Supporting and Exploiting Spatial Memory in User Interfaces

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Contents

Abstract

Spatial memory is an important facet of human cognition – it allows users to learn the locations of items over time and retrieve them with little effort. In human-computer interfaces, knowledge of the spatial location of controls can enable a user to interact fluidly and efficiently, without needing to perform slow visual search. Computer interfaces should therefore be designed to provide support for developing the user's spatial memory, and they should allow the user to exploit it for rapid interaction whenever possible. However, existing systems offer varying support for spatial memory. Many break the user's ability to remember spatial locations, by moving or re-arranging items; others leave spatial memory underutilised, requiring slow sequences of mechanical actions to select items rather than exploiting users' strong ability to index items and controls by their on-screen locations. The aim of this paper is to highlight the importance of designing for spatial memory in HCI. To do this, we examine the literature using an abstract-to-concrete approach. First, we identify important psychological models that underpin our understanding of spatial memory, and differentiate between navigation and object-location memory (with this review focusing on the latter). We then summarise empirical results on spatial memory from both the psychology and HCI domains, identifying a set of observable properties of spatial memory that can be used to inform design. Finally, we analyse existing interfaces in the HCI literature that support or disrupt spatial memory, including space-multiplexed displays for command and navigation interfaces, different techniques for dealing with large spatial data sets, and the effects of spatial distortion. We intend for this paper to be useful to user interface designers, as well as other HCI researchers interested in spatial memory. Throughout the text, we therefore emphasise important design guidelines derived from the work reviewed, as well as methodological issues and topics for future research.

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1

Introduction

Spatial memory plays an important part in our day-to-day lives. In the physical world, our ability to recall spatial information enables us to locate items in our homes without having to search, automatically navigate in previously-encountered environments, drive to work without the use of a map, and perform many other activities that would otherwise require substantial cognitive and physical effort.

Evidence that spatial memory is a particularly powerful capability of the human brain can be found in mnemonic literature [186, 13], and dates back thousands of years. The ancient Greeks and Romans used spatial mental organisations based on the architecture of the time, known as *memory palaces*, to connect, organise, and memorise unfamiliar ideas, particularly for the purposes of public speaking. This was called *the method of loci*. By embedding key images representing topics in a mental representation of a spatial environment, such as the rooms in a familiar building, orators were able to memorise extremely long sequences of topics. These could then be retrieved by mentally walking through the building and viewing the images in their respective spatial locations [186, 13].

In human-computer interaction, spatial memory provides many of

the same benefits as in the real world: a strong spatial knowledge of interface layouts and control locations, particularly in graphical user interfaces, allows users to substantially reduce the cognitive and physical effort required for interaction. Evidence for the benefits provided by spatial memory can be found in the strong correlation between measures of spatial ability and interface performance [55, 104, 130]. Users who are unfamiliar with an interface must spend considerable time searching for controls, because the time to perform visual search is proportional to the number of items [80, 129, 152, 24]. In contrast, users who are familiar with a spatially-stable interface do not need to carry out visual search, and can instead simply retrieve item locations. This is much faster than searching because retrieval time is a logarithmic function of the number of items [73, 83, 24].

Furthermore, extensive spatial knowledge of an application's controls enables interaction *automaticity* [150], which substantially frees the user's cognitive resources from the need to consider interface mechanisms, allowing the user to instead focus on higher-level task considerations. Spatial knowledge of the locations of controls can also decrease the frustration that arises from the need to search for unfamiliar controls or controls that have moved. We therefore contend that allowing and encouraging users to utilise their spatial memory whenever possible should be an important goal for interface designers.

Broadly speaking, there are two classes of task that spatial memory can be applied to: navigating through environments (e.g., [112]), and remembering object locations (e.g., [137]), with only partial correlations in spatial ability between the two [71, 20]. The former task is relevant within certain aspects of HCI, such as navigation through virtual environments (e.g., [32, 144]). The latter task of object location memory, in contrast, is a fundamental component of everyday interaction with computing systems, such as finding items in a menu, finding files on a desktop, or finding apps on an iPhone home screen. The psychology literature reviewed in this paper therefore focuses mainly on object location memory rather than navigation, although we do refer to navigation literature in situations where the findings are broadly applicable.

Our review has three primary goals: first, to summarise the state of HCI and psychology research on spatial memory, in order to provide an introduction for newcomers to the field; second, to provide design guidance in the form of heuristics for user interface engineers, enabling rapid development of interfaces that support spatial memory; and third, to provide methodological advice and identify promising directions for future research. To this end, in each section we extract and formalise key lessons from the literature into 'UI Design Guidelines' for interface designers and 'Methodological Cautions' for researchers; similarly, when results are unclear or useful knowledge is missing from the literature, we identify specific 'Research Questions' that indicate promising avenues for future research.

This review is structured as follows. First, we begin by describing underlying psychological models of spatial memory; we then review the empirically-observable properties of spatial memory; and in later sections we describe concrete exemplars of user interfaces that exploit, affect, or are affected by spatial memory. This progression from abstract to concrete allows us to frame results from the HCI domain in terms of underlying psychological principles, better enabling the generation of general design recommendations.

To elaborate, in Chapter 2, we introduce a set of baseline models and principles from the cognitive psychology literature on spatial memory. We provide evidence distinguishing object memory from navigation, examine Baddeley's model of working memory, discuss the mechanisms by which long-term memories form and decay, and examine spatial reference systems.

Next, in Chapter 3, we turn our attention to the observable properties of spatial recall: that is, empirically-verifiable characteristics that can be used to inform design. Here, we draw conclusions from literature in both the cognitive psychology and HCI domains, investigating the time taken to retrieve spatial information from memory, recall accuracy, the effects of effortful and incidental learning, the capacity and longevity of spatial memory, variation between individuals, and perceptions of performance. In each of these sections, our goal is to draw conclusions about how best to design user interfaces to take advantage

of human spatial abilities.

The findings in these two chapters provide a context for Chapter 4, which presents a summary and analysis of interfaces in HCI research that support, disrupt, or otherwise interact with the user's ability to utilise their spatial memory. We consider space-multiplexed command and navigation interfaces that utilise the whole screen, as well as ways to deal with information spaces that are much larger than the display (such as pan+zoom, scrolling, and overview+detail interfaces); we also consider the ways that interface designs can lead to location changes or distortions of space, and how these strategies affect spatial memory. Finally, we look at differences between interaction techniques, and how extra cues (such as proprioceptive or auditory feedback) can enhance spatial understanding.

We intend that the design lessons and research directions highlighted in the paper will stimulate productive future research and development of interfaces that support and make use of human spatial memory.

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