Chapter 7

General Discussion

This chapter will provide a short conclusion, discussion of future research and a list of original contributions.

7.1 Conclusion

I have proposed to study human hypertext navigation and design from the perspective that users and designers create internal models of the relations among documents in hypertext systems and apply these to respectively the implementation of hyperlink structure and a difference-reduction navigation strategy referred to as Hill-Climbing. These internal models were referred to as Designer and User Mental Models, and were represented by weighted, directed graphs. I proposed to refer to the aggregated mental models of a group of subjects as the group’s Collective Mental Model which can be represented by a directed weighted graph.

I presented a hill-climbing model of human hypertext navigation which aimed to predict human hypertext navigation paths. The model is based on the assumption that human navigators select hyperlinks to increase the associative weight of intermediate path positions to a pre-determined target. The information required to make such an evaluation is stored in the user’s mental model.

Support for this model was generated by reconstructing user navigation paths from a web site log and comparing these user navigation paths to hill-climb model predicted paths. A Levenshtein distance measure was used to perform this comparison. The hill-climb model operated on a Collective
Mental Model representation derived from a set of user request sequences as they were recorded in a web site's log files. The results indicated the hill-climb model can predict the navigation paths of users well above chance levels and above levels recorded for an alternative set of hill-climb model predictions based on document proximities that were derived from the web site's hyperlink structure.

I presented a methodology to adapt a hypertext network's hyperlink structure to the traversal patterns of a group of users, so that hypertext network structure would be determined by the preferences of its users rather than those of a designer. Three learning rules increased hyperlinks weights according to patterns of user hyperlink traversals. The hyperlink structure gradually converged to a stable configuration representing the users' Collective Mental Model. A series of simulations confirmed the reliability and validity of network development.

Finally, I presented a spreading activation system that generated page recommendations for a web site for which a CMM had been generated from user request sequences. A qualitative analysis of the system's functionality indicated its ability to assess the information needs of a user by a continuous process of spreading activation query expansion,

The main tenet of this dissertation research was that human hypertext design and navigation should not be studied as two unrelated activities, determined by the random or unpredictable preferences of designers and users. Rather I proposed that both were constrained by common knowledge of concept relations that designers and users share to a certain extent. The ability to capture this knowledge for a set of documents from the design or navigation behavior of a group of subjects allows the quantitative study of human hypertext design and navigation, and the implementation of systems that exploit this knowledge to improve both hypertext design and retrieval.

The analysis of human-hypertext interaction proposed in this dissertation, in my view, constitutes the basis for a general research program concerning the design and use of hypertext systems and the larger class of Distributed Information Systems. Throughout the dissertation I have provided empirical support for a number of specific hypotheses in human hypertext navigation and design, and, by doing so attempted to partially validate the proposed analysis. This effort is necessarily incomplete given the complexity of the subject of this study. The following sections discuss
some of the many remaining issues for future research.

7.2 Future Research

The research presented in this dissertation touches on a large number of subjects in hypertext navigation and design. In this section, I expand on what I consider the most relevant possibilities for future research. I do so in two contexts: the improvement of the presented research and the expansion of the presented approach to new research subjects. My discussion will be organized according to the sequence of chapters in the dissertation.

7.2.1 Hill-Climb Model

I proposed a hill-climb model of human hypertext navigation and investigated its validity in chapter 4. The validity of the hill-climb model was investigated from an empirical perspective. Consequently, a number of questions regarding its formal and mathematical characteristics remain open to further research.

Properties of CMM

The HCM operates on two representations, namely the hyperlink structure of a hypertext system and the users' CMM. The efficiency of hill-climb searches can be related to the "landscapes" they are required to operate on. For example, hill-climbing is known to perform poorly in landscapes with many local maxima.

A mathematical analysis of how certain properties of the CMM relate to measures of navigation efficiency would be an interesting subject for future research. Certain measures of the CMM could express the degree to which its structure has many or few local maxima, for example "entropy" (Shannon, 1949) (Pierce, 1961). These measures could be related to the success/fail ratios of the HCM in a formal fashion. The results from such an analysis may aid in the formal assessment of specific hypertext designs.

CMM and Hyperlink Structure Relation

The other issue to be investigated is the relation between the CMM structure and hyperlink structure, and how this relation affects the characteristics of the user navigation patterns given they apply a hill-climbing navigation
strategy. Two main issues merit further exploration. First, can a similarity measure between the CMM and hyperlink structure be related to navigation efficiency? Second, given the sparseness of hyperlink structure and the generated CMM, how does this affect the performance of the hill-climb model of navigation?

Future research will focus on whether certain relations between the CMM and hyperlink structure can be mathematically shown to optimize hill-climbing hypertext navigation. It is highly plausible that the efficiency of hill-climbing navigation increases as the structural similarity between the hyperlink structure representation and the CMM structure increases. This is moreover in line with the generally accepted, but often speculative, notion in human-computer interaction that for the user to efficiently interact with a certain system his or her mental model needs to be congruent with the actual behavior and construction of the system.

In section 4.14.2 I provided support for the hypothesis that HCM success rates are related to the associative weight between a navigation path start and target page. These results point to the possibility that human hill-climbing navigation can be optimized by changing hypertext structure to correspond to high associative weights in the CMM. A highly relevant subject for future research would be to not only show that this can be done, but also address the matter in a formal manner to explain this relation. First steps toward such an analysis have been taken.

The representations of the PCP hyperlink structure and the CMM were both highly sparse. The example of a hill-climb search in a hypothetical hypertext network in section 3.6.2 demonstrates how the weights of the incoming connections to a certain target page represent a landscape in which hill-climbing is conducted. When the values of the matrix representing the hypertext network's hyperlink structure are pair-wise compared to these weight values, a sampling of this landscape is conducted so that the best hyperlink alternative can be selected. The degree of sparseness of both CMM and hyperlink structure will strongly affect this process. Given two highly sparse hyperlink and CMM representations, the overlap of available hyperlinks and existing CMM weight values will strongly determine the range of evaluations the HCM can make. A formal analysis of this process is required to improve our understanding of how this sparseness affects navigation ef-

\[1\text{Column vector of CMM matrix corresponding to navigation target}\]
ficiency and which levels are acceptable to generate adequate HCM path predictions.

Extensions of the HCM

The proposed HCM lacked a number of features that are generally used to improve its search efficiency, e.g. backtracking. However, the intention of the proposed HCM was not to provide an efficient search heuristic, but to propose a model of human hypertext navigation that could be reliably compared to user navigation paths. The addition of backtracking or the mentioned selection and target relaxation would render such a comparison highly problematic since the failure or success of the model to predict a specific user navigation path could be attributed to any combination of the HCM extensions.

However, a number of additions to the HCM could be made and empirically tested. The model at present generates HCM path predictions on the assumption that a user is aiming to retrieve a specific page. This is unrealistic since users would not apply a search heuristic if they knew the exact page they are trying to retrieve. In the WWW users would simply enter a URL and retrieve the page directly. However, this assumption is required to generate HCM path predictions.

Future research will focus on how the HCM can be improved by “target relaxation”, as discussed in section 3.6.3. A user could more realistically be assumed to navigate toward a set or “neighbourhood” of pages that corresponds to a certain information need. When a page has been retrieved that is sufficiently similar to this pre-determined, general information need, the navigation path terminates. The HCM could simulate such a procedure by making its stop condition dependent on a threshold. Once a certain page has been retrieved whose association weight relative to a certain goal surpasses the threshold, the path terminates. Lower levels of the threshold would simulate more recreational searches, higher levels could make hill-climbing increasingly directed toward the retrieval of specific pages.

A similar procedure could be applied to the evaluation of HCM path predictions. Rather than to match an entire HCM path prediction to an entire user navigation path, the comparison could be performed based on the associative weights between the pages in the predicted path and the user path. The Levenshtein distances deletion and substitution penalties could
be determined by the association weights in the CMM. When, for example, a predicted path deviates from the user navigation path, the extent of this deviation could be assessed by taking into account the associative weight between retrieved node and predicted node. Similarly, the HCM path prediction could be considered successful when it locates a page with a sufficient associative weight to the presumed user navigation target.

The methodology presented in section 4.14.1 could be applied to study the occurrence of backtracking in user navigation paths. A hypothesis could be formulated that states that users backtrack when they fail to increase the association weight between a subsequent position and the present path position with a certain amount. The evolution of PGAS values in user paths could be used to predict user backtracking. The HCM model could monitor the evolution of PGAS values in its path predictions and backtrack once a certain minimum increase in PGAS value is no longer possible. By comparing the backtracking behavior of the HCM model and backtracking events in user navigation paths, a model could be formulated to predict user backtracking behavior, and extend the HCM with this functionality.

**HCM Evaluation of Hypertext Design Quality**

HCM path predictions were generated from a CMM measurement as well as a set of structural proximities derived from the PCP web site hyperlink structure. Although the matrix representing the CMM, \( H_c \), and the matrix representing structural proximities derived from PCP hyperlink structure, \( \hat{H}^{(m, out)} \), differ strongly in terms of density (respectively 3.1% and 68%) the overall numbers of HCS for HCM path prediction generated from both structures did not (respectively 11% and 14.6% of all generated HCM predictions).

One could speculate that the relatively stable percentage of HCS over all HCM predictions represents a certain characteristic of the PCP web site, namely its ability to support goal-directed user navigation. Lacking a formal analysis of which characteristics of hypertext structures support goal-directed navigation, the HCM predictions may be used to assess or compare the degree to which a web site supports goal-directed navigation by generating large numbers of HCM path predictions, and recording the number of HCS predictions. The application of the HCM to a number of web sites other than the PCP web site will enable such comparisons.
7.2.2 Testing the Hill-Climb Model

I proposed an experimental methodology in which user navigation paths were reconstructed from a web site's log files. A CMM was generated from request sequences stored in a different server log file and used to generate HCM path predictions. These predictions were compared to reconstructed user navigation paths by means of a Levenshtein measure of string distance. Results indicate the HCM predictions match user navigation path above chance levels, and above the levels found for an alternative set of HCM path predictions generated from page proximities derived from hyperlink structure.

CMM Measurements

The generated CMM measurement conducted within the framework of the experimental methodology used in chapter 4 suffers from a number of shortcomings:

1. The CMM generation was based on web log reconstructed request sequences. This introduced a possible bias since the CMM was partly dependent on the hyperlink structure and used to generate HCM path predictions for user paths within that same hyperlink structure.

2. Many request sequences were not constrained by the hyperlink structure of the PCP web site. The degree to which valid associative relations could be derived from these request sequences was unknown.

Both problems are caused by the reliance of the presented methodology on user request sequences from a web site's log file to generate a CMM representation.

Future research will therefore focus on the use of independently constructed CMMs, possibly by means of concept mapping, or the use of a variation of the adaptive hyperlinking methodology discussed in chapter 5. Preliminary tests have been conducted in which subjects navigate a small individual adaptive hypertext network which converges to a representation of their UM. These individual UMs can be used to generate personalized HCM path predictions. In addition, the compatibility of the UMs of different subjects can be evaluated in terms of how well one subject's UM can be used to generate HCM path predictions for another subject navigation behavior.
Sensitivity Analysis

Two conclusions can be drawn from the large number of validity removals discussed in section 4.6.5:

1. The IP-TimeOut methodology fails to reconstruct valid navigation paths.

2. Very few PCP users apply a strictly goal-directed navigation strategy.

Given that at least some PCP users apply a goal-directed navigation strategy it is likely that the IP-TimeOut methodology in a uncertain number of cases fails to reconstruct valid user navigation paths.

The IP-TimeOut path reconstruction methodology uses a number of parameters whose effects on the validity of reconstructed paths is unknown. Most specifically the value of the path determination threshold ($\Delta_t$) can exert a strong influence on the validity and characteristics of the reconstructed navigation paths. A sensitivity analysis is required in which the value of $\Delta_t$ is varied within a certain range. The rate of successful HCM path predictions of user navigation paths can be determined for each value of $\Delta_t$. The variance of results will indicate the sensitivity of the experimental design to the values of $\Delta_t$.

Controlled Experiments

The experimental methodology discussed in section 4.3 relies on the assumptions that user navigation paths can be correctly reconstructed, and that the last page in a reconstructed path corresponds to the user’s target. This introduces a large degree of uncertainty to the experimental methodology and the conclusions that can be drawn from the generated data.

The use of human subjects could solve this methodological problem. Human subjects could be assigned specific start and navigation targets in a given web site. The recorded paths could be compared to the HCM path predictions. This procedure avoids three problems associated with the methodology applied in this dissertation.

First, since the methodology relies on in situ recorded navigation paths, no extensive user navigation path reconstruction methodologies need to be applied. The methodology is therefore no longer dependent on a particular
method for path reconstruction and the possible biases associated with such a procedure.

Second, no assumptions have to be made regarding a reconstructed user path's start and target.

Third, a randomization of user navigation path's start and target pages can be performed so that the generated results are not sensitive to certain biases in the reconstructed navigation paths in terms of the portion of the web site they occurred in.

Different Corpi
The PCP web site can not be considered a typical of hypertext network. Its structure is a hybrid between a well-designed loose hierarchy of concepts, and a certain narrative structure within the content of the pages. Its content is furthermore of a highly specialized nature.

Future research will focus on the use of different corpi to assess the validity of the presented HCM, and an investigation into the extent to which a CMM generated for one web site can be applied to HCM path predictions for another web site.

7.2.3 Dynamic Hypertext Generation
I proposed a system that changed the weights of hyperlinks in a reduced hypertext network according to user traversal patterns. The system was shown to converge reliably to a valid representation of the users' CMM. The re-test reliability and validity of the system were evaluated using a simulation of user hyperlink traversal behavior. The final structure of the generated networks were cross-validated to a set of free word association norms.

Application to Hypertext Systems
The proposed methodology for the automated restructuring of hyperlink structure can in its present form not be applied to actual hypertext networks. Hyperlinks in the present implementation are anchor-less and network structure is communicated to users by rank-ordering of hyperlinks. To implement a similar adaptive hyperlink functionality for hypertext systems with text content the system will have to be extended so that changes in hyperlink structure can be communicated to users by means that address
the integration of the anchors of adaptive hyperlinks into the system's text content.

Future research will focus on how the present representation of hyperlinks as node-to-node edges can be expanded to accommodate for in-text anchors and targets. A system that assigns specific keyterms to hyperlinks which can be matched against text content, can be implemented to adapt hyperlinks that change their position in a node's content according to these keyterms and their weight values.

**Evaluation of Hypertext Network Quality**

The presented adaptive hypertext methodology has been shown to adapt the weight values of hyperlinks in a reduced hypertext network so that network structure reliably converges from an initially random structure to a valid representation of the users' CMM. The experimental networks were initialized to a random structure to avoid experimental biases resulting from an existing hyperlink structure.

The hyperlink structure of most hypertext systems, however, is not random but the result of an explicit design effort. Future research will focus on the use of the adaptive hypertext methodology to assess the quality of an existing hypertext design as follows. Given an existing hypertext network design, this network can be subjected *a posteriori* to the adaptive hypertext methodology. By the hyperlink traversal patterns of the users of the hypertext network its structure will gradually change. The extent to which the hyperlink structure changes from the existing design can then be used as a measure of the quality of the initial structure. A similar system has recently been proposed by (Chan, 1999) who proposes to assess the quality of hypertext design by comparing an existing hypertext network's graph-theoretical structure to frequency counts of hyperlink traversals.