces that use eye-tracking to assess search performance (Tanriverdi & Jacob, 2000; Melcher & Kowler, 2001; Hornof & Halverson, 2003).

The objects particularly employed in formulating the model are textual labels, but as the results of Study I and II show, the model can be extended to explain visual search with icons and graphical IS models. There are plenty of other computerized domains, which employ modern graphical interfaces, and which might thus benefit from the presented model of visual search.

5.1 Practical implications

The cognitive model of visual search confirms and provides some direct practical guidelines for designers on how to spatially organize objects in graphical interfaces in order to facilitate visual search. First, the objects can be spatially organized in regards to any attribute of the target that the user knows. The organizing principle thus does not need to be the primary target attribute to search, for instance, the label. As the user understands the organizating factor, an efficient search strategy can be constructed. The organization is beneficial for both inexperienced users and experienced users, which have learnt about the locations of objects and also perform search on the basis of location memory. Second, these organized groups should be made distinct from each other on the basis of some perceptual grouping factor, for example, spatial proximity, color, or visual similarity. This allows efficient attentional scanning between the groups. Third, specific care should be taken that this perceptual grouping factor corresponds to the underlying, target-relevant organization. If the two organizations do not match each other, search may be interfered, especially when the memory for locations is used to support search. Of these guidelines, the first two (semantic organization and spatial grouping) are commonly recommended in interface design guidelines (Marcus, 1995; Galitz, 1997; Tullis, 1997), but the third is not. Further research is also needed to establish this practice in interface design.

Thinking about the powerful effect a useful spatial arrangement has on search, it should be utilized much more widely than it is now. For instance, web pages are a domain in which users are often inexperienced and thus need support for easier search. Although some conventions on spatial placing of web objects are developing and have been found useful, for instance, left positioning of web link menus (Pearson & van Schaik, 2003), the information in web pages is still often disorganized and unsupportive for visual attention guidance. There are also other studies that speak for systematic organization of information in web pages (Hornof, 2001; Hornof & Halverson, 2003). In addition, web sites should take care of positional consistency of information across separate pages. The results of this dissertation show that learning of spatial locations is gradual, and users may not be able to utilize positional constancy of information in visual search during the first visits to the site. Therefore, for inexperienced users, the same spatial location for certain information on different pages is not as important as semantic organization of the information. For experienced users, semantic organization helps the formation of an internal map of locations of information, on the basis of which the user should be able to attentionally orientate and fixate to the location of desired information even before the page or the information is visually available (Posner, Snyder & Davidson, 1980; Miller, 1988; Hornof & Kieras, 1999). Supporting location memory for search purposes is also important when the user has to scroll information on the screen, and all information is thus not available continuously. This is common in web pages, but also used on small screens such as palm-type personal digital assistants (PDAs). By semantic organization, and for an experienced user, by positional constancy, the user is given the possibility to attend to the location where the information will be after it has been scrolled into view.

Another domain in which the cognitive model of visual search is proposed to be useful is the domain of visualization. The number of innovative visualization applications with visually rich graphical presentations is increasing, and furthermore, the amount and complexity of information presented in these applications is increasing. In particular, the domains of information visualization and semantic spaces especially use spatial attributes, location, relationship, and grouping for representing information. Information visualizations are spatial representations of abstract, non-spatial information and relationships within the information (Ware, 2000). Visualized semantic spaces on their behalf can be thought of as a special case of information visualization. Semantic spaces are graphical representations, in which semantic relationships between pieces of information are mapped to spatial relationships, so that the more semantically related the two objects are, the more spatially close they are (Westerman, 1998; Chen, 1999; Westerman & Cribbin, 2000). Semantic spaces can be useful especially in the retrieval of information, when the user has to search for relevant information from all retrieved information. The motivating hypothesis behind spatial-semantic mapping is that as the user associates semantic facts with spatial positions, and semantic relationships with spatial relationships, navigation (search) in spatial terms is easier. The user can take advantage of "semantic dimensions" (Chen, 1999), which are intuitively used to lead to the searched information. However, currently the understanding on how a human uses and benefits from this kind of semantic space is little, in spite of that research and development of information visualizations has been greatly increasing during recent years (Seagull & Walker, 1992; Stanney & Salvendy, 1995; Card, Mackinlay & Shneiderman, 1999; Chen & Yu, 2000; Robertson, Dantzich, Robbins & al., 2000; Ware, 2000; Westerman & Cribbin, 2000; Spence, 2001).

Information visualization has great potential for conveying information to people in an exciting and cognitively undemanding way, but there are also lots of unsolved problems. It is not surprising that the interest for cognitive theories concerning information visualization has increased in recent years (Lohse, Biolsi, Walker & al., 1994; Scaife & Rogers, 1996; Shneiderman, 1998). In particular, how to map semantic information to spatial locations and arrangements is one of the main challenges of the domain (Card, Mackinlay & Shneiderman, 1999). It has been proposed that an efficient spatial arrangement of data may be essential for understanding the meaning of the visualization (Chen, 1999). The cognitive model of this dissertation is one valuable step on the way, by providing a scientifically grounded base from which to evaluate and study these interfaces, and from which to make design decisions in regards to design of the spatial arrangement of information visualizations. These domains are natural directions into which the cognitive model can be extended.

The contemporary graphical interfaces can be critisized for that the applications for implementing or supporting useful groupings are rare, in spite of that the importance of semantic organization is well recognized in design guidelines (Marcus, 1995; Galitz, 1997; Tullis, 1997), and that there is also supporting research conducted on the topic (Card, 1982; McDonald, Stone & Liebelt, 1983; Halgren & Cooke, 1993). The user may have the possibility to manually organize information spatially, for instance, icons on the screen, but often even this simple possibility is missing. This is a true miss in current interface design, thinking that semantic organization may not only have influences on visual search and information retrieval tasks, but also other tasks that require the use of visual information, extending to recall (Study IV) and an understanding of the contents of the interface (Halgren & Cooke, 1993; Chen, 1999).

One possible way to support semantic organization in different types of graphical interfaces, whether they contain icons, web pages, or an information visualization, is a flexible, user-controlled information organization. This means that the user can set some criterion or criteria according to which the information on the screen would group. A similar system is used with hierarchical file organizing systems, in which the user can arrange files according to their name or modification day, for instance. This flexible organization should be extended with grouping by proximity. In addition, grouping should be two-dimensional at least for icons on the screen. This kind of user-based organizing application could be installed onto the system, and it could arrange all material selected by the user (for instance, documents in a folder or several folders, folders themselves, short-cut icons, even chapters of text) into some grouping. The criteria, also selected or set by the user, could be any attribute that the material contains, such as color, label, file size, folder creation day, and so on. As shown by the results of the studies in this dissertation, people are quick to extract the semantic organizing principle implemented in the display, at least with familiar objects. Semantic organization can be efficiently used in search, at least if the category borders are distinctive.

5.2 Evaluation of the user psychology approach

In this dissertation, a cognitive model is constructed in order to assess the effects of spatial arrangement on visual search tasks in graphical interfaces. This work applies and develops a user psychological approach to human-computer interaction (HCI) tasks. The goal of the user psychology is to construct theoretical frameworks, derived from different fields of psychology, to explain HCI tasks. The emphasis is in understanding a user's psychological functions, and how interaction and interface issues can be assessed within this understanding. This kind of approach, at least specifically concerning visual search, has not been done before.

This dissertation work demonstrates that knowledge of the human cognitive system can be used to construct an explanatory framework, within which interaction phenomena and practical problems can be investigated. This in-depth approach may also provide new innovations for practice (Lewis, 1990). Due to the fact that the speed of change is one major problem in the research of computers, and especially in the research of HCI (Landauer, 1997), understanding the user cognition may prove to be of more value than user test results concerning individual interfaces or their properties. For example, user tests on command-based interface may be obsolete as a majority of modern graphical interfaces are icon- and menu-based, but knowledge of human memory functions is valuable as it is able to explain why graphical interfaces are more efficient than command-based ones.

The cognitive model here is focused on a critical subtask of all visual tasks, visual search. The generalizability of the user cognitive psychology approach to other kinds of interactions may be challenged. It has been argued that certain interactive situations cannot be reduced to descriptions at the level of the basic cognitive processes, and that the task domain and material are more important issues determining user behavior and thus interface design decisions (Lansdale, Scrivener & Woodcock, 1996). Interpreted against this view, a cognitive model of visual search in graphical interfaces may be successful only because it is a simple enough task to allow for reduction, and which is also well established in cognitive psychology. Visual search is an important user task because of the graphical nature of the interface, but other similar accounts that would be based on the basic cognitive processes may be difficult to find.

However, it is argued that HCI can be analyzed at the level of the cognitive processes, perhaps not only one process, but at least with a few basic processes. The model of visual search includes the attention and memory processes. In addition to these, visual perceptual processes are, of course, one natural possibility what a user cognitive psychology approach can explain in regards to HCI tasks. For instance, an increasing number of studies are focusing on graphical interfaces capitalizing three-dimensional perception and memory (Wann & Mon-Williams, 1996; Westerman, 1998; Risden, Czerwinski, Munzner & al., 2000; Robertson, Dantzich, Robbins & al., 2000; Cockburn & McKenzie, 2002; Irani & Ware, 2003), as well as spatial visualization ability and its relationship to navigational problems (Vicente & Williges, 1988; Seagull & Walker, 1992; Chen & Czerwinski, 1997). These research efforts show that the significance of understanding the user cognition has been recognized, and that the modern interfaces entail many such design issues that can be assessed by using cognitive psychological knowledge of the user.

In spite of the interest in cognitive aspects of the user in HCI, research approaches aiming to explain user behavior from a wider point of view, that is, constructing theoretical models of the user behavior in HCI tasks, are rare. One reason may be found in cognitive psychology per se. Research in cognitive psychology has produced a large database of empirical data about human performance in different tasks, theories integrating that data and a set of techniques for research. However, there is a difficulty in integrating the problem presented at the level of practice to theories and findings of cognitive psychology. Basic cognitive psychology has studied narrow problems and the theories integrating individual findings may be irrelevant or difficult to relate to the problem (Nickerson & Landauer, 1997). For instance, in cognitive psychology there has been controversy about whether visual attention operates on a spatial representation or on object-based representation (Posner, 1980; Duncan, 1984; Duncan & Humphreys, 1989; Theeuwes, 1993; Lamy & Tsal, 2001). For the problem presented in this dissertation, both these theoretical viewpoints seem relevant, because the view of space-based attention explains how location memory guides attention, and the view of object-based attention better accounts for the grouping effects in attentional selection. The conflicting theoretical viewpoints, however, impede the integration of the findings in order to explain human behavior in real-world tasks. Thus, more integrative theories in cognitive psychology are needed if it is to be applied to HCI research on a wider basis. There is a demand for cognitive theories explaining HCI (Lohse, Biolsi, Walker & al., 1994; Scaife & Rogers, 1996; Shneiderman, 1998). Cognitive psychology probably will make a major contribution to HCI research, at least in the long term (Nickerson

& Landauer, 1997; Gopher & Koriat, 1999). Learning to capitalize on the scientific property of cognitive psychology in applied domains is in the early stages, but its potential is huge.

5.3 Contributions

The main contributions of this dissertation are in the research field of HCI. The contributions are two-fold. They concern both user interface design and its practical problems, and the research approach within which these problems are assessed. From a practical point of view, the contributions are in regard to the problem of spatial arrangement of interface objects in graphical interfaces. Two important arrangemental aspects, semantic organization and spatial grouping, are unconfounded and their effects on visual search as well as location memory are studied separately. It is shown that both these arrangemental aspects have relevance in several computerized domains in which graphical interfaces are used to convey information from a computer system to a user. The effects of spatial arrangement are explained within a cognitive model of visual search. The model provides an understanding of the user's search behavior in graphical interfaces. The model helps interface designers to justify their decisions about the spatial arrangement of objects in an interface.

The other contribution of the dissertation is at the level of research approaches to HCI. In particular, the dissertation applies and develops the user psychology approach. Cognitive theories to explain HCI are needed (Lohse, Biolsi, Walker & al., 1994; Scaife & Rogers, 1996; Shneiderman, 1998), and this dissertation work makes important points about the construction of these theories. It is shown that it is possible to find relevant psychological information to construct integrative theoretical accounts, whithin which the user behavior in applied HCI tasks can be explained. It is also argued that building these theoretical accounts may not be easy because of the current psychological knowledge is less concerned with real-world tasks than theoretical constructs. However, the dissertation strongly speaks for the study of the user in addition of the study of the computer. Emphasizing the user is important as computer systems and interfaces are likely to change fast, and by studying the user, interaction tasks can be understood in a more profound and tenable way.

6 CONCLUSIONS

This dissertation provides a cognitive model of visual search in HCI tasks to explain the effects of spatial arrangement of graphical interface objects on search. The research approach employed in this dissertation is two-fold in nature, integrating applied and theoretical findings and viewpoints from cognitive psychology to HCI research. The viewpoints of basic cognitive psychology research are reflected in the attempts to uncover some fundamental principles regarding visual search, and to use rigorous and controlled experimentation in assessing the research questions. On the other hand, the model is motivated by a real-world problem and pursues ecologically valid research settings.

Spatial arrangement of interface objects is suggested to have important consequences for user behavior, such as search for information, in addition to understanding and learning of the contents of the interface. For the practical problem of how to support user behavior, in particular, a visual search task among spatially arranged interface objects, cognitive psychology research provides a large database of empirical data about search, attention, and memory. This dissertation shows that user cognitive functions are important in the context of interaction with graphical interfaces, and it is possible to derive explanatory frameworks from cognitive psychology, within which interaction can be explained. The cognitive model presented in this dissertation has the potential to explain search behavior in graphical interfaces in several computerized domains, from information visualizations and semantic spaces to new interface innovations.

It is emphasized that the contribution of cognitive psychology to HCI is not just to solve interface design problems by using the knowledge of the user's cognitive processes to construct lists of principles and guidelines for design. A more important and tenable goal is to increase the understanding about the interaction between the internal processes of the user and the external "information artifacts", such as computer interfaces (Green, Davies & Gilmore, 1996). This dissertation is one approach to provide an explanatory framework to a user's cognitive behavior in HCI, but there is a need for theoretical models that are also able to explain different and more complex user behavior. This user psychology approach requires the integration of cognitive psychology knowledge across the scientific field. It is argued that at the current level of cognitive psychology, the findings and theories are not easily applied to practical problems. This poses specific difficulties in regards to HCI research. However, there are indications that the focus of cognitive research is moving in a more integrative and applied direction. Thus, the user cognitive psychology approach will probably have a major influence on HCI research in the near future.

REFERENCES

Allport, A. 1992. Attention and Control: Have We Been Asking the Wrong Questions? A Critical Review of Twenty-Five Years. In D. E. Meyer & S. Kornblum (Eds.). Attention and Performance XIV. London, England: The MIT Press, 183-218.

Andrade, J. & Meudell, P. 1993. Is Spatial Information Encoded Automatically in Memory? Quarterly Journal of Experimental Psychology: Human Experimental Psychology 46A (2), 365-375.

Awh, E., Jonides, J. & Reuter-Lorenz, P. A. 1998. Rehearsal in Spatial Working Memory. Journal of Experimental Psychology: Human Perception & Performance 24 (3), 780-790.

Awh, E., Dhaliwal, H., Christensen, S. & Matsukura, M. 2001. Evidence for Two Components of Object-Based Selection. Psychological Science 12 (4), 329-334.

Axia, G. & Caravaggi, D. 1987. Effects of Spatial Arrangement on 4- and 6-Yr.-Old Children's Memory. Perceptual & Motor Skills 65 (1), 283-293.

Banks, W. P. & Prinzmetal, W. 1976. Configurational Effects in Visual Information Processing. Perception & Psychophysics 19 (4), 361-367.

Baudisch, P., DeCarlo, D., Duchowski, A. T. & Geisler, W. S. 2003. Attentive User Interfaces: Focusing on the Essential: Considering Attention in Display Design. Communications of the ACM 46 (3), 60-66.

Benbasat, I. & Todd, P. 1993. An Experimental Investigation of Interface Design Alternatives: Icon Vs Text and Direct Manipulation Vs Menus. International Journal of Man-Machine Studies 38 (3), 369-402.

Broadbent, D. 1958. Perception and Communication. London, UK: Pergamon Press.

Brown, T. L., Gore, C. L. & Carr, T. H. 2002. Visual Attention and Word Recognition in Stroop Color Naming: Is Word Recognition "Automatic?" Journal of Experimental Psychology: General 131 (2), 220-240.

Bruce, V. 1981. Visual and Semantic Effects in a Serial Word Classification Task. Current Psychological Research 1 (3), 153-161.

Byrne, M. D. 2001. ACT-R/PM and Menu Selection: Applying a Cognitive Architecture to HCI. International Journal of Human-Computer Studies 55, 41-84.

Card, S. K. 1982. User Perceptual Mechanisms in the Search of Computer Command Menus. In Proceedings of the first major conference on Human factors in computers systems. ACM, 190-196.

Card, S. K., Moran, T. P. & Newell, A. 1983. The Psychology of Human-Computer Interaction. Hillsdale, NJ: LEA.

Card, S. K., Mackinlay, J. D. & Shneiderman, B. (Eds.). 1999. Readings in Information Visualization: Using Vision to Think. San Francisco: Morgan Kaufmann Publishers, Inc.

Chalmers, P. A. 2003. The Role of Cognitive Theory in Human-Computer Interface. Computers in Human Behavior 19, 593-607.

Chen, C. 1999. Information Visualisation and Virtual Environments. London: Springer-Verlag.

Chen, C. & Yu, Y. 2000. Empirical Studies of Information Visualization: A Meta-Analysis. International Journal of Human-Computer Studies 53 (5), 851-866.

Chen, C. & Czerwinski, M. 1997. Spatial Ability and Visual Navigation: An Empirical Study. In T. Graham (Ed.). The New Review of Hypermedia and Multimedia. London: Taylor Graham Publishing, 67-89.

Christensen, L. B. 1997. Experimental Methodology. Needham Heights, MA: Allyn and Bacon.

Chua, K.-P. & Chun, M. M. 2003. Implicit Scene Learning Is Viewpoint-Dependent. Perception & Psychophysics 65, 72-80.

Chun, M. M. & Jiang, Y. 1998. Contextual Cueing: Implicit Learning and Memory of Visual Context Guides Spatial Attention. Cognitive Psychology 36, 28-71.

Cockburn, A. & Mckenzie, B. 2002. Evaluating the Effectiveness of Spatial Memory in 2D and 3D Physical and Virtual Environments. CHI Letters 4 (1), 203-210.

Donald, M. 1991. Origins of Modern Mind: Three Stages in the Evolution of Culture and Cognition. Cambridge, MA: Harvard University Press.

Driver, J. & Baylis, G. C. 1989. Movement and Visual Attention: The Spotlight Metaphor Breaks Down. Journal of Experimental Psychology: Human Perception & Performance 15 (3), 448-456.

Duncan, J. 1984. Selective Attention and the Organization of Visual Information. Journal of Experimental Psychology: General 113 (4), 501-517.

Duncan, J. & Humphreys, G. W. 1989. Visual Search and Stimulus Similarity. Psychological Review 96 (3), 433-458.

Egeth, H. E. & Yantis, S. 1997. Visual Attention: Control, Representation, and Time Course. Annual Review of Psychology 48, 269-297.

Egly, R., Driver, J. & Rafal, R. D. 1994. Shifting Visual Attention between Objects and Locations: Evidence from Normal and Parietal Lesion Subjects. Journal of Experimental Psychology: General 123 (2), 161-177.

Ehret, B. D. 2002. Learning Where to Look: Location Learning in Graphical User Interfaces. In Proceedings of the SIGCHI '02. ACM, 4, 211-218.

Ellis, N. R. 1990. Is Memory for Spatial Location Automatically Encoded? Memory & Cognition 18 (6), 584-592.

Eriksen, C. W. & Yeh, Y.-Y. 1985. Allocation of Attention in the Visual Field. Journal of Experimental Psychology: Human Perception & Performance 11 (5), 583-597.

Eriksen, C. W. & St James, J. D. 1986. Visual Attention within and around the Field of Focal Attention: A Zoom Lens Model. Perception & Psychophysics 40 (4), 225-240.

Eysenck, M. W. & Keane, M. T. 1995. Cognitive Psychology: A Student's Handbook. East Sussex, UK: Psychology Press.

Fisk, A. D. & Schneider, W. 1983. Category and Word Search: Generalizing Search Principles to Complex Processing. Journal of Experimental Psychology: Learning, Memory, & Cognition 9 (2), 177-195.

Fleetwood, M. D. & Byrne, M. D. 2001. Modeling Icon Search in ACT-R/PM. In Proceedings of the International Conference on Cognitive Modeling. LEA.

Friedman-Hill, S. & Wolfe, J. M. 1995. Second-Order Parallel Processing: Visual Search for the Odd Item in a Subset. Journal of Experimental Psychology: Human Perception & Performance 21 (3), 531-551.

Galitz, W. O. 1997. The Essential Guide to User Interface Design: An Introduction to Gui Design Principles and Techniques. New York: Wiley.

Gittins, D. 1986. Icon-Based Human-Computer Interaction. International Journal of Man-Machine Studies. Special Issue: Constructing user interfaces 24 (6), 519-543.

Gopher, D. & Koriat, A. 1999. Bridging the Gap between Basic and Applied Research on the Cognitive Regulation of Performance. In D. Gopher & A. Koriat (Eds.). Attention and Performance XVII: Cognitive Regulation of Performance: Interaction of Theory and Application. Cambridge, Massachusetts: The MIT Press, 3-14.

Gray, W. D. & Fu, W.-T. 2001. Ignoring Perfect Knowledge in-the-World for Imperfect Knowledge in-the-Head: Implications of Rational Analysis for Interface Design. In Proceedings of the Conference on Human Factors in Computing Systems. ACM.

Green, A. J. K. & Barnard, P. J. 1990. Iconic Interfacing: The Role of Icon Distinctiveness and Fixed or Variable Screen Locations. In Proceedings of the INTERACT 1990. 457-462.

Green, T. R. G., Davies, S. P. & Gilmore, D. J. 1996. Delivering Cognitive Psychology to HCI: The Problems of Common Language and of Knowledge Transfer. Interacting with Computers 8 (1), 89-111.

Halgren, S. L. & Cooke, N. J. 1993. Towards Ecological Validity in Menu Research. International Journal of Man-Machine Studies 39 (1), 51-70.

Hasher, L. & Zacks, R. T. 1979. Automatic and Effortful Processes in Memory. Journal of Experimental Psychology: General 108 (3), 356-388.

Helmholtz, H. 1866/1925. Physiological Optics. New York: Dover.

Henderson, L. & Chard, J. 1978. Semantic Effects in Visual Word Detection with Visual Similarity Controlled. Perception & Psychophysics 23 (4), 290-298.

Hirtle, S. C. & Jonides, J. 1985. Evidence of Hierarchies in Cognitive Maps. Memory & Cognition 13 (3), 208-217.

Hirtle, S. C. & Mascolo, M. F. 1986. Effect of Semantic Clustering on the Memory of Spatial Locations. Journal of Experimental Psychology: Learning, Memory, & Cognition 12 (2), 182-189.

Hirtle, S. C. & Kallman, H. J. 1988. Memory for the Locations of Pictures: Evidence for Hierarchical Clustering. American Journal of Psychology 101 (2), 159-170.

Hollan, J., Hutchins, E. & Kirsh, D. 2000. Distributed Cognition: Toward a New Foundation for Human-Computer Interaction Research. ACM Transactions on Computer-Human Interaction (TOCHI) 7 (2), 174-196.

Hommel, B., Gehrke, J. & Knuf, L. 2000. Hierarchical Coding in the Perception and Memory of Spatial Layouts. Psychological Research 64 (1), 1-10.

Hornof, A. J. & Kieras, D. E. 1997. Cognitive Modeling Reveals Menu Search Is Both Random and Systematic. In Proceedings of the Conference on Human Factors in Computing Systems. ACM, 107-114.

Hornof, A. J. & Kieras, D. E. 1999. Cognitive Modeling Demonstrates How People Use Anticipated Location Knowledge of Menu Items. In Proceedings of the Conference on Human Factors in Computing Systems. ACM, 410-417.

Hornof, A. J. 2001. Visual Search and Mouse-Pointing in Labeled Versus Unlabeled Two-Dimensional Visual Hierarchies. ACM Transactions on Computer-Human Interaction (TOCHI) 8 (3), 171-197.

Hornof, A. J. & Halverson, T. 2003. Modeling User Behavior: Cognitive Strategies and Eye Movements for Searching Hierarchical Computer Displays. In Proceedings of the Conference on Human Factors and Computing Systems. ACM, 249-256.

Horowitz, T. S. & Wolfe, J. M. 1998. Visual Search Has No Memory. Nature 394 (6693), 575-577.

Howes, A. & Young, R. M. 1997. The Role of Cognitive Architecture in Modelling the User: Soar's Learning Mechanism. Human-Computer Interaction 12, 311-343.

Humphreys, G. W. & Bruce, V. 1989. Visual Cognition: Computational, Experimental, and Neuropsychological Perspectives. Hillsdale, NJ, England: Lawrence Erlbaum Associates, Inc.

Hutchins, E. 1995. Cognition in the Wild. Cambridge, MA: MIT Press.

Irani, P. & Ware, C. 2003. Diagramming Information Structures Using 3D Perceptual Primitives. ACM Transactions on Computer-Human Interaction (TOCHI) 10 (1), 1-19.

Jiang, Y. & Chun, M. 2001. Selective Attention Modulates Implicit Learning. Quarterly Journal of Experimental Psychology (A) 54 (4), 1105-1124.

Johnston, W. A. & Dark, V. J. 1986. Selective Attention. Annual Review of Psychology 37, 43-75.

Jonides, J. & Gleitman, H. 1972. A Conceptual Category Effect in Visual Search: O as Letter or as Digit. Perception & Psychophysics 12 (6), 457-460.

Jonides, J. & Gleitman, H. 1976. The Benefit of Categorization in Visual Search: Target Location without Identification. Perception & Psychophysics 20 (4), 289-298.

LaBerge, D. 1983. Spatial Extent of Attention to Letters and Words. Journal of Experimental Psychology: Human Perception & Performance 9 (3), 371-379.

Lamy, D. & Tsal, Y. 2001. On the Status of Location in Visual Attention. European Journal of Cognitive Psychology 13 (3), 305-342.

Landauer, T. K. 1997. Behavioral Research Methods in Human-Computer Interaction. In M. Helander, T. K. Landauer & P. V. Prabhu (Eds.). Handbook of Human-Computer Interaction. Amsterdam: Elsevier, 203-227.

Lansdale, M. W., Scrivener, S. A. R. & Woodcock, A. 1996. Developing Practice with Theory in HCI: Applying Models of Spatial Cognition for the Design of Pictorial Databases. International Journal of Human-Computer Studies 44 (6), 777-799.

Larkin, J. H. & Simon, H. A. 1987. Why a Diagram Is (Sometimes) Worth Ten Thousand Words. Cognitive Science 11 (1), 65-100.

Lewis, C. H. 1990. A Research Agenda for the Nineties in Human-Computer Interaction. Human-Computer Interaction 5, 125-143.

Lohse, G. L., Biolsi, K., Walker, N. & Rueter, H. H. 1994. A Classification of Visual Representations. Communications of the ACM 37 (12), 37-49.

Lohse, J. 1991. A Cognitive Model for the Perception and Understanding of Graphs. In Proceedings of the Conference on Human Factors in Computing Systems (CHI'91). ACM, 137-144.

Mandler, J. M., Seefmiller, D. & Day, J. 1977. On the Coding of Spatial Information. Memory and Cognition 5 (1), 10-16.

Marcus, A. 1995. Principles of Effective Visual Communication for Graphical User Interface Design. In R. M. Baecker, W. Buxton & J. Grudin (Eds.). Readings in Human-Computer Interaction: Toward the Year 2000. San Francisco, CA: Morgan Kaufman, 425-441.

McDonald, J. E., Stone, J. D. & Liebelt, L. S. 1983. Searching for Items in Menus: The Effects of Organization and Type of Target. In Proceedings of the 27th Annual Meeting of Human Factors Society. Human Factors Society, 834-837.

McNamara, T. P., Hardy, J. K. & Hirtle, S. C. 1989. Subjective Hierarchies in Spatial Memory. Journal of Experimental Psychology: Learning, Memory, & Cognition 15 (2), 211-227.

Melcher, D. & Kowler, E. 2001. Visual Scene Memory and the Guidance of Saccadic Eye Movements. Vision Research. Special Issue: Eye movements and vision in the natural world: In honour of Han Collewijn 41 (25-26), 3597-3611.

Miller, J. 1988. Components of the Location Probability Effect in Visual Search Tasks. Journal of Experimental Psychology: Human Perception & Performance 14 (3), 453-471.

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P. & Hegarty, M. 2001. How Are Visuospatial Working Memory, Executive Functioning, and Spatial Abilities Related? A Latent-Variable Analysis. Journal of Experimental Psychology: General 130 (4), 621-640.

Naveh-Benjamin, M. 1987. Coding of Spatial Location Information: An Automatic Process? Journal of Experimental Psychology: Learning, Memory, & Cognition 13 (4), 595-605.

Naveh-Benjamin, M. 1988. Recognition Memory of Spatial Location Information: Another Failure to Support Automaticity. Memory & Cognition 16 (5), 437-445.

Navon, D. 1977. Forest before Trees: The Precedence of Global Features in Visual Perception. Cognitive Psychology 9 (3), 353-383.

Neisser, U. 1964. Visual Search. Scientific American 210 (6), 94-102.

Neisser, U. & Beller, H. K. 1965. Searching through Word Lists. British Journal of Psychology 56 (4), 349-358.

Neisser, U. 1967. Cognitive Psychology. New York: Appleton-Century-Croft.

Neisser, U. & Becklen, R. 1975. Selective Looking: Attending to Visually Specified Events. Cognitive Psychology 7 (4), 480-494.

Newby, E. A. & Rock, I. 1998. Inattentional Blindness as a Function of Proximity to the Focus of Attention. Perception 27 (9), 1025-1040.

Nickerson, R. S. & Landauer, T. K. 1997. Human-Computer Interaction: Background and Issues. In M. Helander, T. K. Landauer & P. V. Prabhu (Eds.). Handbook of Human-Computer Interaction. Amsterdam: Elsevier, 3-31.

Norman, D. A. 1988. The Design of Everyday Things. New York: Currency-Doubleday.

Norman, K. L., Weldon, L. J. & Shneiderman, B. 1986. Cognitive Layouts of Windows and Multiple Screens for User Interfaces. International Journal of Man-Machine Studies 25 (2), 229-248.

Olson, G. M. & Olson, J. S. 2003. Human-Computer Interaction: Psychological Aspects of the Human Use of Computing. Annual Review of Psychology 54, 491-516.

Oulasvirta, A. & Saariluoma, P. Long-Term Working Memory and Interrupting Messages in Human-Computer Interaction. Behaviour & Information Technology. In press.

Ozok, A. A. & Salvendy, G. 2000. Measuring Consistency of Web Page Design and Its Effects on Performance and Satisfaction. Ergonomics 43 (4), 443-460.

Palmer, S. E. & Rock, I. 1994. Rethinking Perceptual Organization: The Role of Uniform Connectedness. Psychonomic Bulletin and Review 1 (1), 29-55.

Parker, G., Franck, G. & Ware, C. 1998. Visualization of Large Nested Graphs in 3D: Navigation and Interaction. Journal of Visual Languages and Computing (9), 299-317.

Parush, A., Nadir, R. & Shtub, A. 1998. Evaluating the Layout of Graphical User Interface Screens: Validation of a Numerical Computerized Model. International Journal of Human-Computer Interaction 10 (4), 343-360.

Pashler, H. E. 1998. The Psychology of Attention. Cambridge, MA, US: The MIT Press.

Pearson, R. & Van Schaik, P. 2003. The Effect of Spatial Layout of and Link Colour in Web Pages on Performance in a Visual Search Task and an Interactive Search Task. International Journal of Human-Computer Studies 59 (3), 327-353.

Peterson, M. S. & Kramer, A. F. 2001. Attentional Guidance of the Eyes by Contextual Information and Abrupt Onsets. Perception and Psychophysics 63, 1239-1249.

Pollitzer, E. & Edmonds, E. 1996. Editorial: The Evolving Partnership between Cognitive Science and HCI. International Journal of Human-Computer Studies 44 (6), 731-741.

Pomerantz, J. R. 1981. Perceptual Organization in Information Processing. In M. Kubovy & J. R. Pomerantz (Eds.). Perceptual Organization. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Posner, M. I., Snyder, C. R. & Davidson, B. J. 1980. Attention and the Detection of Signals. Journal of Experimental Psychology: General 109 (2), 160-174.

Posner, M. I. 1980. Orienting of Attention. Quarterly Journal of Experimental Psychology 32 (1), 3-25.

Postma, A. & De Haan, E. H. F. 1996. What Was Where? Memory for Object Locations. Quarterly Journal of Experimental Psychology: Human Experimental Psychology. Special Issue: Working Memory 49A (1), 178-199.

Preece, J., Rogers, Y., Sharp, H., Benyon, D., Holland, S. & Carey, T. 1994. Human-Computer Interaction. Harlow, England: Addison-Wesley.

Proctor, R. W. & Vu, K.-P. L. 2002. Human Information Processing: An Overview for Human-Computer Interaction. In J. A. Jacko & A. Sears (Eds.). The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies, and Emerging Applications. Mahwah, NJ: Erlbaum, 35-51.

Rayner, K. 1983. Visual Selection in Reading, Picture Perception, and Visual Search. In H. Bouma & D. G. Bouwhuis (Eds.). Attention and Performance X. London, UK: Lawrence Erlbaum Associates, 67-96.

Risden, K., Czerwinski, M. P., Munzner, T. & Cook, D. B. 2000. An Inital Examination of Ease of Use for 2D and 3D Information Visualizations of Web Content. International Journal of Human-Computer Studies 53 (5), 695-714.

Ritter, F. E., Baxter, G. D., Jones, G. & Young, R. M. 2000. Supporting Cognitive Models as Users. ACM Transactions on Computer-Human Interaction 7 (2), 141-173.

Ritter, F. E. & Young, R. M. 2001. Embodied Models as Simulated Users: Introduction to This Special Issue on Applying Cognitive Models to Interface Design. International Journal of Human-Computer Studies 55, 1-14.

Robertson, G., Dantzich, M. V., Robbins, D., Czerwinski, M., Hinckley, K., Risden, K., Thiel, D. & Gorokhovsky, V. 2000. The Task Gallery: A 3D Window Manager. In Proceedings of the CHI. ACM Press, 494 - 501.

Rock, I. & Gutman, D. 1981. The Effect of Inattention on Form Perception. Journal of Experimental Psychology: Human Perception & Performance 7 (2), 275-285.

Saariluoma, P. Explanatory Frameworks for Interaction Design. In A. Pirhonen, H. Isomäki, C. Roast & P. Saariluoma (Eds.). Future Interaction Design. Springer-Verlag. In press.

Saariluoma, P. & Kujala, S. 1996. Semantic Distance and Single Cue Use in Category Search. Scandinavian Journal of Psychology 37 (3), 317-328.

Scaife, M. & Rogers, Y. 1996. External Cognition: How Do Graphical Representations Work? International Journal of Human-Computer Studies 45 (2), 185-213.

Schaffer, D., Zao, Z., Greenberg, S., Bartram, L., Dill, J., Dubs, S. & Roseman, M. 1996. Navigating Hierarchically Clustered Networks through Fisheye and Full-Zoom Methods. ACM Transactions on Human-Computer Interaction 3 (2), 162-188.

Schneider, W. X. 1993. Space-Based Visual Attention Models and Object Selection: Constraints, Problems, and Possible Solutions. Psychological Research/Psychologische Forschung 56 (1), 35-43.

Seagull, F. J. & Walker, N. 1992. The Effects of Hierarchical Structure and Visualization Ability on Computerized Information Retrieval. International Journal of Human-Computer Interaction 4 (4), 369-385.

Shaw, M. L. & Shaw, P. 1977. Optimal Allocation of Cognitive Resources to Spatial Locations. Journal of Experimental Psychology: Human Perception & Performance 3 (2), 201-211.

Shaw, M. L. 1978. A Capacity Allocation Model for Reaction Time. Journal of Experimental Psychology: Human Perception & Performance 4 (4), 586-598.

Shepard, R. N. 1967. Recognition Memory for Words, Sentences, and Pictures. Journal of Verbal Learning & Verbal Behavior 6 (1), 156-163.

Shiffrin, R. M. & Schneider, W. 1977. Controlled and Automatic Human Information Processing: II. Perceptual Learning, Automatic Attending and a General Theory. Psychological Review 84 (2), 127-190.

Shinoda, H., Hayhoe, M. M. & Shrivastava, A. 2001. What Controls Attention in Natural Environments? Vision Research. Special Issue: Eye movements and vision in the natural world: In honour of Han Collewijn 41 (25-26), 3535-3545.

Shneiderman, B. 1998. Designing the User Interface: Strategies for Effective Human-Computer Interaction. Reading, Massachusetts, USA: Addison-Wesley.

Spence, R. 2001. Information Visualization. Harlow, UK: Pearson Education Limited.

Sperling, G. 1960. The Information Available in Brief Visual Presentation. Psychological Monographs 74 (11), 29.

Standing, L., Conezio, J. & Haber, R. N. 1970. Perception and Memory for Pictures: Single-Trial Learning of 2500 Visual Stimuli. Psychonomic Science 19 (2), 73-74.

Stanney, K. M. & Salvendy, G. 1995. Information Visualization: Assisting Low Spatial Individuals with Information Access Tasks through the Use of Visual Mediators. Ergonomics 38 (6), 1184-1198.

Stolz, J. A. & Mccann, R. S. 2000. Visual Word Recognition: Reattending to the Role of Spatial Attention. Journal of Experimental Psychology: Human Perception & Performance 26 (4), 1320-1331.

Suchman, L. A. 1987. Plans and Situated Actions: The Problem of Human-Machine Communication. Cambridge: Cambridge University Press.

Tanriverdi, V. & Jacob, R. J. K. 2000. Interacting with Eye Movements in Virtual Environments. CHI Letters 2 (1), 1-6.

Theeuwes, J. 1993. Visual Selective Attention: A Theoretical Analysis. Acta Psychologica 83, 93-154.

Treisman, A. 1982. Perceptual Grouping and Attention in Visual Search for Features and for Objects. Journal of Experimental Psychology: Human Perception & Performance 8 (2), 194-214.

Treisman, A. 1988. Features and Objects: The Fourteenth Bartlett Memorial Lecture. Quarterly Journal of Experimental Psychology: Human Experimental Psychology 40A (2), 201-237.

Treisman, A. M. & Gelade, G. 1980. A Feature-Integration Theory of Attention. Cognitive Psychology 12 (1), 97-136.

Tsal, Y. & Bareket, T. 1999. Effects of Attention on Localization of Stimuli in the Visual Field. Psychonomic Bulletin & Review 6 (2), 292-296.

Tullis, T. S. 1997. Screen Design. In M. Helander, T. K. Landauer & P. Prabhu (Eds.). Handbook of Human-Computer Interaction. Amsterdam: Elsevier Science, 503-531.

Wann, J. & Mon-Williams, M. 1996. What Does Virtual Reality NEED?: Human Factors Issues in the Design of Three-Dimensional Computer Environments. International Journal of Human-Computer Studies 44, 829-847.

Ware, C. 2000. Information Visualization: Perception for Design. San Francisco: Morgan Kaufmann Publishers.

Vertegaal, R. 2003. Attentive User Interfaces: Introduction. Communications of the ACM 46 (3), 30-33.

Westerman, S. J. 1998. A Comparison of the Cognitive Demands of Navigating Two- Versus Three-Dimensional Spatial Database Layouts. Ergonomics 41 (2), 207-212.

Westerman, S. J. & Cribbin, T. 2000. Mapping Semantic Information in Virtual Space: Dimensions, Variance and Individual Differences. International Journal of Human-Computer Studies. Special Issue: Empirical evaluation of information visualizations 53 (5), 765-787.

Vicente, K. J. & Williges, R. C. 1988. Accommodating Individual Differences in Searching a Hierarchical File System. International Journal of Man-Machine Studies 29, 647-688.

Wiedenbeck, S. 1999. The Use of Icons and Labels in an End User Application Program: An Empirical Study of Learning and Retention. Behaviour & Information Technology 18 (2), 68-82.

Wolfe, J. M. 1998. What Can 1 Million Trials Tell Us About Visual Search? Psychological Science 9 (1), 33-39.

Wolfe, J. M., Butcher, S. J., Lee, C. & Hyle, M. 2003. Changing Your Mind: On the Contributions of Top-Down and Bottom-up Guidance in Visual Search for Feature Singletons. Journal of Experimental Psychology: Human Perception & Performance 29 (2), 483-502.

Von Wright, J. M. 1970. On Selection in Visual Immediate Memory. Acta Psychologica 33, 280-292.

Woodman, G. F., Vogel, E. K. & Luck, S. J. 2001. Visual Search Remains Efficient When Visual Working Memory Is Full. Psychological Science 12 (3), 219-224.

Woods, D. D. 1984. Visual Momentum: A Concept to Improve the Cognitive Coupling of Person and Computer. International Journal of Man-Machine Studies 21, 229-244.

Zhai, S. 2003. Attentive User Interfaces: What's in the Eyes for Attentive Input. Communications of the ACM 46 (3), 34-39.

YHTEENVETO (FINNISH SUMMARY)

Tietokoneet ovat monilla elämänaloilla jokapäiväisessä käytössä. Tietokoneiden visuaaliset käyttöliittymät toimivat "ikkunana" tietokoneen tai tietojärjestelmän sisältämään tietoon. Eräs käyttöliittymätutkimuksen tavoite on suunnitella käyttöliittymät siten, että niiden välittämä tieto on mahdollisimman helposti käyttäjän omaksuttavissa ja ymmärrettävissä. Käyttöliittymän visuaalisesta käytettävyydestä kertoo muun muassa se, kuinka helposti ja nopeasti käyttäjä löytää näytöltä haluamansa tiedon tai muun kohteen (objektin). Tähän visuaalisen etsinnän tehokkuuteen vaikuttavat sellaiset asiat kuin näytöllä olevien objektien visuaaliset piirteet (esimerkiksi väri ja muoto), objektien sijainti ja niiden keskinäinen järjestys näytöllä. Väitöskirjatutkimus keskittyy juuri objektien järjestykseen ja sen vaikutuksiin visuaalisissa hakutehtävissä. On oletettu, että järjestyksellä on vaikutusta paitsi hakutehtävän vaikeuteen, myös tiedon ymmärtämiseen ja oppimiseen käyttöliittymässä, mutta asiaa ei ole juurikaan tutkittu.

Väitöskirjatutkimuksessa lähestytään ongelmaa käyttäjäpsykologian näkökulmasta. Käyttäjäpsykologiassa tarkastellaan ihmisen ja tietokoneen välistä vuorovaikutusta tutkimalla käyttäjän psykologisia prosesseja ja kehittämällä psykologisia selityskehyksiä käyttäjän toiminnalle tietokoneen kanssa. Väitöskirjassa käytetään kognitiivisen eli tiedonkäsittelypsykologian selityskehystä tiedon järjestelyongelman analysoimiseen käyttöliittymässä. Kognitiivisen psykologian tietämyksen perusteella rakennetaan visuaalisen etsinnän malli, jonka avulla voidaan selittää tiedon järjestelyn vaikutuksia hakutehtävän tehokkuuteen. Visuaalisen etsinnän mallia kehitetään ja sovelletaan neljässä kokeellisessa tutkimuksessa. Tutkimusten tulokset osoittavat, että malli sopii selittämään tiedon järjestelyn vaikutuksia visuaalisen etsinnän tehokkuuteen. Mallia myös kehitetään tulosten pohjalta eteenpäin.

Väitöskirjatutkimuksessa arvioidaan käyttäjäpsykologista näkökulmaa ihmisen ja tietokoneen välisen vuorovaikutuksen tutkimisessa. Väitöskirjassa osoitetaan, että psykologisen tietämyksen perusteella on mahdollista rakentaa selittäviä tietokehyksiä vuorovaikutuksessa esiintyville käytännön tason ongelmille, ja ratkaista näitä ongelmia tieteellisen tietämyksen avulla. Ympäristön muuttuessa yhä tietokoneistetummaksi myös vuorovaikutusongelmat lisääntyvät ja monipuolistuvat, ja käyttäjäpsykologinen näkökulma voi tarjota laaja-alaisempaa ja kestävämpää tietoa kuin yksittäisten käyttöliittymien käytettävyystestaukset ja –vertailut. Väitöskirjassa kyseenalaistetaan kuitenkin perinteisen kognitiivisen psykologian tutkimuksen sopivuus tähän tarkoitukseen. Enemmän käytännön ongelmista ponnistava ja laajemmin kognitiivisen psykologian teorioita ja tutkimuslöydöksiä yhdistelevä tutkimus soveltuisi paremmin myös ihmisen ja tietokoneen välisen vuorovaikutuksen tutkimiseen. Merkkejä tästä suunnasta onkin jo nähtävissä kognitiivisen psykologian tutkimuksessa.

J Y V Ä S K Y L Ä   S T U D I E S   I N   C O M P U T I N G

1 Ropponen, Janne, Software risk management - foundations, principles and empirical findings. 273 p. Yhteenveto 1 p. 1999.

2 Kuzmin, Dmitri, Numerical simulation of reactive bubbly flows. 110 p. Yhteenveto 1 p. 1999.

3 Karsten, Helena, Weaving tapestry: collaborative information technology and organisational change. 266 p. Yhteenveto 3 p. 2000.

4 Koskinen, Jussi, Automated transient hypertext support for software maintenance. 98 p. (250 p.) Yhteenveto 1 p. 2000.

5 Ristaniemi, Tapani, Synchronization and blind signal processing in CDMA systems. - Synkronointi ja sokea signaalinkäsittely CDMA järjestelmässä. 112 p. Yhteenveto 1 p. 2000.

6 Laitinen, Mika, Mathematical modelling of conductive-radiative heat transfer. 20 p. (108 p.) Yhteenveto 1 p. 2000.

7 Koskinen, Minna, Process metamodelling. Conceptual foundations and application. 213 p. Yhteenveto 1 p. 2000.

8 Smolianski, Anton, Numerical modeling of two-fluid interfacial flows. 109 p. Yhteenveto 1 p. 2001.

9 Nahar, Nazmun, Information technology supported technology transfer process. A multi-site case study of high-tech enterprises. 377 p. Yhteenveto 3 p. 2001.

10 Fomin, Vladislav V., The process of standard making. The case of cellular mobile telephony. - Standardin kehittämisen prosessi. Tapaustutkimus solukkoverkkoon perustuvasta matkapuhelintekniikasta. 107 p. (208 p.) Yhteenveto 1 p. 2001.

11 Päivärinta, Tero, A genre-based approach to developing electronic document management in the organization. 190 p. Yhteenveto 1 p. 2001.

12 Häkkinen, Erkki, Design, implementation and evaluation of neural data analysis environment. 229 p. Yhteenveto 1 p. 2001.

13 Hirvonen, Kullervo, Towards Better Employment Using Adaptive Control of Labour Costs of an Enterprise. 118 p. Yhteenveto 4 p. 2001.

14 Majava, Kirsi, Optimization-based techniques for image restoration. 27 p. (142 p.) Yhteenveto 1 p. 2001.

15 Saarinen, Kari, Near infra-red measurement based control system for thermo-mechanical refiners. 84 p. (186 p.) Yhteenveto 1 p. 2001.

16 Forsell, Marko, Improving Component Reuse in Software Development. 169 p. Yhteenveto 1 p. 2002.

17 Virtanen, Pauli, Neuro-fuzzy expert systems in financial and control engineering. 245 p. Yhteenveto 1 p. 2002.

18 Kovalainen, Mikko, Computer mediated organizational memory for process control. Moving CSCW research from an idea to a product. 57 p. (146 p.) Yhteenveto 4 p. 2002.

19 Hämäläinen, Timo, Broadband network quality of service and pricing. 140 p. Yhteenveto 1 p. 2002.

20 Martikainen, Janne, Efficient solvers for discretized elliptic vector-valued problems. 25 p. (109 p.) Yhteenveto 1 p. 2002.

21 Mursu, Anja, Information systems development in developing countries. Risk management and sustainability analysis in Nigerian software companies. 296 p. Yhteenveto 3 p. 2002.

22 Seleznyov, Alexandr, An anomaly intrusion detection system based on intelligent user recognition. 186 p. Yhteenveto 3 p. 2002.

23 Lensu, Anssi, Computationally intelligent methods for qualitative data analysis. 57 p. (180 p.) Yhteenveto 1 p. 2002.

24 Ryabov, Vladimir, Handling imperfect temporal relations. 75 p. (145 p.) Yhteenveto 2 p. 2002.

25 Tsymbal, Alexey, Dynamic integration of data mining methods in knowledge discovery systems. 69 p. (170 p.) Yhteenveto 2 p. 2002.

26 Akimov, Vladimir, Domain Decomposition Methods for the Problems with Boundary Layers. 30 p. (84 p.). Yhteenveto 1 p. 2002.

27 Seyukova-Rivkind, Ludmila, Mathematical and Numerical Analysis of Boundary Value Problems for Fluid Flow. 30 p. (126 p.) Yhteenveto 1 p. 2002.

28 Hämäläinen, Seppo, WCDMA Radio Network Performance. 235 p. Yhteenveto 2 p. 2003.

29 Pekkola, Samuli, Multiple media in group work. Emphasising individual users in distributed and real-time CSCW systems. 210 p. Yhteenveto 2 p. 2003.

30 Markkula, Jouni, Geographic personal data, its privacy protection and prospects in a location-based service environment. 109 p. Yhteenveto 2 p. 2003.

31 Honkaranta, Anne, From genres to content analysis. Experiences from four case organizations. 90 p. (154 p.) Yhteenveto 1 p. 2003.

32 Raitamäki, Jouni, An approach to linguistic pattern recognition using fuzzy systems. 169 p. Yhteenveto 1 p. 2003.

33 Saalasti, Sami, Neural networks for heart rate time series analysis. 192 p. Yhteenveto 5 p. 2003.

34 Niemelä, Marketta, Visual search in graphical interfaces: a user psychological approach. 61 p. (148 p.) Yhteenveto 1 p. 2003.