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DESIGNERS' MODELS OF THE HUMAN-COMPUTER INTERFACE

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INTRODUCTION

Do people's cognitive models of the human-computer interface (HCI) differ as a function of their experience with HCI design? A cognitive model can be defined as a representation of a person's knowledge consisting of (1) a set of elemental concepts (elements in a model of an HCI might include windows, menus, tables, and graphics), (2) the relations among the elements (for example, a mouse and a touch screen might be related as input devices), and (3) the relations among groups of associated elements (for example, a group of input devices might be related to a group of user-computer dialogue techniques). (See [4], [7], and [10] for additional definitions.)

Cognitive modeling in the area of human-computer interaction has generally focused on how the user represents a system or a task [4]. The results of this approach provide information relevant to Norman's concept of a user's model [9]. In contrast, the present paper focuses on the models of HCI designers, specifically on designers' declarative knowledge about the HCI. Declarative knowledge involves the facts about a given domain and the semantic relations among those facts (e.g., [1]); for example, knowing that the mouse, trackball, and touch screen are all types of interactive devices. The results of our approach provide information relevant to Norman's concept of a design model [9].

Understanding design models of the HCI may produce two types of benefits. First, interface development often requires inputs from two different types of experts—human factors specialists and software developers. The primary work of the human factors specialists may involve identifying the ways in which a system should display information to the user, the interactive dialogue between the user and system, and the types of inputs that the user should provide to the system. The primary work of the software developers may center around writing the code for a user interface design and integrating that code with the rest of the system. Given the differences in their backgrounds and roles, human factors specialists and software developers may have different cognitive models of the HCI. Yet, they have to communicate about the interface as part of the design process. If they have different models, their interactions are likely to involve a certain amount of mis-communication. Second, the design process in general is likely to be guided by designers' cognitive models of the HCI, as well as by their knowledge of the user, tasks, and system. Designers in any field do not start with a *tabula rasa*; rather they begin the design process with a general model of the object that they are designing, whether it be a bridge, a house, or an HCI.

Our approach to a design model of the HCI was to have three groups make judgments of categorical similarity about the components of an interface: (1) human factors specialists with HCI design experience, (2) software developers with HCI design experience, and (3) a baseline group of computer users who had no experience in HCI design. The components of the user interface included both display components such as windows, text, and graphics, and user interaction concepts, such as command language, editing, and help. The judgments of the three groups were analyzed using hierarchical cluster analysis [8],

and Pathfinder ([12] and [13]). These methods indicated, respectively, (1) how the groups categorized the concepts, and (2) network representations of the concepts for each group. The Pathfinder analysis provides greater information about local, pairwise relations among concepts, whereas the cluster analysis shows global, categorical relations to a greater extent.

METHOD

SUBJECTS

Thirty-five subjects (members of a NASA Space Station *Freedom* user interface working group, employees at Lockheed and AT&T Bell Laboratories, and students at Rice University) were assigned to one of three groups on the basis of their work and/or academic experience in human factors and software development: human factors specialists (n = 13), software developers (n = 11), and computer users with no experience in HCI design (n = 11). The human factors specialists reported that their median years of working experience in human factors was 4.5, in user interface issues was 4.5, and in software development was 2. The software development group reported substantially more software experience than the human factors group, a median of 5.5 years of work, slightly longer experience with interface issues, a median of 6 years, but markedly less human factors experience, 1 year. The non-HCI group's relevant experience was minimal, with only software courses (median number of courses = 1) and experience as users of software (primarily for word processing).

MATERIALS

A questionnaire was designed to investigate individual's models and knowledge of the HCI. The first part of the questionnaire consisted of a list of 50 HCI terms (for example, auditory interface, characters, command language, and keystroke) selected from (1) the indices of CHI Proceedings from 1986 to 1988 and (2) recent general books on human-computer interaction ([2], [3], [10], and [11]). Terms were selected based, in part, on their co-occurrence in these sources and the

frequency of occurrence within the sources. The terms were presented in alphabetical order.

The final part of the questionnaire asked for information about the subject's experience with and knowledge of human factors and software design. The answers from this section were used in assigning subjects to one of the three groups.

PROCEDURE

Subjects read a set of general instructions that oriented them to the tasks. Included in these instructions was a comprehensive example that had the subjects apply the procedure to a set of food concepts. Then, subjects started with Part I by reading through the entire list of 50 terms.

If a subject was unfamiliar with a term, he or she was instructed to cross that term off the list. Next, subjects sorted related terms into 'piles' by writing the terms into columns on a data sheet. Subjects could place items in more than one pile or leave items out of any pile.

RESULTS

The results from Part I of the questionnaire were analyzed using two multivariate statistical techniques—hierarchical cluster analysis [8] and Pathfinder analysis ([12] and [13]). The cluster analysis indicates how subjects categorize concepts, whereas the Pathfinder analysis provides a network representation of the concepts.

CLUSTER ANALYSIS: CATEGORIES OF DECLARATIVE KNOWLEDGE

To prepare the data for the cluster analysis, a co-occurrence matrix of the concepts was created for each subject. When a subject placed two concepts in the same pile, a count was entered into the corresponding cell of the matrix. Then, the matrices for all of the subjects within a group were combined. The co-occurrence matrices for each group were converted to dissimilarity matrices by subtracting the co-occurrence value from the

number of subjects plus 1, and a minimum-distance hierarchical cluster analysis was performed.

The cluster analysis displayed in Figures 1A, 1B, and 1C shows substantial differences between the non-HCI group and the experts, but reveals some similarities and dissimilarities between the two expert groups. The data displayed includes only those clusters in which 50% or more of the subjects in that group sorted the items into the same pile. The figures show (1) subclusters with a relatively small number of concepts and for which agreement of categorical co-occurrence was the greatest, and (2) various levels of superclusters consisting of one or more subclusters and additional concepts. The strength of agreement within a group (i.e., the percentage of subjects who placed the concepts in the same category) is indicated by the percentage in the cluster boundary and by the width of the line around a cluster (thicker lines indicate greater agreement). The label for a cluster, selected by the authors, is in bold above the cluster.

The two expert groups had both a greater number of clusters and generally more complex hierarchical relations among the clusters than did the non-HCI group. In addition, both expert groups differed substantially from the nonexpert group in the content of their clusters, with two exceptions: (1) All three groups had relatively high agreement that the terms, *expert user*[1] and *novice user*, belonged to the same cluster, which was hierarchically unrelated to other clusters, and (2) the three groups of subjects categorized *mouse, touch screen, trackball* and *interactive devices* together. However, the types of devices were not part of a larger hierarchy for the non-HCI group, but were included in the Interaction Techniques supercluster for both expert groups. Other areas of basic agreement between the two expert groups were a Guidance/Help supercluster and an Output cluster.

The cluster analysis shows two key areas of disagreement between the human factors and software experts: (1) the contents and organization of the Display Elements cluster and (2) the relation of software concepts to other user interface concepts. In the Display Elements cluster, human factors experts had three categories at the same level in the hierarchy—Textual Elements[2], Graphical Elements, and Tabular Elements. In contrast, software experts had a Graphical Elements subcluster which was nested in a Coding/Graphics subcluster, which, in turn, was nested in a larger Nontextual Display Elements subcluster. Note also that the software developers grouped *color coding* and *highlighting* in the Display Elements subcluster, whereas the human factors specialists grouped those two concepts with *data grouping* and *symbolic codes* in a separate cluster, Display Coding. This difference in categorizing display coding concepts may be due to a greater emphasis by human factors experts on the similarities in function among methods for coding information on a display.

As Figure 1B shows, the software group included six software concepts concerned with the user interface and applications in the User Interface Elements supercluster. In contrast, the human factors group categorized the software-related concepts in a separate supercluster unconnected to other user interface concepts. This finding suggests that, in the software developers' design model, software is more fully integrated with other HCI concepts than it is in the human factors specialists' model.

PATHFINDER: NETWORKS OF DECLARATIVE KNOWLEDGE

The similarity matrices derived from the sorting data for each group were also analyzed with the Pathfinder algorithm using the Minkowski r-metric, $r = \infty$ and $q = 49$ (see [13]). The Pathfinder algorithm generated a network solution for each of the three matrices. However, the network for the non-HCI group was exceedingly complex and difficult to

[1]In the description that follows, the terms from the questionnaire are italicized.

[2]Names for the subclusters are indicated in Figure 1 by a boxed label with an arrow pointing to the specified subcluster.

A

Users
- Expert Users
- Novice Users 73%

Display of Information
- Menus
- Titles & Labels
- Tables 73%
- Text
- Windows
- Message Area 64%

Display of Information
- Graphics
- Icons 55%

Interactive Devices
- Mouse
- Touch Screen 82%
- Trackball 64%
- Interaction Devices 55%

Screen Primitives
- Characters
- Cursor 55%

Data Manipulation
- Paging & Scrolling
- Searching 100%
- Exiting
- Saving Data 73%
- Color Coding
- Highlighting
- Editing 64%

B

Users
- Expert Users
- Novice Users 73%

Help
- On-line Help
- User Guidance 82%
- Printed Manuals 73%

User Interface Elements
- Interaction Devices
- Mouse
- Touch Screen
- Trackball 91%
- Function Keys
- Keyboard Input 82%
- Auditory Interface
- Command Keystrokes
- Command Language
- Natural Language 73%
- Speech Recognition 64%

- Graphics
- Icons 91%
- Color Coding
- Highlighting
- Windows 82%
- Cursor
- Display of Information
- Menus
- Command Line/Area
- Titles & Labels
- Message Area 73%
- Characters
- Tables
- Text 64%

Application Software
- Programming
- Prototyping
- UIMS
- Interactive Devices 55%

Data Manipulation
- Saving Data
- Searching 73%
- Exiting 64%
- Editing
- Paging & Scrolling 64%
- Data Entry 55%

Output
- Output Devices
- VDT 82%
- Hardcopy Presentation 55%

Interaction Techniques

Display Elements

C

Users
- Expert Users
- Novice Users 92%

Data Manipulation
- Saving Data
- Searching 100%
- Exiting 85%
- Editing 77%
- Data Entry
- Paging & Scrolling 69%

Help
- On-line Help
- Printed Manuals 77%
- User Guidance 62%

Output
- Hardcopy Presentation
- Output Devices
- VDT 54%

Software
- Programming
- Prototyping 85%
- Display Manager
- UIMS 69%
- Application Software 54%

User Interface Elements
- Mouse
- Touch Screen
- Trackball 100%
- Interactive Devices 92%
- Function Keys
- Keyboard Input 77%
- Command Language
- Natural Language 85%
- Direct Manipulation 77%
- Command Keystrokes
- Interactive Dialogues 69%
- Auditory Interface
- Speech Recognition 62%

Interaction Techniques

- Characters
- Cursor
- Message Area
- Command Line 77% — Textual
- Icons
- Windows 77% — Graphical
- Tables
- Titles & Labels 77% — Tabular
- Menus
- Text
- Graphics 69%

Display Elements

- Color Coding
- Highlighting 100%
- Data Grouping
- Symbolic Codes 62% — Display Coding
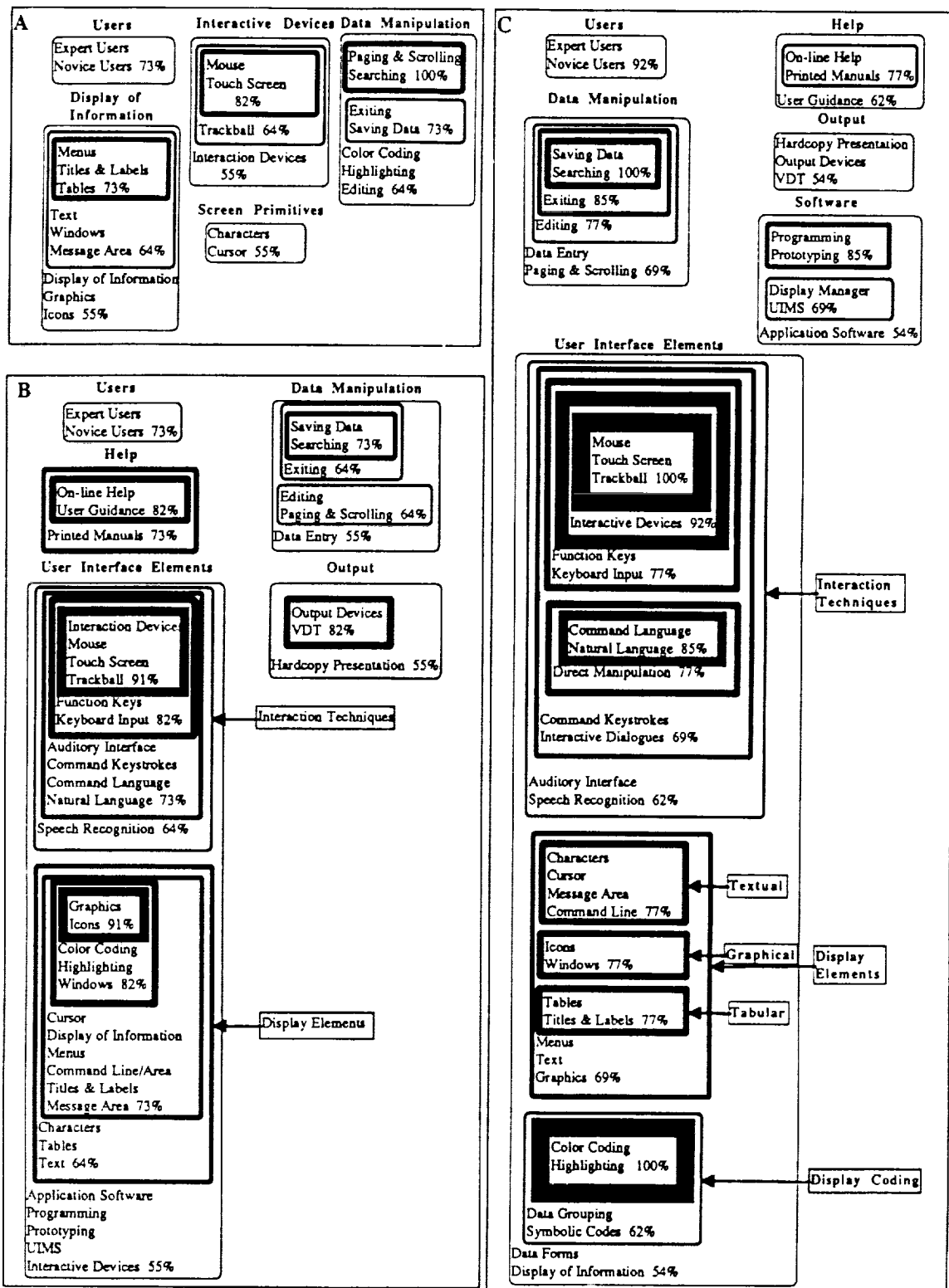
- Data Forms
- Display of Information 54%

Figure 1. Cluster analysis for non-HCI subjects (1A), software developers (1B), and human factors specialists (1C).

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interpret, with 171 links among the 50 concepts. Consequently, we will only focus on the more interpretable results from the two expert groups. The human factors group had 81 links and the software experts 69 links among the 50 nodes. Figure 2 shows the results of the Pathfinder analysis for the human factors (2A) and software experts (2B). The graphs show each concept as a node in a network and show the links between the nodes. The strength of each link is represented by its width, with wider lines indicating stronger connections.

Human Factors Specialists. The network representation for the human factors experts consists primarily of subnetworks of interconnected concepts, indicated in Figure 2A by the dashed lines around the groups of concepts (with subnetwork labels, selected by the authors, contained in the boxes pointing to the relevant subnetwork). Subnetworks were defined as groups of three or more concepts, in which each concept linked directly to at least two other concepts in that subnetwork, and in which the interconcept distance was no greater than two links for all concepts. This definition maintains a high level of interconnection and close association of concepts within the subnetwork. With the exception of *speech recognition*, which appears in both Input Devices and Advanced User Interface Techniques, the subnetworks are cleanly separated, in that the concepts are not shared by subnetworks.

Each subnetwork for the human factors experts connects with other subnetworks. Several of the subnetworks have a direct link between two concepts. For example, the User-Computer Dialogue Methods subnetwork and the Input Devices subnetwork are connected by a link between *command keystrokes* and *function keys*. The other subnetworks make connections through one or two intermediate concepts. For example, *menus* provides a conceptual connection between User-Computer Dialogue Methods and Graphical Display Elements. Similarly, *data forms* links the Data Manipulation subnetwork to Information Display Types.

Only a few concepts are offshoots of a subnetwork unconnected to another concept— *graphics, natural language, command line,* and *user guidance.* The major departure from the subnetwork structure is the string of concepts related to software, with *display of information* linked to *display manager,* which connects with *UIMS,* which in turn links to *prototyping,* and so on.

Software Developers. The structure of the network representation for the software experts (Figure 2B) consists of both (1) central nodes from which links radiate out in axle and spoke fashion and (2) subnetworks consisting of interconnected concepts. We defined a central node as a concept with at least three links in addition to any links it might have within a subnetwork. Central nodes are shown in grey in the figure; as in Figure 2A, subnetworks are bounded by a dashed line with labels contained in boxes.

The software experts had only two subnetworks containing more than three concepts, Data Manipulation and Information Output, and had only three triads of concepts. Among the central nodes, both *mouse* and *expert users* are of interest because they link directly to other central nodes, with *mouse* having strong connections to *interactive devices* and *keyboard input* and *expert users* weakly linked to *programming* and *natural language.* In addition, *mouse* functions both as a member of a subnetwork and as a central node. *Graphics* is also well connected, with membership in two subnetworks and central node status.

Comparing the Expert Groups. The networks reveal important differences between the two expert groups. Overall, the ratio of the number of links shared by the two groups to the total number of links was 0.23. Looking at specific concepts, several of the concepts that have only one link in one group's representation are strongly interconnected in the other group's network. For example, *graphics* and *natural language* are linked directly to a number of other concepts in the software experts' network, but have only one link apiece for human factors experts.
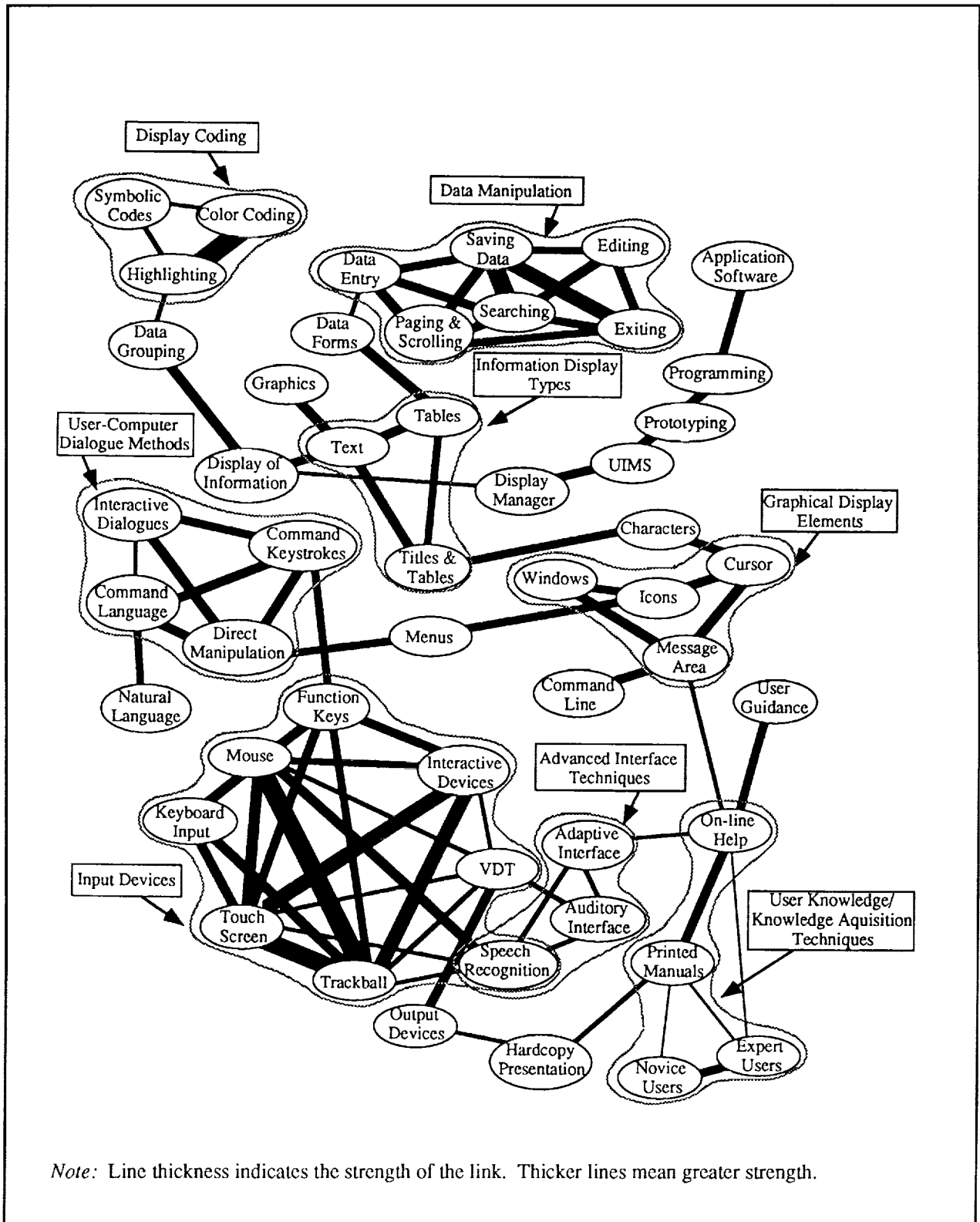
Note: Line thickness indicates the strength of the link. Thicker lines mean greater strength.

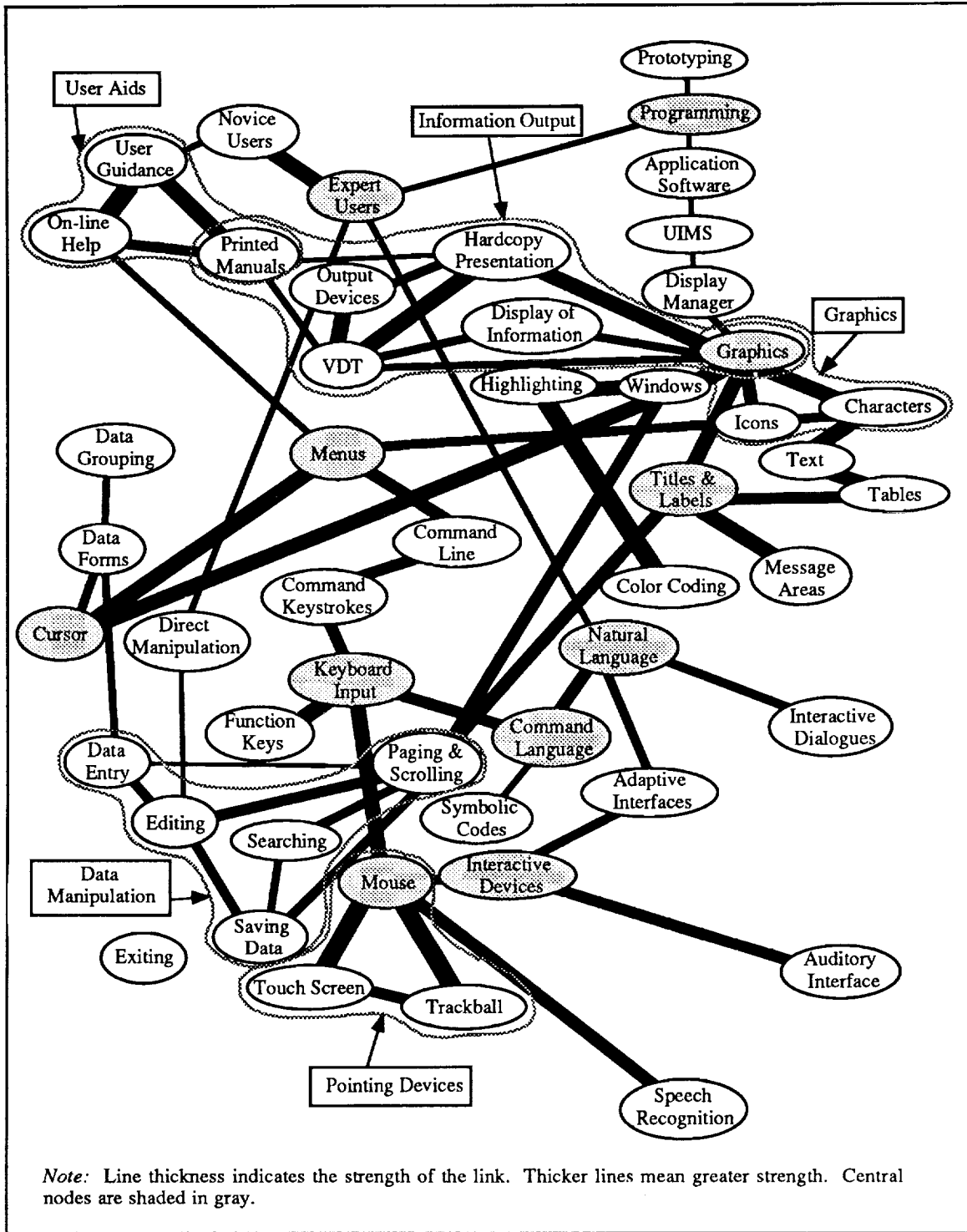**Figure 2A.** Pathfinder network for human factors specialists.

Figure 2B. Pathfinder network for software developers.

On the other hand, *function keys* is a member of the Input Devices subnetwork and connects that subnet work to the User-Computer Dialogues subnetwork for human factors experts, but links only with *keyboard input* for software experts. An additional difference is

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that the networks for the software and human factors experts show no overlap between the concepts that link to only one other concept.

When a concept has the same number of direct links for the two groups, it may reveal important differences in the design models if it differs in the other concepts to which connections are made. For example, look at *user interface management system* in Figures 2A and 2B. For both groups, one of its connections is with *display manager*, indicating knowledge of the relationship between the software that manages the entire user interface and the software that writes to the screen. For human factors experts, the other connection of *UIMS* is with *prototyping*, suggesting that the prototyping capability is an important part of a UIMS for interface designers with a human factors background. However, for software experts, *UIMS* connects with *application software*, which is consistent with the software architecture of the user interface—with the UIMS interacting with the application software, as well as the display manager.

DISCUSSION

GENERAL EFFECTS OF HCI DESIGN EXPERIENCE

The data from both the cluster analysis and Pathfinder analysis show differences as an effect of expertise in human-computer interaction. Both expert groups had (1) a greater number of clusters containing more concepts and (2) more complex hierarchical structures of the clusters than did the non-HCI group. The Pathfinder solution for the non-HCI group was a mass of links between concepts with minimal differentiation. In contrast, both expert groups showed substantial and meaningful differentiation of groups of concepts within the networks. These findings indicate that training and experience with HCI design has a clear impact on the mental model of the interface. This finding, by itself, may not be surprising. However, many people outside of the field of human-computer interaction may hold contrary opinions—for example, that HCI design is simply a matter of common sense or that computer users' experience is the equivalent of HCI design experience. The present data argue against those opinions by showing the effects of user interface design experience.

EFFECTS OF SPECIFIC HCI DESIGN EXPERIENCE

Differences between the mental models of experts and novices abound (for example, see [5]). We present evidence here that experts may differ in their cognitive models as a function of their roles and experience in a common area of expertise.

The Pathfinder analyses suggest that the different types of experts differ in the overall organization of their cognitive models. Human factors experts had a network made up of distinct subnetworks, with the subnetworks tending towards heavy internal interconnection with a single connection between subnetworks. The software experts' cognitive model had multiple organizing schemes, including central nodes, as well as complex and simple subnetworks. Cooke, Durso, and Schvaneveldt [6] have shown that the network representations derived by Pathfinder are related to recall from memory, with closely linked items in the Pathfinder network being more likely to be recalled together. Consequently, recall of an HCI concept may tend to have an effect that is localized within the subnetwork for human factors experts. However, recall of that same concept may spread more broadly for software experts. For example, a software developer who thinks of *keyboard input* would be likely to recall *mouse, function key, command keystrokes*, and *command language*. In contrast, *keyboard input* would be most likely to produce recall of only *mouse* and *function keys* for human factors experts. The localization of recall might help human factors experts to maintain a more focused stream of thought, but the broader spread of recall may help software experts to think more innovatively about HCI concepts by activating more varied concepts.

Differences in the concepts that are linked or in the categories in which HCI designers place

concepts might be expected as a function of experience. For example, software developers would be much more likely to see the relations between software and other HCI concepts than would human factors specialists. However, why would these two groups have very different organizing schemes for their concepts? One possibility is that software developers have to be concerned with both the ways in which the HCI software will be used and with the methods for implementing the software. In other words, their cognitive model may represent a compromise between knowledge about the function and about the implementation of the human-computer interface. In contrast, the cognitive model of human factors specialists may be more closely tied only to function.

PRACTICAL IMPLICATIONS

The Pathfinder and cluster analyses showed substantial differences in the number of connections and the conceptual links for a variety of the HCI concepts, such as *graphics* and *function keys*. These findings suggest that design team members with different types of expertise should take care to define their terms when discussing the conceptual categories— user interface elements and display coding— and about specific concepts like graphics, function keys, speech recognition, and natural language. A term like graphics may evoke a more elaborate set of associated concepts for design team members with backgrounds in software development than it does for those in human factors, whereas function key may evoke more concepts for human factors specialists.

One way of eliminating the problems of miscommunication due to different design models might be to train all of the designers to think alike. However, even if this were possible, it might lead to unintended problems in user interface design. Diversity of thinking may improve the design process. Thus, training out the diversity might result in a team that could not make conceptual breakthroughs or recognize when they were going down a blind alley. The best user interface designs are likely to emerge when the human factors

specialists on a team can think their way and the software developers can think their way, but when each member understands the meaning of the others' thoughts when expressed in language or design. The representation of design team members' cognitive models described in this paper provides the first step in enhancing that understanding.

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