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Supporting and Exploiting Spatial Memory in User Interfaces

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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.

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.

2

The Psychology of Spatial Memory

In this chapter, we provide a high-level introduction to relevant psychological models and theories of spatial memory. Since this paper concerns the application of spatial memory to HCI, it is tempting to take a black-box approach and limit our analysis to the empirically observable characteristics that occur during interaction; however, as we will see in Chapter 3, some knowledge of the underlying psychological theory is necessary to better comprehend the observed phenomena. It is worth noting that although we attempt to draw a distinction between models in this chapter and empirical work in Chapter 3, there is inevitably some overlap between the two, as empirical work often informs the development of models and vice versa.

First, we introduce and justify a separation between the concerns of spatial memory in navigation and spatial memory for object locations (as pertinent to computer displays). Second, we summarise the literature on short-term memory, focusing on Baddeley’s working memory model [8]. Third, we examine models of long-term memory (LTM), including theories of how short-term memories are consolidated into LTM, theories of forgetting, models of skill acquisition, and the amount of effort involved in learning. Finally, we examine ways in which spatial

information is encoded relative to its surroundings, discussing reference frames and landmarks.

We focus on theories relevant to *spatial* memory; for an overview of memory in general, we refer the reader to Baddeley [6].

2.1 Navigation vs. memory for object locations

We make a distinction in this work between two classes of spatial tasks: navigation, and remembering the locations of objects in a static display. Maguire et al. [112] noted the general consensus in the field of neuroscience that “navigation is not the same as table-top tests of spatial memory [...] and that direct inferences cannot be made about one from the other” (p. 171). Indeed, the two task types, while both “spatial”, are quite different: when remembering object locations on a table-top or display, the entire space is generally static and visible; conversely, the user’s viewpoint during navigation tasks is dynamic, with only part of the space visible at any one time. Hegarty et al. [71] showed that ability in the two types of spatial tasks is only partially correlated. Furthermore, memory-impaired patients exist who have difficulty with navigation, but not table-top memory [116, 65], and vice versa [113].

Siegel and White’s seminal framework [157] of the development of spatial knowledge in large-scale environments is one area where navigation and object memory overlap. The framework suggests that people’s mental models of their environments are made up of landmark, route, and survey knowledge, where survey knowledge implies the ability to visualise a map-like overview of the space (similar to viewing a 2D arrangement of objects).

In HCI, navigation itself is relevant in the specific context of wayfinding in virtual environments (e.g., [32]), but the primary use for spatial memory in standard desktop and mobile interfaces is to remember the locations of on-screen controls. Therefore, while some of the literature discussed in this review is necessarily from the navigation domain, our focus is on memory for object locations (particularly in small-scale displays such as computer screens).

2.2 Working memory

Baddeley and Hitch's famous model of working memory [8, 4] proposes four separate subcomponents. The first is a *central executive*, which controls and runs in parallel with three slave systems: the *phonological loop*, the *visuo-spatial sketchpad*, and the more recently proposed *episodic buffer*. Since our work concerns spatial memory, we investigate only the visuo-spatial sketchpad here.

As suggested by the name, the visuo-spatial sketchpad is designed to handle visual and spatial tasks: for example, maintaining visual images (such as faces) for short periods of time, visualizing a route to a destination, or mentally manipulating objects. In situations where there are multiple ways to complete a mental task, the sketchpad can offer significant advantages: for example, there is evidence that people can remember a longer list of directions if they encode the information visuo-spatially (i.e., by visualising the route), rather than verbally remembering the directions [14]. However, maintaining this kind of information in working memory is prone to disruption by the presence of visual distractors, even when that information is not deliberately attended to [109]. As one might expect, visual and spatial stimuli are the primary disruptors of the sketchpad, rather than other sensory input [110].

While the visuo-spatial sketchpad model incorporates both spatial and visual working memory, there is evidence to suggest that the two may, in fact, be separate systems [64, 136, 145]. Tests that have been developed to measure memory span also show that the two components may be separable. In Corsi's block test [119], an array of nine blocks is placed on a table; the experimenter indicates a sequence of blocks by tapping on them, and the subject has to recreate the sequence from memory (Figure 2.1). The Corsi block test therefore utilises both sequential and spatial aspects of short-term memory, but does not require memorisation of a visual image. The corresponding test for visual memory is the visual patterns test [145], in which the subject is given a square grid of 50% randomly filled cells and has to remember which cells were filled (Figure 2.1). Concurrent visual interference decreases performance on the visual patterns test, but not on the Corsi test,

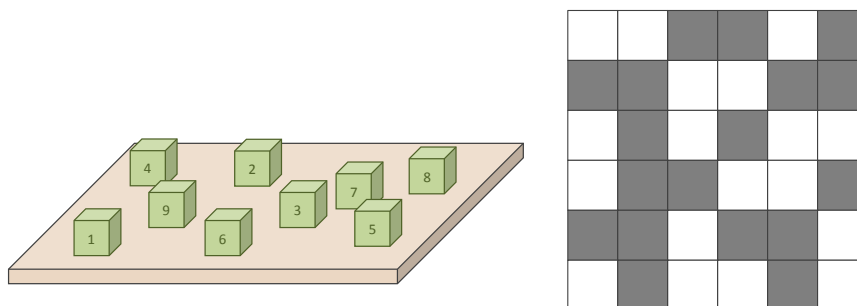


Figure 2.1: Left: In the Corsi block test, a set of blocks are laid out on a table and the experimenter taps some of them in sequence. The subject then attempts to recreate the sequence from memory. Right: The visual patterns test involves subjects being shown a square matrix where 50% of the cells are filled. The matrix is then hidden, and subjects are asked to recreate it from memory. Images adapted from [5].

while spatial interference has the converse effect, suggesting that the two tasks utilise separate cognitive subsystems [145].

Spatial information is not purely visual, since hearing and proprioception also provide us with data about the spatial relationships around us. However, since computer interfaces are primarily (though not exclusively) visual, we are mostly interested in visual inputs to spatial memory. Attempting to distinguish between visual and spatial components of the sketchpad is therefore unnecessary for our purposes; we discuss the effects of auditory and proprioceptive feedback separately in Section 4.4.

2.3 Long-term memory

Long-term memory encodes associations between items in a persistent way, providing access to information over a much longer time period than what is possible with working memory. In addition to the duration of memory, long-term memory has a very large capacity, and these two characteristics make long-term memory the basis for much of human learning [107].

Long-term memory may be divided into different components [7], grouped into the two main categories of declarative and implicit mem-

ory. Declarative memory includes storage of semantic facts (e.g., “Paris is the capital of France”), and storage of episodes (i.e., episodic memory, in which people store specific details of past events). Implicit memory includes procedural skills (e.g., riding a bicycle), primed memories, and classical conditioning. Spatial memory does not generally appear as a separate component in models of long-term memory; rather, several components can play roles in spatial remembering. For example, people can remember locations as facts (e.g., “my pen was on the left side of my desk”), as physical procedures (e.g., building up ‘muscle memory’ for reaching for a car’s gear lever), and even episodes (e.g., remembering an object’s location by visualizing its most recent use).

In this section we investigate three separate topics that are important for long-term spatial memory. First, we look at literature on the process of encoding and storing things in long-term memory (called consolidation), as well as the process of recall and the problem of forgetting. Second, we look at material from the domain of cognitive skill development, which studies the progression of skill performance with practice. Finally, we look at psychology theories of automatic and effortful learning in spatial memory.

2.3.1 Storage and retrieval of long-term memories: consolidation and forgetting

A great deal of research has been carried out on how long-term memories are formed, and we provide only a brief overview here. There are several ways in which this process can occur, leading to different recall rates and levels. First, the number of times (or amount of time) an idea appears in working memory has an effect on long-term storage: the more frequently an association is used, the better it will be remembered. Second, the levels-of-processing effect [30] suggests that recall is a function of the depth of mental processing, with surface-level characteristics (e.g., words or word sounds) leading to more rapid decay than semantic processing (e.g., associations based on meaning, experience, or emotion). Third, the context in which a memory was stored becomes part of the association, leading to a phenomenon in which memories are better retrieved when a person is in the same physical and emotional

context as they were when storing the memory. Fourth, the intentionality and effort put into remembering appears to affect the storage of the memory (see further discussion of effort below).

Much of our knowledge about how retrieval from long-term memory works is based on the opposite of retrieval – that is, forgetting. As with storage, there are several ways in which a memory could fail to be retrieved: for example, the association could simply decay over time (less-used associations are harder to retrieve), or the trigger for a long-term memory could be lost or confused with another (e.g., through interference).

Throughout the 20th century, the relative contribution of these mechanisms of forgetting were a source of debate amongst psychologists. Evidence was produced in favour of both simple decay over time [38] and interference from other memories [178] as factors contributing to the degradation of memory, with no unified model fully explaining all reported phenomena. Elmes’s experiment [41] is one of the few empirical studies on forgetting that focuses primarily on human spatial memory. He found that spatial memory is affected by both *proactive* interference, where the presence of existing memories makes it more difficult to form new memories (for example, re-learning the layout of an interface after a software update that causes it to change); and *retroactive* interference, where the acquisition of new memories degrades the quality of previously acquired memories (for example, learning a new interface may degrade spatial memory of previously learned interfaces).

Wixted [183] provides a comprehensive review of forgetting research in general, in which he integrates existing empirical evidence into a model primarily based on the idea of consolidation. In Wixted’s model, memories take time to be consolidated into long-term memory, and mental exertion involving unrelated information interferes with that process (an example of retroactive interference). According to Wixted, acquiring new memories partially degrades the quality of memories that have been recently formed – the more recent the memory, the more affected it is by interference.

However, in the context of *spatial* recall, Tlauka et al. [172] found no effect of increased mental exertion on recall accuracy, suggesting that

Wixted's model is still incomplete (or perhaps that spatial memory is different to other types of memory, an assertion supported by Elmes [41]). Despite the absence of a formal model for spatial memory, there is useful evidence to suggest that forgetting is affected by several factors – including interference (both proactive and retroactive) [41, 178], the similarity of interfering material [99], and time-based decay [38].

Research Question 1 *How does interference affect spatial memory in user interfaces? Does learning the layout of one spatial interface compromise retrieval for another previously-learned spatial interface? Are there factors (e.g., similarity of locations or of icons) that affect this interference?*

Research Question 2 *How long does spatial memory for a user interface last? Is it as resilient to decay as other spatial memories from everyday life?*

2.3.2 Skill acquisition

While Ebbinghaus's forgetting curve [38] accurately describes the decay of memory for declarative knowledge over time, an interesting exception can be found in the literature on skill acquisition. Baddeley [6] summarises the results of studies that show that while complex skills such as cardiac resuscitation are prone to forgetting in the same way as declarative knowledge, certain types of closed-loop skills are not: riding a bicycle or piloting an aircraft being two examples [6]. In the context of user interfaces, it is unclear to what extent spatial memory of control locations constitutes declarative knowledge, and to what extent it is a result of muscle memory (though see Section 3.4.2 for evidence that the rate of long-term spatial forgetting is low).

Fitts and Posner's [49] influential model identifies cognitive, associative, and autonomous phases of psychomotor skill acquisition, where the cognitive phase involves consciously forming declarative mental

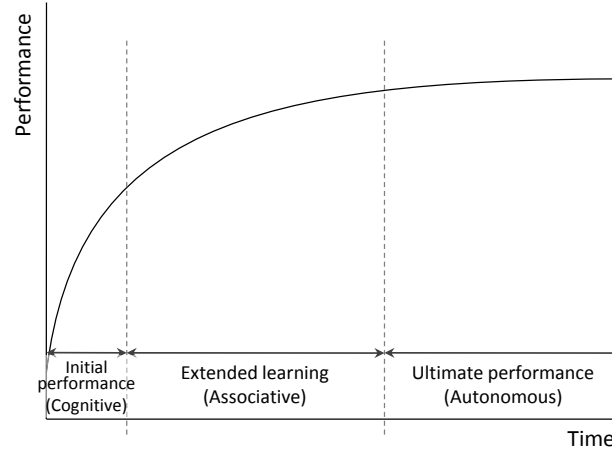


Figure 2.2: A characterisation of the progression from novice to expert skill level in a user interface. Adapted from [149].

models of the activity, the associative phase encodes motor actions in long-term memory through repetition, and the final autonomous phase allows people to perform the skill without conscious effort, freeing up cognitive resources for other tasks. Empirically speaking, however, Newell and Rosenbloom [127] showed that performance improvements followed a continuous power law rather than a set of phases; replication of this effect in HCI was provided by Card [18], who studied a single user's progression to automaticity over thousands of trials. Cockburn et al. [24] and Scarr et al. [149] used this observation to model the transition from novice to expert behaviour in user interfaces (Figure 2.2).

2.3.3 Automatic and effortful learning

In 1979, Hasher and Zacks [69] proposed a framework separating automatic and effortful memory processes. By their definition, an effortful memory process is one which requires intentional memorisation and can therefore be disrupted by concurrent task load, while an automatic process happens incidentally. They hypothesised that spatial knowledge was encoded by a largely automatic process, based on earlier results

showing that spatial location memory showed little advantage of intentional over incidental learning [115, 180]. An experiment by Andrade and Meudell [3] found further evidence to support this hypothesis, with their results showing no effect of concurrent task load (counting aloud by ones, and counting aloud by sevens) on the accuracy of spatial memory for words displayed in random corners of a computer screen. Similarly, Rothkopf [143] found that subjects developed incidental memory for the on-page location of sentences after reading a 3000-word text, even though they had not been instructed to memorise locations.

However, the opposite result was found by Naveh-Benjamin [124, 125], who showed that performance in both spatial recall and recognition tasks was improved when participants had a lower concurrent task load, and when they explicitly intended to learn the information; in addition, performance was also significantly affected by individual differences.

Evidence in the navigation literature suggests that certain kinds of spatial information and location cues are more readily encoded automatically than others. Van Asselen et al. [179] had study participants walk a route through an unfamiliar building, with half focusing on the route and half not. The ability to recognise landmarks and place them in the correct order did not differ between the two groups, but those who focused on the route were able to construct better maps and made fewer mistakes when finding their way back to the beginning of the route. Self-directed exploration can also provide benefits: Hazen [70] found that children who explored a playhouse developed a more accurate knowledge of spatial layout than those who were led around by their parents. However, it is unclear whether the benefits of self-direction are due to increased attention, or deeper encodings caused by the ability to make decisions and learn from mistakes [20].

The structure in which spatial information is presented may also have an effect on whether it can be encoded automatically or not. Doeller and Burgess [36] found that object locations were learned automatically in relation to local boundaries (such as the edge of a table or frame of a computer screen), but that spatial relationships between landmarks had to be learned intentionally. There is also evidence to

suggest that proactive interference makes spatial learning more difficult – in other words, the more information one attempts to learn at once, the more difficult learning becomes [33].

In the static object layouts used by computer interfaces, it is likely that spatial memory can be encoded both automatically and effortfully: while there is evidence that it largely develops as a byproduct of interaction [93, 108, 39], intentional practice has been shown in some cases to provide better long-term retention [106, 39, 20]. We refer the reader to Chrastil and Warren’s [20] detailed review of intentional and automatic spatial learning for more information.

2.4 Spatial reference systems

Information about the location of an object cannot exist in isolation – it must be described in relation to something else. Even ‘absolute’ location descriptors such as Cartesian co-ordinates are defined in terms of an origin point and a set of reference axes. Human spatial memory is no different. In this section we discuss frames of reference and landmarks, both of which provide spatial structure in relation to which other locations can be described.

2.4.1 Frames of Reference

Psychology research shows that when we learn the locations and spatial structures of objects in our environment, we encode them in terms of some spatial frame of reference [155, 122]. Experiments conducted by Mou and McNamara [122, 123] strongly suggest that these intrinsic reference systems are derived from properties of the objects and their surroundings. Explicit rectangular boundaries, such as the walls of a room or the edges of a table, can generate a frame of reference, but a grid-based item layout can also generate an implicit axis of reference. Mou and McNamara [122] showed that people can remember item locations more accurately when they view an object layout from an axis-aligned viewpoint, even if locations were originally learnt from a non-aligned viewpoint.

There is clear evidence showing that boundaries can enhance, but

also bias, the accuracy of spatial recall. Nelson and Chaiklin [126] asked participants to recall the location of a dot relative to an enclosing frame border. Recall accuracy was higher the closer the dot was to the border, and inaccurate guesses tended to err in the direction of the nearest border, rather than towards the centre. Igel and Harvey [84] found that the presence of a visual frame increased accuracy overall when participants were asked to remember multiple dot locations. These results suggest that spatial recall in command interfaces may be enhanced by the presence of visual boundaries.

Research Question 3 *Further research is needed to determine the value of boundaries and partitions when designing control layouts.*

Huttenlocher et al. [82] proposed that since spatial memory is inexact, people increase their accuracy using a two-level encoding which contains both a fine-grained location and a higher-level spatial category (which is determined by the structure of the stimulus). When asked to reproduce exact locations, they will combine the two values. Huttenlocher et al. produced evidence of this in a task which required users to reproduce the location of a dot within a circle: participants spontaneously divided the circle into four quadrants, and used the implicit borders to improve their recall accuracy [82]. The idea of a two-level spatial encoding was further developed into a predictive model of location memory by Lansdale [102].

Egocentric frames of reference, where object locations are encoded in relation to the position and orientation of the body, are also possible. These are typically used to remember locations which are invariant to body position and orientation – one example might be a person who keeps their house keys in their left-side trouser pocket. Conscious manipulation can alter what kind of reference frame is used: Mou et al. [121] demonstrated that in an augmented reality environment, users were able to change from an environmental to an egocentric frame of reference after experience and instruction.

2.4.2 Landmarks

Like frames of reference, landmarks provide a kind of spatial anchor in relation to which other locations may be defined. However, the information provided by landmarks is usually not as rich – a landmark normally serves to identify a single point in space, rather than imply a set of axes through its structure. In the traditional sense, the word “landmarks” normally refers to unique human-made or natural structures; more generally, however, landmarks can be generated by any visually salient or memorable element of a scene [162].

In many situations, landmarks are extremely important to the development of spatial memory. Allen [2] states that “individuals use landmarks as organizing features within the context of spatial events” (p. 629), and showed that subjects performed much better at a distance-estimation task after being shown images of a landmark-heavy journey. Siegel and White’s [157] three-tiered model of landmark, route, and survey knowledge suggests that landmark knowledge is the first type of spatial knowledge to develop when exploring a new environment. Indeed, there is substantial literature highlighting the importance of landmarks in the navigation domain, which we do not review – instead, we refer the interested reader to Freksa and Mark [162].

For table-top object layouts, Mou et al. [123] showed that locations are encoded in terms of inter-object relationships. This suggests that landmarks may be useful in HCI as a way of enhancing spatial knowledge of computer interfaces. One example where landmarks play an important role is in pan-and-zoom interfaces, where they serve as a way to orient oneself (see Section 4.2.1). This effect is most noticeable in situations where landmarks are absent (such as when a map interface is zoomed in too far), resulting in “desert fog” [92]. We discuss further applications of landmarks in HCI in Section 4.2.3.

3

Observable Properties of Spatial Memory

While Chapter 2 focused on psychological theory, the aim of this chapter is to summarise the empirically observable properties of human spatial memory, with an emphasis on those aspects most relevant to human-computer interaction. Extensive prior research, both in psychology and in HCI, has examined and identified human capabilities for spatial memory; this chapter summarises and distills key findings from that research. Throughout this chapter, we identify ways in which the given empirical results can be used to inform design.

Specifically, we identify and examine six properties of spatial memory. First, we discuss literature on the *time* to retrieve item locations from memory. Since re-finding previously seen objects often involves elements of both memory and visual search, this section also reviews literature on visual search.

The second section examines the *accuracy* with which people can remember spatial locations in the absence of feedback, as well as the effects of frames of reference on a person's ability to recall locations. Note that there is a blurred distinction between the literature on retrieval time and accuracy, as there are several ways in which the two attributes interact. For example, as a user improves their recall accu-

racy for a given item location, the time taken to find that item decreases (since less visual search is required); conversely, if a user attempts to guess target locations as quickly as possible (thus reducing the time available to query their spatial memory), their overall accuracy will decrease.

The third section discusses *effort*. This includes both the effort of memorisation and the effort of recall, though we focus on the differences between automatic and effortful spatial learning, linking back to the theories presented in Chapter 2.

Fourth, we discuss *retention* – in other words, the capacity of the human brain to remember spatial locations, and the length of time these memories persist. As in other sections, we frame empirical results in terms of the theories presented in Chapter 2 on working memory, long-term memory, and forgetting.

In the final two sections, we look at *variation* in human ability, as well as people’s *perceptions* of their own ability and how they can differ from reality.

3.1 Retrieval time

As spatial memory develops, users become more efficient at locating controls. A novice with poor spatial knowledge will rely on slow visual search to find items, while a practiced user can quickly retrieve item locations from memory [24]. The mechanisms by which these skills develop were discussed in Section 2.3; here, we discuss user performance in visual search and spatial retrieval. Note that although the process of visual search is distinct from the processes involved in spatial memory, it is important to review elements of visual search because novices must use visual search as the first step in learning item locations. Once stable spatial locations have been learned, visual search becomes unnecessary.

3.1.1 Visual search

Visual search has proven to be a difficult process to model, with empirical studies often producing conflicting results. Specifically, there has been little consensus on whether humans attend to items sequentially,

randomly, or in parallel; however, regardless of the underlying process, the average time required for visual search tends to be a linear function of the number of candidate items [80, 129, 152].

In this section we discuss visual search processes, as well as other factors (such as orderings, groupings, and saliency effects) that affect people's ability to find items.

Is visual search random, sequential, or parallel?

Early work by Krendel and Wodinsky [100] and Engel [42] reported experimental results suggesting that visual search is completely random (i.e., people examine locations at random until the target is found, possibly revisiting already-visited items in the process). Both experiments were performed using random two-dimensional arrangements of stimulus items, unlike the linear command lists used in modern-day menus or grid-based arrangements of toolbar icons. Card [17] was the first to study visual search in mouse-based linear menus. In a menu of randomly-arranged items, his results (for a small three-user study) showed no difference in search time for different positions in the menu, providing further evidence for randomly-ordered search.

In contrast, Lee and McGregor [103], in their examination of optimal menu structures, proposed a sequential model of visual search where items are examined in top-to-bottom order. In a follow-up paper [111], they re-examined Card's assumptions, and determined that his empirical data could be equally well described by a sequential model. They concluded that either model may be possible, and that users may employ different visual search strategies depending on the application.

Furthermore, Nilsen [129] presented an experiment showing that visual search for individual items was a linear function of that item's position in the menu, strongly suggesting that participants were performing a sequential, top-to-bottom search. Hornof and Kieras [80] and Byrne et al. [16] further investigated this data and derived more complex models, each involving elements of both sequential *and* random search; Hornof and Kieras also provided a key result showing that users do not necessarily consider each menu item individually, and in fact can evaluate several items in parallel if the items can simultaneously fit into

the fovea [80].

UI Design Guideline 1 *During visual search, people can examine multiple items in parallel if they fall within one foveal scan. Designers should allow users to search items in parallel by reducing the blank space between items.*

Importantly, however, all three models of search (sequential, random, and partially parallel) provide the same observable relationship: average search time in a menu is consistently a linear function of the number of items [80, 129, 152].

Note that while some researchers have suggested applying the information-theoretic Hick-Hyman law [73, 83] to visual search (e.g., [182, 184]), others have argued that this is erroneous [151, 22] because the Hick-Hyman law (further discussed in Section 3.1.2) models decision time, not search.

Orderings and groupings

Card [17] followed up his initial menu search work with a second experiment investigating the difference between menu arrangement schemes. His results showed that an alphabetical layout enabled faster visual search than random or categorical layouts, and that a categorical layout was faster than random. However, the advantage of an alphabetical layout only generalises to situations where users know the command name in advance, and can therefore anticipate the position of the command in the list. Furthermore, the categorical layout may have been unfairly disadvantaged by the fact that Card's implementation did not display labels for each category, forcing users to attend to the items within each one in order to infer what the category was. In any case, differences between the three conditions disappeared on the final block, once users were sufficiently familiar with item locations. Somberg [161] reports very similar results, with alphabetic and frequency-based arrangements enabling faster search initially, but with positionally-constant menus proving significantly faster after several blocks of trials.

UI Design Guideline 2 *Orderings (such as alphabetic) and semantic categorisations can help novice users, by allowing them to infer item locations without needing to visually scan the entire item set.*

In a further study, Hornof [79] compared visual search strategies in grouped menu layouts, investigating both labelled and unlabelled groups. When groups were unlabelled, the partially-random search strategy proposed by Byrne et al. [16] provided the best fit to the data. With labelled groups, users were able to perform a faster hierarchical search: first searching for the target group name, and then searching within that group for the target item. However, such efficient hierarchical searches can only be conducted when the user can predict the name of the relevant group in advance. To compound the issue, generating meaningful category names for commands in real-world applications can often be a difficult task. Nevertheless, in situations where category labels are present, we argue based on Hornof's results that they should be visually emphasised.

UI Design Guideline 3 *When multiple groups of items are displayed simultaneously, provide salient labels for groupings to encourage hierarchical search.*

Visual saliency and pre-attentive effects

For visual search in images or structures more complex than linear menus, no models have been developed that accurately characterise search processes. While some researchers (e.g., [87, 135]) have proposed visual saliency-based models of search, in which the eye fixates on visible features in decreasing order of saliency, empirical tests of these models have given mixed results [87, 72]. The order in which features are attended to during visual search appears to depend heavily on the nature of the task [141], as well as complex cognitive factors such as the subject's semantic knowledge of the information being viewed [72].

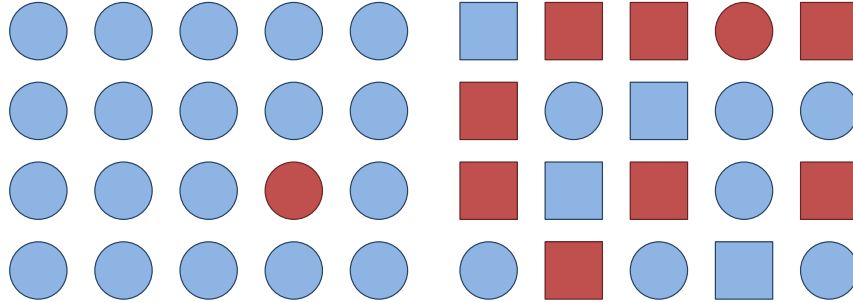


Figure 3.1: In the left image, the single differentiable feature (colour) allows the red circle to be found pre-attentively. In the right image, the conjunction of features (both colour and shape) requires a slower, more sequential search.

However, one aspect of visual search is somewhat better understood: the concept of *pre-attentive* or parallel search, which can be performed without the need to sequentially scan through individual items [174, 173]. Pre-attentive search occurs when a subject is instructed to find an item based on one differentiating *separable feature* of that item, where the separable feature may be a quality such as colour, brightness, or shape; but does not occur when items are differentiated by a conjunction of features. For example, finding a red circle in a field of blue circles can be done pre-attentively, but finding a red circle in a field of red and blue squares and circles can not (Figure 3.1).

The ability to exploit pre-attentive search to decrease retrieval time, however, relies on the subject knowing in advance that their intended target is going to have a particular differentiating feature [58]. In HCI, this means that visually distinctive icons can exhibit ‘pop-out’ effects if the user knows what they are looking for. However, artificially encouraging pre-attentive search can be difficult – for example, highlighting likely items with a distinctive colour will only create a pre-attentive effect if the user expects their target to be in that colour (see Section 4.3.3 for more on adaptive highlighting techniques).

Methodological Caution 1 *When examining spatial memory in*

visual interfaces, researchers should use visually homogeneous targets to avoid confounds caused by visual pop-out effects.

One technique that has been shown to cause an *involuntary* attentional shift is *abrupt onset*, where one item appears instantly and others appear after a delay [185]. Yantis and Jonides showed that the involuntary capture of attention caused by abrupt onset was not replicable using salient features (such as colour) [91]. In HCI, Findlater et al. used this idea to speed up visual search with their *ephemeral adaptation* system (see Section 4.3.3).

3.1.2 Spatial retrieval

While visually searching for items is usually a linear process, repeated searches for the same items allow users to naturally develop a memory for the locations of these items (assuming they remain spatially stable). Measuring the speed of item retrieval from spatial memory during in-the-field computer use is a difficult task – for example, it is unclear when spatial retrieval ends and when mechanical target acquisition begins. For this reason, retrieval time is usually examined indirectly. In HCI experiments, one approach is to measure total retrieval time, and subtract pointing time based on a Fitts' Law model calibrated to the individual user (e.g., [148]).

Generally, it is accepted that the time to retrieve a spatial location from memory is a logarithmic function of the number of items. Sears and Shneiderman [152] observed that menu selection times increased linearly with menu length for unfamiliar items, but only logarithmically for items that were frequently selected. Cockburn et al. [24] suggested that these expert selections could be accurately described by the *Hick-Hyman Law* of choice reaction time [73, 83], which states that the time taken for a human to make a decision is proportional to the information content of that decision (which in turn is a logarithmic function of the number of available choices).

Cockburn et al. developed and empirically validated a model of menu selections that incorporates linear visual search, Hick-Hyman logarithmic decision making, and the transition from novice to expert

behaviour. The model incorporates Newell and Rosenbloom’s assertion (see Section 2.3.2) that as users become familiar with selecting commands, their task times improve following a power law of practice [127].

Importantly, if users have perfect spatial knowledge of items, item arrangements designed to shorten visual search times will no longer provide any benefit. Card’s 1984 study [17] demonstrates this effect, with differences in search time between alphabetical, semantic and random layouts disappearing once users had learned item locations. In practice, however, location knowledge is rarely perfect (see Section 3.2), and expert users are unlikely to know the locations of *every* command in an application, so techniques designed to reduce visual search may still be useful.

Methodological Caution 2 *When experimenting on interfaces that alter spatial locations, it is important to allow users enough time to develop expertise.*

3.2 Accuracy

As discussed earlier, retrieval time is dependent on the user’s underlying knowledge of target locations, and better knowledge allows users to avoid visual search. It therefore follows that the reduction in task time with practice, which follows a power law, is simply a manifestation of an underlying improvement in the user’s spatial knowledge.

In HCI experiments, the accuracy of spatial knowledge is usually measured indirectly through task time, which is arguably the more important dependent variable. When experimenting on a standard visual interface, it can be difficult to differentiate between visual search and spatial recall behaviours in users. However, a few studies have investigated spatial accuracy directly, using ‘invisible’ interfaces that lack visual feedback, and measuring accuracy as the dependent variable rather than selection time. We review these studies here.

When visual (or other) feedback *is* present, item locations can be encoded in terms of landmarks and frames of reference (as discussed

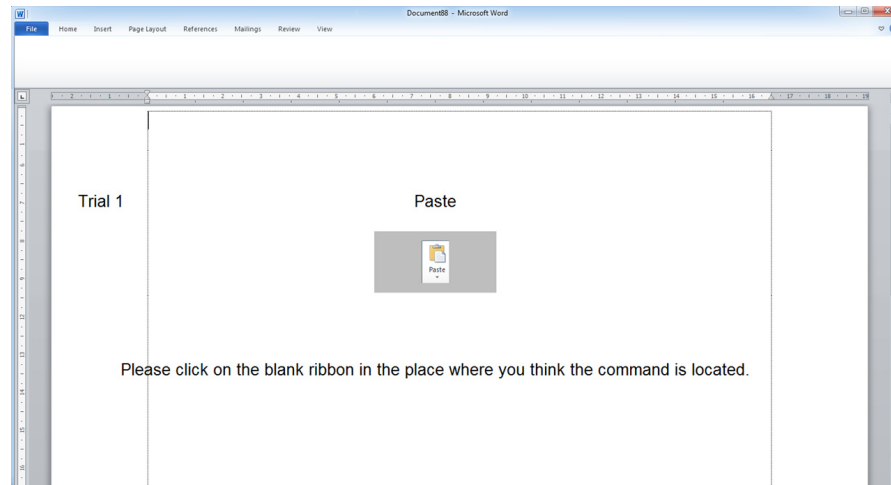


Figure 3.2: An experiment studying memory for control locations in Microsoft Office (from [147]). Subjects were prompted with the name and icon of a control, and asked to recall its location on a blank Ribbon.

in Section 2.4.1). The presence of a frame of reference can contribute substantially to a user’s ability to recall spatial locations, allowing them to find familiar objects from different viewpoints. We therefore also discuss results relating to frames of reference in HCI below.

3.2.1 Recalling the locations of invisible items

One way to measure the accuracy of spatial recall, without using selection time as a proxy, is to remove all visual feedback and ask subjects to point at the areas where they believe items to be located. While this kind of experiment has been performed many times in the psychology domain, the generalisability of such experiments is heavily dependent on the circumstances of the experiment, the amount of learning taking place before the recall tests, and other factors that are difficult to control. To narrow down the range of results, we only look at invisible-object studies in HCI, taking care to identify the amount of prior learning before recall in each case.

One way to measure typical levels of spatial knowledge is to evaluate participants’ existing expertise with applications they use frequently.

On the desktop, Scarr et al. [147] performed an experiment with Microsoft Office users, asking them to select the location of known commands within a blank Ribbon (Figure 3.2). 50% of command locations were known to within 100 pixels, suggesting a strong memory for item locations; especially given participants' tendency to report as 'familiar' "all of the commands that they had previously used in the interface, rather than just those they used frequently" (p. 259). Gustafson et al. [62] performed a similar study on mobile phones, showing similar results: regular iPhone users were asked to recall the locations of applications on their home screen, with 68% of locations being recalled correctly.

UI Design Guideline 4 *Users develop an accurate memory for the locations of frequently accessed interface items.*

Research Question 4 *Exactly how accurate is absolute spatial memory, and what is the interaction between retrieved approximate memory and local visual search? How does this change as a user progresses towards expertise?*

For 3D interaction, Li et al. [105] investigated users' spatial and proprioceptive ability to replicate angular directions, mapping application commands to a spherical co-ordinate space in a 180 degree hemisphere in front of the user's body. To minimise the effect of errors, they recommended dividing the space into 7 horizontal and 4 vertical partitions. In this case, participants were not trained – they were simply given angular directions and had to point in those directions while blindfolded.

Cockburn et al. [21] studied three similar 'air pointing' systems: aiming the pointer at a virtual screen, positioning the pointer within a virtual 2D plane, and positioning the pointer within a virtual 3D volume. In their experiment, participants first completed 48 training trials (12 blocks of 4 targets) with full visual feedback, before interacting with conditions providing progressively reduced feedback. Pointing

within a 2D plane enabled the highest accuracy, with ray-casting quick but inaccurate and 3D volume pointing slow, inaccurate, and requiring the highest cognitive and physical effort.

3.2.2 Frames of Reference

In Section 2.4.1, we reviewed literature showing that spatial information is often encoded in terms of a frame of reference. The air-pointing studies in the previous section examined recall accuracy in egocentric frames of reference without feedback – here, we discuss the manipulation and creation of visual reference frames in order to enhance spatial memory.

Hinckley et al. [75], studying the manipulation of virtual invisible objects, found that using the non-dominant hand to create a proprioceptive frame of reference increased users’ accuracy in a memory task. Based on this idea, Gustafson et al.’s *imaginary interface* system [61] required users to form an L shape with their non-dominant hand, generating an explicit reference axis relative to which the other hand could interact. They found that use of the non-dominant hand in this way partially alleviated effects caused by disorientation (such as physically turning around between tasks), and that interaction accuracy in a coordinate pointing task was relative to the Manhattan distance from the user’s fingertips.

Scarr et al. showed benefits for keeping item locations in desktop and mobile interfaces stable with respect to a frame of reference [148]. Altering the reference axes (e.g., by translating, scaling, or rotating the display) was shown to have little effect on item selection time, as long as item locations relative to the axes were kept constant. Rotation was an exception, with selection times increasing linearly with the degree of rotation; Cooper [29] found a similar linear increase for mental rotation tasks.

3.3 The role of effort in forming spatial memories

In Section 2.3.3, we discussed psychological theory implying that certain types of spatial information are learnt automatically, but that

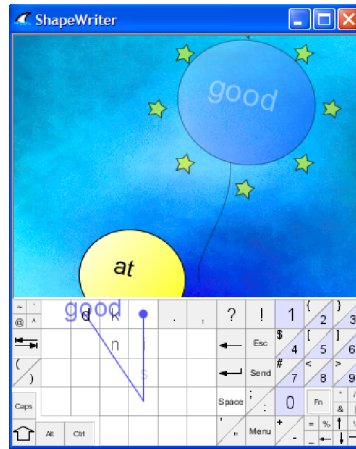


Figure 3.3: Cockburn et al.’s gesture keyboard training game (from [26]). Users must temporarily brush virtual ‘frost’ off the keyboard with a stylus in order to see underlying key labels.

effortful learning can provide benefits in terms of long-term retention.

In HCI, benefits of effortful spatial learning have been observed in training interfaces. Cockburn et al. [26] developed a training interface for a virtual gesture keyboard that required ‘frost-brushing’: that is, in order to view the labels on the keys, users had to brush away virtual ‘frost’ with a stylus, which re-formed soon afterward (Figure 3.3). In this way, users were forced to attend to and memorise key locations, in order to avoid having to brush away the frost every time a word was typed. The effortful training was shown to be a more effective use of training time than simple repetition, although the authors cautioned that an excessive level of difficulty may cause users to become frustrated and give up.

UI Design Guideline 5 *In training systems, forcing users to intentionally memorise item locations can increase long-term retention. However, such systems must be careful to provide a level of difficulty appropriate to the user’s skill level.*

Ehret [39] showed a similar effect in a simple item-selection ex-

periment. He examined the repeated selection of buttons representing colours, and manipulated the meaningfulness of the button labels: the most meaningful was a display of the colour itself, followed by the name of the colour, an arbitrary icon, and no feedback at all. Ehret found that the colour-display condition enabled the fastest interaction, but performed significantly worse than the other three in a spatial recall test. Ehret concludes that “locations are learned more quickly when the least-effortful strategy available in the interface explicitly requires retrieval of location knowledge” (p. 1).

Experiments like Ehret’s imply an interesting trade-off between enabling low task times and encouraging long-term learning. For example, interfaces can speed up visual search for items by highlighting a subset of the most likely selections [46, 48], or through the use of visit wear [158], yet there is evidence to suggest that doing so decreases spatial learning, since users become less reliant on their spatial memory [158]. Similar results have been shown in the wayfinding literature, with the presence of GPS devices decreasing users’ navigation ability [86]. The best approach for designers therefore depends on the goal of the system: if the explicit aim is training, then requiring more effort can be beneficial; if the aim is simply to allow faster interaction, then making the interface *less* effortful (e.g., by adding highlighting) is probably the better approach (although problems can arise when the highlighting is removed).

UI Design Guideline 6 *Increasing the amount of required effort can increase the effectiveness of training interfaces, while reducing effort can increase overall interface performance. Designers should tailor the amount of effort required to interact in accordance with the goals of the system.*

3.4 Retention

As discussed in Chapter 2, cognitive psychologists generally divide the concept of memory into two separate systems: short-term (or work-

ing) memory, and long-term memory, each with substantially different properties. Measurements of retention, such as how much spatial information can be remembered, and how long it can be remembered for, are therefore highly dependent on which aspect of memory is being utilised.

To re-iterate from Chapter 2, working memory is known to have a limited capacity, with information fading over short periods of time, while the capacity and duration of long-term memory is significantly higher, but more difficult to study. Here, we examine empirical literature from psychology and HCI on the capacity and duration of both working and long-term spatial memory.

3.4.1 Short-Term Retention

In general, it is known that short-term visual and spatial memory is limited [137, 5, 61]. In Postma and De Haan's study of short-term object location memory, the accuracy with which subjects could remember object locations diminished as more locations had to be simultaneously remembered [137]. Participants in Gustafson et al.'s study [61] demonstrated reduced accuracy in drawing long, complex gestures, suggesting that participants' visuospatial memory for the locations of earlier strokes was fading over time. Baddeley states that the capacity of visual working memory is typically limited to three or four items [5].

Attempts to measure the duration of short-term spatial memory have had varied results. Thomson [171] and Steenhuis and Goodale [163] asked participants to walk to nearby target locations with their eyes closed; the two studies found that target accuracy appeared to decrease after 8 seconds and 30 seconds, respectively, of walking with no visual feedback. Similar experiments in manual aiming have shown that accuracy begins to deteriorate after only 2 seconds without visual feedback [40]. While the duration appears to be highly variable, it is clear that people are able to hold recently-seen visual imagery in their heads at least for a few seconds.

Hole [77] investigated decay effects in visuospatial memory, asking subjects to determine which of two sequentially presented dot pairs had the greater degree of separation. Accuracy decreased linearly as the

delay between presentations was increased from 0 to 30 seconds (i.e., a longer delay required a larger difference between the two dot pairs in order for subjects to choose the correct one). They also demonstrated interference caused by extraneous visual information: when a distractor dot pair was presented between the two stimulus pairs, subjects' spatial accuracy was halved.

3.4.2 Long-Term Retention

While little research has been done to specifically determine the capacity of long-term spatial memory, anecdotal evidence from daily life (e.g., the sheer number of routes and object locations that we accumulate over the course of our lives) suggests that it is very high. Some studies provide hints to the scale of our spatial memory, although they do not identify upper bounds: Jiang et al. [89] investigated spatial contextual memory, showing that people have a large implicit memory for contextual cues. Across the course of a week, they trained participants to find T-shaped targets amongst 60 repeated displays filled with L-shaped distractors, intermixed with 1800 homogeneous non-repeated displays. Participants were reliably able to locate targets much faster on the displays that had been seen before, even though all displays were highly similar.

In the HCI domain, Robertson et al. studied long-term memory for document locations in their Data Mountain system [142, 31]. In their first experiment, participants placed and interacted with a set of webpage thumbnails on a virtual inclined plane. Six months later, they were given five minutes to review their old layouts, and were asked to find items again; they displayed a similar level of performance to that of the first experiment. However, it is unclear to what extent participants were simply using the five minutes to re-learn item locations. At the time of writing, we are unaware of any other HCI studies in HCI investigating long-term memory for spatial locations; more research in this area is clearly needed.

Research Question 5 *Further research is needed to determine the upper limits of long-term retention, and characterise the decay of spatial memory over time.*

3.5 Variation in ability

When it comes to spatial tasks, as with many other human capabilities, abilities can vary widely between individuals. For example, Hegarty et al. [71] had subjects walk a route through a building, then asked them to point in the direction of landmarks that were encountered during the route and estimate distances between them. The highest-performing participants “could point to unseen landmarks in the environment with less than 10° of absolute error” and “showed an almost perfect correlation between their estimates of distances among landmarks and the true distances”, while the lowest-performing participants had scores “not significantly different from chance” (p. 173).

Certain demographic factors have been found to have effects on spatial ability. For example, there are well-documented differences between the sexes in certain types of spatial tasks. In general, women tend to have better memory for object locations than men [37], while men tend to be better at aiming and throwing projectiles [66, 181], as well as mental rotation tasks, spatial visualisation (e.g., paper folding tests), disembedding (finding a simple figure hidden in a more complex one), and field independence (e.g., perceiving and drawing absolute horizontal and vertical slopes). We refer the reader to [67] and [98] for complete reviews of sex differences in spatial tasks.

Methodological Caution 3 *When spatial memory plays a role in an experiment, assess individual differences in participants’ spatial abilities using a test such as that of Eales and Silverman [37]; participants can then be divided into a ‘high spatial’ group and a ‘low spatial’ group for later analysis.*

Light and Zelinski [106] reported an experiment in which adults

aged 18-35 were better able to reconstruct a map of town landmarks than adults aged 51-80, suggesting a deterioration of spatial memory with age. However, other studies investigating the effects of age have had mixed results (e.g., [117, 134]), with differences possibly explained by the visual distinctiveness of stimuli used in the experiment [153].

Cultural differences can also lead to differences in spatial ability. Kearins [96] found significantly stronger visual spatial memory in Australian Aboriginal children compared to Australian children of European descent, though it was unclear whether the difference was due to natural endowment, or simply due to differing child-rearing practices between the two cultures. Similar cultural differences have been found between Scottish and Zairian children [12], and Japanese and Caucasian adults [53], although the latter study takes care to point out that experiential factors may have a large effect, and cautions against over-generalisation.

Methodological Caution 4 *HCI researchers should be cautious when generalising results of spatial memory experiments to all user populations.*

These individual differences in spatial ability imply a risk for interface designers, which is that interfaces designed to exploit spatial memory may be less effective, or even detrimental, for users with poor spatial ability. However, more research is needed in this area.

Research Question 6 *Research is needed to determine the effects of interfaces designed to exploit spatial memory on low spatial-ability users, and identify methods (such as ability-based interface customisation) that could mitigate these effects.*

3.6 Perception of ability

People perceive their spatial abilities to be lower than they actually are. In Cockburn and McKenzie's comparison of 2D and 3D interfaces

[27], participants predicted low performance in a spatial retrieval task, but rated their performance significantly higher after the task was complete, implying an initial lack of trust in their spatial memory. Andrade and Meudell [3] reported a similar phenomenon: many of their participants reported that they guessed their way through a spatial memory test, even though they achieved recall scores that were significantly above chance. This may stem from the automatic, rather than conscious, nature of spatial contextual memory [89].

While in the case of spatial memory, people may be unaware or mistrusting of their own capabilities, it is worth noting that in other situations people will often rely on their (potentially erroneous) memory rather than consulting documentation. Gray and Fu [59] performed an experiment in which participants were told to program a VCR, with reference materials to verify that their actions were correct. When there was even a slight perceived cost to accessing the reference information (such as a single click being required to open it), participants tended to rely on the imperfect knowledge in their head, rather than verifying their actions against the correct information given to them.

3.7 Summary

In this chapter, we discussed the properties of spatial recall, and applied our findings to derive design guidelines for HCI. First, we examined the time required for spatial recall, noting that pure recall from spatial memory follows the Hick-Hyman Law of choice reaction time, while visual search requires an amount of time linear in the number of displayed items (though certain orderings, groupings, and saliency effects can be employed to reduce search times). We then examined people's ability to accurately recall item locations, observing that accuracy is high for interfaces people are familiar with; we also discussed how cues such as frames of reference and landmarks can be used to improve recall accuracy.

Next, we summarised the effects of effort on spatial learning, showing that forcing users to deliberately memorise item locations can improve recall. We also discussed short-term and long-term retention for

item locations, with short-term memory displaying limited capacity and duration, but long-term memory exhibiting no obvious upper bound for either. Finally, we discussed differences in ability between demographic groups, and showed that people often underestimate their own spatial abilities.

4

Interfaces and Spatial Memory

The preceding chapters were concerned with the capabilities and development of spatial memory, and drew information mainly from cognitive psychology literature. In this chapter, we refocus our attention on HCI, investigating systems and interfaces that support or disrupt spatial memory in some way, and distilling lessons learnt from the evaluations of these systems.

When considering spatial properties of user interfaces, it is possible to divide UIs into two classes: those that display an entire information space at once, and those that show only small portions at a time. We first look at situations in which it is possible to simultaneously display all of the items in an information space, the benefits of such an approach, and the applications of such spatial displays to desktop interfaces. When this approach is not feasible due to space restrictions, designers must either provide a user-controllable *viewport* to the space, or somehow *distort* the space such that the information can fit on the screen, with each approach affecting spatial memory differently. We therefore look at the different ways this can be achieved, and examine how these techniques support or hamper the user's spatial abilities. Additionally, we examine the effects on spatial memory of various types

of non-visuospatial cues and feedback.

4.1 Single-view spatial displays

In 2D interfaces, such as those displayed on standard computer monitors, any data to be displayed is necessarily mapped to 2D space. When this mapping is spatially stable, users naturally learn locations as a side effect of use, increasing their performance to a high level over time [93, 108, 39, 24]. However, techniques that dynamically alter the mapping of data to screen co-ordinates, such as scrolling, can reduce users' ability to remember item locations; and interfaces that are designed to manage complexity, such as hierarchical menus, can limit the usefulness of spatial memory by requiring the user to perform comparatively slow mechanical actions to select items.

Many systems in HCI have shown that displaying all of the items in an information space, in a non-overlapping spatially consistent layout, can solve both of these problems (see Figures 4.1 and 4.3 for examples). Displays such as these reduce mechanical navigation time compared to collapsible hierarchical structures (like menus) [147], provide an instant overview of the information space [131, 23], and allow users to utilise their spatial memory to quickly access items they have encountered before [63, 147], among other benefits. Here, we investigate some of the research interfaces in HCI that follow this principle of simultaneous presentation, and show how they affect task times and spatial memory in comparison with traditional methods of interaction.

4.1.1 Advantages of spatial layouts over scrolling

Several research projects have shown the value of spatial layouts for working with documents compared to more traditional techniques such as scrolling. In 1997, O'Hara and Sellen [131] studied differences in reading behaviour between paper and on-line documents. When interacting with paper, all participants unclipped the documents they were given and arranged them spatially on the desk, citing advantages such as quick cross-referencing and "gaining a sense of overall structure" (p. 339). The authors noted that digital techniques for managing docu-

ments, such as scrolling and paging, were “irritatingly slow and distracting” (p. 338), and that they significantly reduced the user’s ability to use spatial memory for navigation. In a follow-up paper [132], they developed a focus+context reading interface which showed an overview of the whole page, and displayed one full-size sentence at a time. The interface with the overview proved to better support incidental learning of spatial locations than a standard scrolling interface.

Similar results in favour of spatial overviews in document navigation were demonstrated by Cockburn et al. [23]. Their *Space-Filling Thumbnails* system allowed users to view a spatially consistent overview of a document, in which thumbnails of every page were arranged in a 2D layout and scaled such that all of the pages could fit in one window (Figure 4.1). Space-Filling Thumbnails were shown to be better than six other document navigation methods in terms of both visual search and retrieval of locations from spatial memory, with spatial retrieval being particularly quick [23].

UI Design Guideline 7 *Offering users a spatially-stable visual overview of an information space can greatly improve their ability to navigate to known locations, as well as reducing visual search time.*

Spatial arrangements have been shown to be beneficial in many other application domains. Tak et al.’s Spatially Consistent Overview Thumbnail Zones (SCOTZ) [165, 166] provides a full-screen, spatially stable interface for window switching, allowing quick revisitation. SCOTZ divides the screen into application zones that grow based on the frequency of use. The problem of dynamic data sets, as well as changing zone sizes, is alleviated by the use of spatially stable treemap algorithms [176, 164], which keep items as close as possible to their original locations when the data set changes. SCOTZ showed significant advantages over existing window switching tools [166].

Gutwin and Cockburn’s ListMap design [63] laid out a list of items in a 2D grid that required no scrolling (Figure 4.2). Task times with ListMaps were significantly lower than with the scrolling list for re-

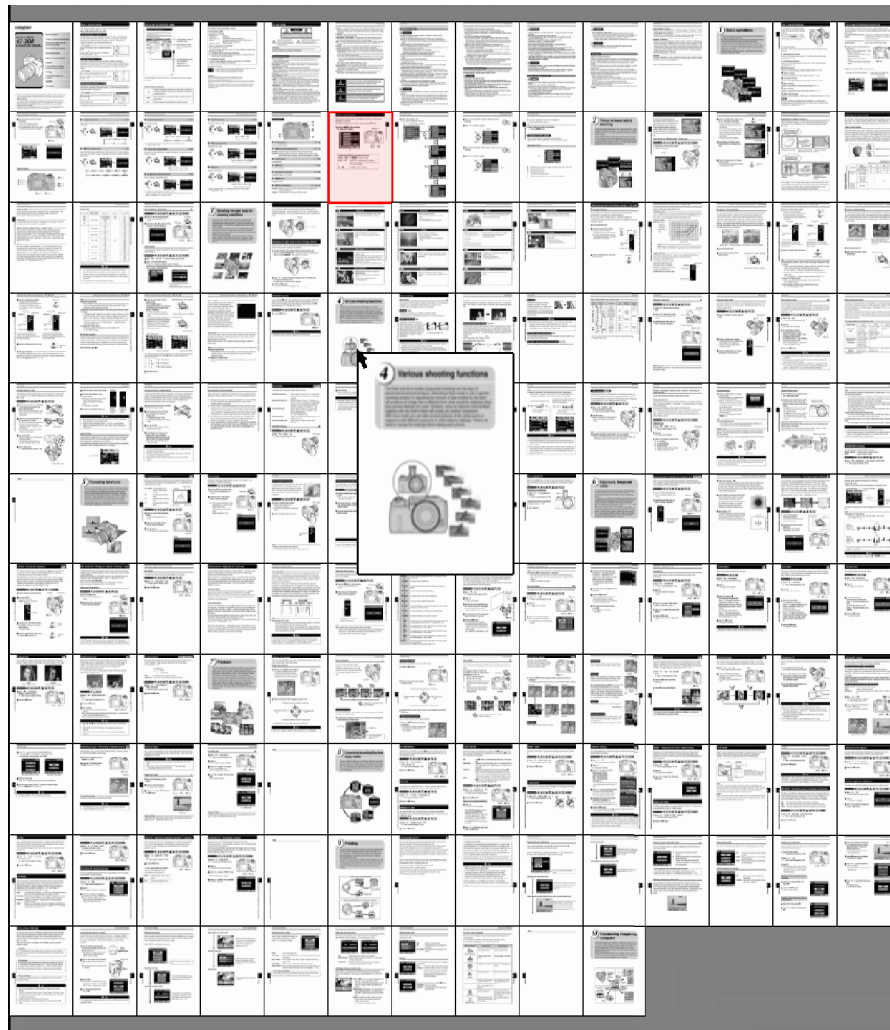


Figure 4.1: Space-Filling Thumbnails allow an entire document to be displayed on a single screen, using a spatially-stable arrangement. Image from [23].



Figure 4.2: A ListMap displaying a list of system fonts. Image from [63].

visitation, but significantly higher for users who had to find items for the first time. However, their interface constrained item sizes to 23×14 pixels, and used only textual item names (which required a mouse-over to view in full), making visual search costly and time-consuming.

Robertson et al.'s Data Mountain [142, 31] was a document management system that allowed users to arrange their documents on a 3D inclined plane. In a study using web-page thumbnails, the spatial arrangement of items proved to be more efficient than Internet Explorer's Favorites system (a scrolling list), although the authors did not separate the relative contribution of the third dimension, the thumbnail images, the ability of users to organise and cluster items according to their preference, and other factors.

Later, Cockburn and McKenzie [28] isolated and studied the 3D aspect of Data Mountain, comparing it to a 2D equivalent as well as a real-world 3D interface (in order to avoid the technological limitations of virtual 3D). Their study showed no spatial memory benefits for the 3D interfaces (failing to replicate an earlier study by Tavanti and Lind [170]), indicating that the main strength of Data Mountain was its 2D spatial layout, which enabled users to remember items by location. This idea is supported by results in psychology – Shelton and McNamara [154] found that memory for 3D scenes was strongly viewpoint-dependent, suggesting that people may not automatically

encode three-dimensional information.

UI Design Guideline 8 *There is little evidence that 3D depth effects improve spatial memory for object layouts.*

4.1.2 Spatial layouts and menu hierarchies

As shown in the previous section, spatial arrangements support quick revisitation; and when spatial knowledge of an interface is strong, reduction of selection times tends to be bottlenecked by navigation costs such as scrolling or navigating hierarchical menus. However, hierarchies serve specific benefits, particularly for novice users [76], in that they reduce information load and provide a categorical structure to guide the user's search for commands [146]. This naturally leads to the question: how deep should hierarchies be?

There has been considerable investigation into how best to design menu hierarchies, with literature on the appropriate breadth and depth of menu systems dating back to Miller [118]. Miller's initial experiment evaluated different hierarchical arrangements of 64 menu items, ranging from one broad menu containing all 64 items to a tree of depth 6 with two choices at each level. His results showed a U-shaped function for selection time, with the two-level, eight-choice-per-level layout the most efficient; these findings were replicated in similar studies by Snowberry et al. [160] and Kiger [97]. However, other studies, such as that of Landauer and Nachbar [101], showed benefits for flatter hierarchies, contradicting Miller's results.

The difference appears to lie in the predictability of item locations, either by inference based on an understanding of the layout (such as an alphabetical order) or by pre-existing spatial knowledge. Miller's menu items were randomly ordered, while Landauer and Nachbar's were ordered alphanumerically, enabling the user to anticipate the locations of the items. Based on this, Cockburn and Gutwin [22] developed a predictive model that explained and integrated the results of previous studies. They demonstrated that certain types of data organisation (such as alphabetic or categorical ordering), as well as expertise with

spatial locations, allow for logarithmic search time; and that this kind of search favours broad, shallow hierarchies. Conversely, visually searching data that is structured unpredictably is aided by a small amount of hierarchy, as per Miller's original results [118]. However, interfaces are rarely arranged randomly. Furthermore, it takes only a few repeated selections for users to develop strong knowledge of an item's location (e.g., [24, 147]), suggesting that the "broad and shallow" arrangement is more generally useful.

UI Design Guideline 9 *Broad, shallow hierarchies offer optimal navigation time, particularly when item locations are highly predictable or when users have existing spatial knowledge of the interface.*

Recently, there have been investigations in HCI into interfaces that completely flatten hierarchical structures. Parallel dropdown menus, which display all menus on the system simultaneously, are a simple example. Quinn and Cockburn [138] compared fully parallel menus, partially parallel menus (i.e., standard dropdown menus) and serial menus (where only the item under the user's cursor is visible). They found no significant difference between partial and parallel menu types in terms of selection time, although the experiment was of insufficient length to properly examine learning effects or revisitation times. Experiments in web page menus showed favourable results for parallelisation, particularly for experienced users [76]. The design of ExposeHK [114], a system for overlaying hotkey bindings on top of corresponding commands, also suggested the use of parallel menus to display all application commands at once, with a brief analysis showing that modern screens are large enough to display the entire set of top-level menus in most applications.

Scarr et al.'s CommandMaps [147] applied the parallel menu idea to the Microsoft Office Ribbon interface, converting it into a full-screen 2D layout that showed all command tabs at once (Figure 4.3). CommandMaps again showed significant task time advantages over standard alternatives (menus and Ribbons) for revisitation, but with no disadvantage for novice use. Importantly, CommandMaps (and other

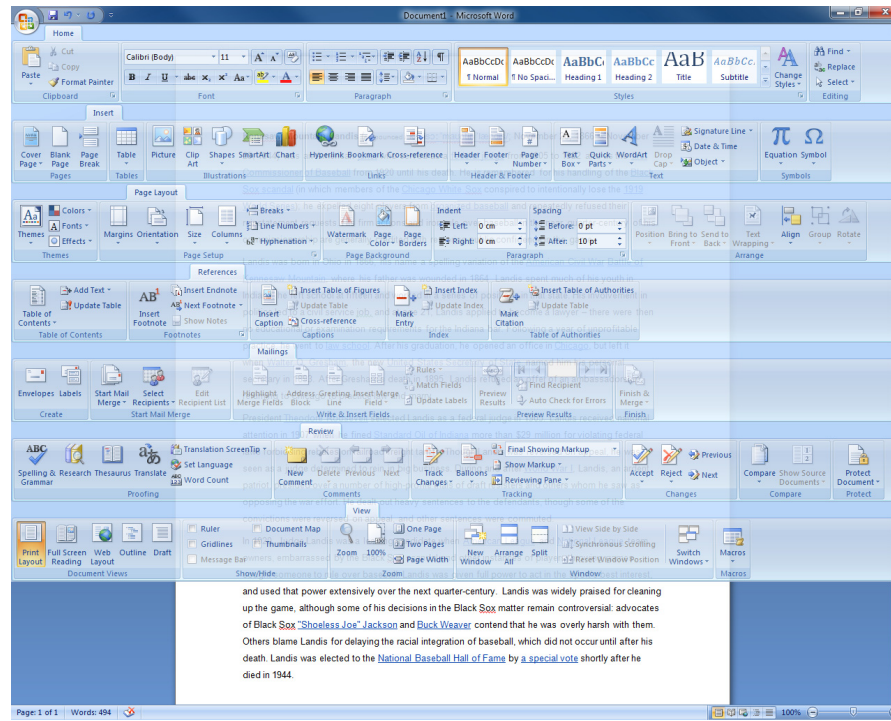


Figure 4.3: A CommandMap prototype based on the Microsoft Office Ribbon, which displays seven Ribbon tabs simultaneously. Image from [147].

parallelised interfaces) can still contain *visual* hierarchies and groupings to aid visual search – it is only *mechanical* hierarchies (i.e., in terms of number of movements or command actions) that result in higher task times.

4.2 Viewports and spatial memory

In the previous section, we discussed the advantages of simultaneous spatial interfaces, which show an entire information space at once. However, this kind of interface is not always feasible, particularly when the size of the dataset is larger than the display can handle.

One way to solve this issue, while maintaining the internal spatial relationships of the dataset, is to provide a *viewport* to the information

space that allows the user to view a manageable subset of the space. This subset is normally controlled through the use of pan and zoom tools (though see Smith and Taivalsaari's "stationary scrolling" [159] for an alternative, spatially constant way to view subsets of data). In panning and zooming interfaces, the user's ability to build an accurate mental model of the space and navigate around it depends on whether or not an overview is visible [15, 132], whether recognisable landmarks and spatial indicators are present [92], and whether constant reference points are available to anchor the position of the viewport [95]. We summarise the challenge of pan-and-zoom interfaces and discuss the importance of each of these factors below.

4.2.1 Panning and zooming

Interfaces for viewing large information spaces, such as maps, typically offer two ways to change the view of the data: panning (i.e., translating the viewport), and zooming (i.e., scaling the data).

The ability to zoom and pan in user interfaces creates two challenges for spatial memory. First, the user can no longer learn item locations relative to the boundary of the viewport, since it changes with every navigation action. Instead, the user must learn locations relative to nearby landmarks, in order to mentally assimilate them into a global picture of the space (this process is suggestive of Siegel and White's progression from landmark to survey knowledge – see Section 2.1). This implies that location learning in a pan-and-zoom interface may be less automatic than in a static interface (see Section 2.3.3). It also creates a risk that no known landmarks will be visible, requiring the user to alter their zoom level to determine where they are (the worst case of this effect is known as "desert fog" [92], where the zoom level is so extreme that no landmarks are visible at all). The second challenge is that when attempting to revisit a previously-seen location, the user must first establish the current position of the viewport (again integrating visible landmarks with a mental global picture of the space), before they can determine how to proceed.

Bederson [11] summarises the advantages and challenges of zoomable user interfaces (ZUIs). One of the things he notes is that

ZUIs have the potential to “tax human short-term memory [...] because users must integrate in their heads the spatial layout of the information” (p. 4). However, this effect can be alleviated somewhat through animation: Bederson and Boltman [10] showed that the use of animation when zooming enhanced spatial comprehension of an information space. It is worth noting, however, that studies of animation in other areas have provided inconclusive results: see Tversky et al. [177].

UI Design Guideline 10 *Illustrate panning and zooming transitions with animation whenever possible.*

4.2.2 Overviews

As noted in Section 4.1.1, spatial layouts of the entire information space make it easy for users to build a spatial model of that space. When using an overview of this kind as the primary view is infeasible, it can sometimes be useful to add a low-detail overview as a secondary window to the data. Overviews of this kind are typically displayed in a separate on-screen location to the primary view, displaying a low-detail version of the entire information space, as well as indicating the location of the primary viewport within that space. Overviews are present in many computer games, such as *Starcraft*, in the form of “mini-maps”, and standard scrollbars are essentially simple, one-dimensional overviews.

Intuitively, it seems that an overview should provide benefits for spatial memory and interaction, since they allow the user to anchor the detailed information in their primary viewport to its absolute spatial location. Burigat et al. [15] presented evidence to support this on mobile devices, demonstrating that the presence of an overview in a ZUI increased spatial recall accuracy. Similarly, in mobile reading interfaces, O’Hara et al showed that page overviews support incidental learning of spatial locations in reading interfaces, while pure scrolling interfaces do not [132].

However, some results have shown that overviews are not always useful. Hornbaek et al. [78] found no benefit for overviews in a zoomable map application, with subjects actually performing worse on navigation

time and recall accuracy when an overview was present. Nevertheless, a majority of participants preferred the overview interface, making comments like “It is easier to keep track of where I am” (p. 376).

4.2.3 Artificial landmarks and visual cues

Since object locations are generally defined in relation to the positions of other objects (see Section 2.4.2), landmarks are extremely important when it comes to encoding and retrieving location knowledge. In viewport interfaces, landmarks provide another potential method for users to mentally consolidate the data they can see into their overall spatial understanding.

In situations where natural landmarks are not available, dynamically generating artificial landmarks based on user behavior can be useful for supporting revisitation. Alexander et al. [1] applied this to within-document navigation with their Footprints Scrollbar, which places coloured marks in the scrollbar at recently visited document locations. The results indicate that these visual cues can act as landmarks which significantly decrease revisitation time.

Dynamic landmarking has also been applied successfully to two-dimensional interfaces. Skopik and Gutwin [158], in their investigation of fisheye views, noted that revisitation is difficult when distortion causes items to move around, particularly in featureless landscapes. To solve this problem, they added “visit wear” (derived from Hill et al.’s *read wear* [74]) to show previously visited locations, improving revisitation performance. Skopik and Gutwin noted that the risk of this approach is an increase in visual clutter, although this effect can be mitigated by fading out wear marks over time, or allowing the user to customise the visibility of the wear.

Importantly, Quinn et al. [139] found no benefit for dynamic landmarks in a situation where item locations were already easily predictable. In these cases, spatial memory is likely strong enough to find items without the use of visual landmarks. Quinn et al. also caution against the overuse of landmarks, finding that the extraneous visual clutter can distract users and decrease their performance.

UI Design Guideline 11 *Artificial landmarks can improve visual search in scrolling and fisheye interfaces. However, they should be used sparingly to avoid visual clutter.*

In viewports of two-dimensional data spaces, it can sometimes be useful to visualise the locations of objects that are outside the current viewport. City Lights [189], Halo [9], and Wedge [60] (Figure 4.4) are all examples of systems that provide visual indicators of the presence of off-screen objects, with the latter two techniques providing information about both distance and direction.



Figure 4.4: Left: Wedge uses isosceles triangles to indicate the positions of off-screen items. Image from [60]. Right: Canyon uses a ‘paper-folding’ metaphor to display items outside the primary view, where distance is indicated by the depth of the ‘folds’. Image from [85].

Another application of such visualisations exists when data is dynamic, or when more detail is desired for several separate locations. In these cases, simple overview+detail interfaces are insufficient, as it becomes difficult or impossible to simultaneously visualise all of the salient data points. Ion et al. [85] solved this problem for large dis-

plays with their Canyon visualisation (Figure 4.4), which augments an overview+detail interface with a paper-folding metaphor to display the relationships between out-of-view objects and the main focal region.

In summary, we recommend that artificial landmarks and other visual cues be used when existing landmarks are scarce (“desert fog” situations), in order to help a user orient themselves in scrolling, panning and zooming interfaces; or to indicate salient information displayed off-screen. We conclude that they are less useful in static interfaces, which typically have a frame of reference by which locations can be remembered, and interfaces with many existing landmarks, when adding extra landmarks simply increases visual clutter.

4.2.4 Situated information spaces

In 1993, Fitzmaurice [51] introduced the idea of *situated information spaces*, where a data set is mapped into real-world space, and a spatially aware handheld display can be used as a viewport to visualise the data. Zooming and panning navigation can then be achieved in a natural way, as if looking through a handheld “window” into the virtual world. In terms of spatial memory, the theoretical advantage of this approach is that the user can utilise reference points in the environment to anchor their mental map of the data, reducing the potential for getting lost compared to standard panning interfaces.

However, studies on situated information spaces so far have been limited by the sensing capabilities and response rates of hardware, removing the illusion of the display as a ‘window’ to the data. Fitzmaurice et al.’s *Chameleon* [52, 50] was the first implementation of such a system. They found that the movable display provided comparable depth perception ability to that achieved with a standard display, but interaction performance was hindered by hardware limitations – however, they did not investigate spatial memory. A later version mounted on a mechanical arm, the *Boom Chameleon* [175], showed benefits for examining 3D objects, although spatial memory was again not measured.

Yee’s *peephole displays* [187] applied the Chameleon concept to mobile devices. Yee’s prototype showed advantages over a conventional interface for drawing applications, but no difference for map naviga-

tion. However, Yee was also affected by hardware limitations, noting that “peephole techniques would work much better on a faster and brighter display” (p. 5).

Pahud et al. [133] studied spatial recall performance using Chameleon-style interaction on a mobile device, and found no significant differences compared to standard ‘pinch-flick-drag’ interaction.

Recently, peephole displays have also begun to appear on mobile projectors, where the “window” to the data is projected into the environment, rather than being displayed on a handheld device. Kaufmann and Ahlstrom [94, 95] studied map navigation and spatial memory in projected peephole interfaces, and found that they offered better spatial recall accuracy than standard touch-screen panning interfaces for both users and observers of the application.

Rädle et al. [140] studied the use of a tablet computer as a viewport into a wall-sized display. To navigate around the space, they compared standard pan-and-zoom techniques to peephole interaction, which required physical movement of both user and device. Memory for object locations was no different between techniques immediately after the experiment, but a further experiment conducted after 15 minutes of distraction showed increased accuracy in the peephole condition, suggesting that peephole interaction may have benefits for long-term spatial memory.

4.3 Distorting space

Another way to deal with large information spaces is to *distort* the contents of the space such that the most relevant information is more accessible than the rest. This can be done in different ways, depending on the type of data being displayed. In continuous spaces, such as maps, techniques such as pointing lenses can be used to view certain areas in more detail: one well-studied example is the *fish-eye view* [54], which allows the user to magnify an area of interest in an information space while maintaining the connectedness of the area to its surroundings (Figure 4.5). With discrete data that does not have an inherent spatial arrangement, such as sets of commands, designers have the flexibility



Figure 4.5: Fisheye views seamlessly integrate a high-detail ‘focus’ region with its low-detail surroundings.

to move and rearrange the discrete parts of the set in any way they choose, in order to make some commands more easily accessible or fit the constraints of the containing interface.

In general, changing the locations of interface objects in this way disrupts a user’s ability to use their spatial location knowledge. For this reason, interface design guidelines often promote either spatial stability (e.g., Hansen’s ‘display inertia’ [68]) or the more general concept of ‘consistency’ [35, 128, 156]. However, there are situations in which system designers may choose to disrupt spatial memory in pursuit of other goals. In the rest of this section, we discuss the situations where this may occur, analyse existing interfaces that distort space and break the principle of spatial consistency, and identify instances where alternative, spatially-consistent designs can improve performance.

We examine two categories of spatial distortion. First, we look at focus+context and adaptable interfaces, two situations where the distortion is *user-controlled*. Second, we examine *system-controlled* distor-

tions, such as those generated by adaptive interfaces, and automatic re-arrangement of controls when window geometry changes.

4.3.1 Focus+context interfaces

Like an overview+detail interface (discussed in Section 4.2.2), a focus+context interface is designed to provide an overview of the space, while allowing the user to view a specific region (the focus area) in more detail. However, a focus+context display removes the discontinuity between the two regions, “integrating focus and context into a single display where all parts are concurrently visible” ([25], p. 10). The most commonly studied example of a focus+context interface is the *fisheye view*, shown in Figure 4.5.

The fisheye view provides a distortion of visual space while leaving the motor space undistorted (i.e., clicking at the cursor position in the centre of the lens is equivalent to clicking without the lens present). However, despite the fact that the primary goal of a fisheye lens is to enable better understanding of the underlying dataset, these visual distortions can actually increase confusion and disorientation [19] and impair the user’s ability to make spatial judgements. This problem is exacerbated when the user has no easy way of mapping magnified items to their positions in the regular, un-distorted space. Zanella et al. [188] reduced these problems in maps by adding visual cues that made the fisheye mapping more explicit, with both a cartographic grid overlay and shading to better indicate the fisheye ‘bubble’ making it easier for users to comprehend the effects of the distortion.

UI Design Guideline 12 *Using visual cues to make view distortions more explicit can increase spatial comprehension.*

Skopik and Gutwin [158] examined the use of fisheye views in both maps and discrete graphs, and also found that people had difficulty remembering object locations due to the distortion. Their solution used dynamic landmarks in the form of “visit wear” (see Section 4.2.3) to provide spatial points of reference for users.

4.3.2 Adaptable interfaces

In contrast to *adaptive* interfaces, where changes to the interface are determined by the system, *adaptable* interfaces can be directly modified and customised by the user. Findlater and McGrenere [44] compared static, adaptive and adaptable menu systems and found that adaptive menus performed the worst, due to their lack of predictability, while static menus were the most efficient. Participants, however, thought they were most efficient with adaptable menus, even though this was not the case; they also preferred the adaptable menus overall. This suggests that greater control over an interface can provide users with higher perceived performance and satisfaction.

UI Design Guideline 13 *Allowing users to customize the interface to their personal needs can increase satisfaction.*

4.3.3 Adaptive interfaces

Adaptive interfaces are interfaces which “automatically tailor the presentation of functionality to better fit an individual user’s tasks, usage patterns, and abilities” [43]. In practice, an adaptive interface typically develops a model of the user’s behavior over time, and uses it to alter the interface for the purposes of reducing visual search time or motor movement.

There are several ways in which interfaces can be altered. First, items can be moved: for example, pull-down menus could dynamically re-arrange themselves such that the most frequently used items are near the top (e.g., [120, 152]), enabling lower pointing times for the most commonly accessed targets. Sears and Shneiderman [152] showed efficiency benefits for this type of design in an experiment where item ordering was pre-determined: that is, items were sorted based on *a priori* knowledge of their selection frequencies and did not move during the experiment. However, when menus change dynamically, the cost of unpredictable command locations can outweigh the benefits of the adaptation [120, 44].

UI Design Guideline 14 *Adaptive systems that frequently change item locations prevent users from developing a spatial knowledge of controls. Avoid this whenever possible.*

There have been several approaches to mitigate this issue. At the algorithmic level, some adaptive algorithms are more stable than others: frequency-based sorting is much more stable than recency-based sorting, for example [24]. Fitchett and Cockburn’s AccessRank [47] attempts to create predictive lists that are both accurate *and* stable, although its use in real interfaces has not been explicitly evaluated. Importantly, stability of results is likely to be more important than the understandability of an algorithm, at least in terms of task time: participants in a study by Gajos et al. [57] performed no better with recency-based adaptation than with purely random adaptation (i.e., where controls promoted by the adaptive interface were chosen at random), even though they indicated that the recency-based strategy was much more predictable.

Another alternative is to adapt the interface by *copying* items into an easily-accessible area, rather than rearranging the existing items. Gajos et al.’s Split Interface [56], which copied frequently used items in Microsoft Office into a designated toolbar, was faster than the standard interface and also preferred by users. The risk of duplicating items is that it may introduce a decision cost – users will not always find the item they need in the predicted subset, so an optimal selection strategy requires them to decide which location to look in first. Howes et al. [81] showed that providing shortcuts to items slows down users for items that have no shortcuts – presumably since participants were checking the shortcut area before looking for items in the standard location.

Some adaptive interfaces preserve spatial layout and make purely visual changes, aiming to accelerate visual search rather than navigation time. Previous work has shown that colour-based highlighting (e.g., [46, 56]) has proven ineffective in aiding visual search, perhaps because of the failure of colour to compete with existing saliency effects in the interface. Solutions that reduce the saliency of non-highlighted items have fared better. Findlater et al.’s *ephemeral adaptation* [46] success-

fully aids visual search by immediately displaying predicted items, and fading in other items over time; their idea was based on the known pre-attentive effects of abrupt onset (see Section 3.1.1). Fitchett et al. [48] also showed benefits for stencil-based highlighting, which increases the relative visual saliency of highlighted items by adding a dark translucent layer to the rest of the interface.

UI Design Guideline 15 *Visual highlighting can speed up search for certain items, if it is done in a way that increases the items' salience relative to the surrounding alternatives. This can be done by adding emphasis to predicted items, or subtracting emphasis from all non-predicted ones.*

According to Fitts' Law, pointing times can also be reduced by increasing target sizes. Cockburn et al. [24] investigated *morphing menus*, where frequently used menu items grow in size, but item ordering is maintained. However, they found no benefit over traditional menus. Tak et al.'s SCOTZ window-switching system [165, 166] also increases the size of items over time in a 2D layout, but attempts to reduce the movement of items by using a relatively stable treemap layout. As a result of this, items gradually drift over time, but do not move substantially between invocations of the tool.

Importantly, however, spatial stability is not always the most important concern in an adaptive interface, particularly when screen size is constrained. Findlater et al. [45] evaluated an adaptive split menu with differing levels of accuracy on both small and large screens. Results suggest that the adaptation is of little use on large screens, even at 80% accuracy, but that the high cost of regular navigation on small screens makes the adaptation worthwhile. This result suggests that when navigation cost is low, such as on large screens with shallow hierarchies and rapid input techniques, predictability and consistency (i.e. spatial stability) are the most important factors. When navigation cost is high, e.g. on small-screen devices using constrained input methods such as rocker switches, consistency is less important and rearranging to improve navigation may be the best strategy to increase efficiency.

UI Design Guideline 16 *Adaptive interfaces that move items are most useful when the navigation cost to access an item is high, such as on small-screen devices. In this case, the benefit of reducing navigation time can outweigh the drawback of spatial unpredictability.*

4.3.4 Responding to changing display parameters

In general, computer interface layouts are subject to certain parameters, such as the amount of data to be displayed, and the available area in which to display it. If these parameters never change, it is easy to maintain spatial consistency. However, when window geometry changes, or when new items need to be added to the display, interface designers must find a way to adapt the existing spatial layout to accommodate the changes.

The most common approach in these situations is to rearrange existing items – for example, when a file browser window (displaying a tile view) is resized, items are usually reflowed from left to right, top to bottom to fit the new window bounds. Similarly, when new files are added to a folder, they are inserted to maintain the existing order, necessitating a shift in location for all of the items following the insertion point (unless the folder is sorted by creation date, in which case the new file is inserted at the end).

However, in situations where spatial memory is a primary concern, there are alternative techniques available to support these changing parameters. When datasets change, minimizing the change in item locations can be done by adding new items at the end of lists [148], or using relatively stable visualisations such as treemaps [165, 176, 164]. Scarr et al. [148] studied the case when window boundaries change, and observed that if item locations are kept constant relative to a frame of reference (i.e., the window border), expert performance enabled by spatial memory is largely maintained (see Section 2.4.1 for more on the importance of reference frames to spatial memory). The implication of this result, verified in a second study, is that revisitation time can be reduced in interfaces with changing window boundaries by scaling the

entire interface to fit, rather than reflowing items (Figure 4.6).

UI Design Guideline 17 *Interfaces can avoid disrupting spatial memory by keeping existing items spatially consistent relative to a salient frame of reference, such as the window border.*

Research Question 7 *How does interference affect spatial memory in user interfaces? Does learning the layout of one spatial interface compromise retrieval for another previously-learned spatial interface? Are there factors (e.g., similarity of locations or of icons) that affect this interference?*

4.4 Non-visuospatial cues and feedback

The use of spatial memory can often be enhanced by the presence of contextual cues or feedback. For example, in Section 2.3.1, we discussed how recall of a specific memory can be influenced by cues that were present when that memory was encoded. Similarly, recall may be aided by the presence of feedback that is either non-visual (such as proprioceptive feedback during selection) or non-spatial (such as text labels on items). In this section, we examine interfaces that provide direct proprioceptive feedback (such as touch screens), we identify the importance of visual and textual cues for confirmation, and we discuss the effects of auditory and environmental factors.

4.4.1 Proprioceptive feedback

When a user makes a physical movement to interact with a computer, such as typing on a keyboard or using a touchscreen, they receive proprioceptive feedback. With practice, interactions with the computer can then be encoded in terms of the required motor actions (i.e., using muscle memory), rather than declarative knowledge of item locations.

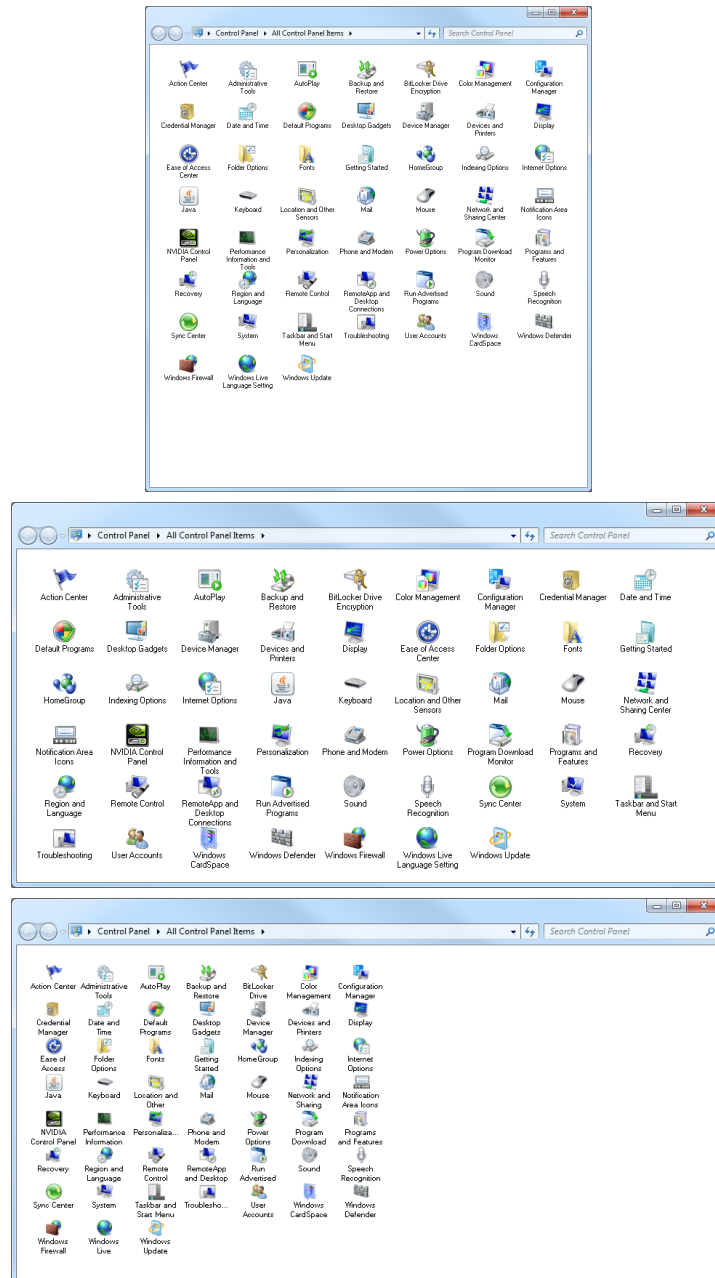


Figure 4.6: Top: The Windows 7 control panel before the window is resized. Centre: The resized Windows 7 control panel with items re-arranged using a 'reflow' strategy. Bottom: The resized Windows 7 control panel with the item grid scaled to fit. Images adapted from [148].

Tan et al. showed that direct proprioceptive interaction with items (i.e., using a touch screen vs. using a mouse and monitor) can enhance spatial learning, especially for females [168]. The advantages of direct interaction were also shown by Jetter et al. [88], who performed a study showing that touch interaction improved spatial recall compared to the mouse in a panning interface, but not when using a panning+zooming interface. They hypothesised that the changing visual and motor distances induced by zooming negated the proprioceptive benefits of the direct interaction with the surface.

It is also possible that the feedback gained while placing items, such as in file browsers or Robertson's Data Mountain [142], may enhance users' spatial memory for the items they placed. Subjects in the Data Mountain study certainly displayed strong spatial recall, but more research is needed to determine the role of manual object placement in these results.

Research Question 8 *Allowing users to manually place objects may enable better memory for spatial layouts, at the cost of substantial additional time and effort on the part of the user. More research is needed to determine whether the cost/benefit tradeoff is worthwhile – in other words, whether manually arranging on-screen items is more beneficial than spending the same amount of time on normal interaction.*

4.4.2 Visual and textual cues

As discussed in Section 3.2, spatial memory can often be imprecise: users often know the approximate locations of controls they have used, but their knowledge is rarely exact. Combined with the fact that people often mistrust their own spatial abilities (see Section 3.6), this suggests that relying on spatial memory *by itself* may not be an effective method of interaction for most users.

Jones and Dumais [90] performed an experiment where subjects read news articles and virtually filed them into either a spatial arrangement of unnamed categories, a list of named categories, or a spatial

arrangement of named categories. Participants were then given statements about each of the articles, and had to choose the article that each statement belonged to. The named spatial index performed better than the name-only index, suggesting a benefit of spatial arrangement, but the spatial-only index performed the worst by far.

Czerwinski et al.'s follow-up experiment on the Data Mountain system [31] studied the effects of the presence of thumbnail images on spatial retrieval of documents. When the thumbnails were removed, subjects' performance dropped, but returned to normal after a few trials (though mouse-over text was still available for users to verify their selections). Czerwinski et al. observed subjects "homing in on the cluster of web pages they knew to contain the target page, after which they would use the mouse-over text to find the specific target page" (p. 7).

The results of these two studies show that people can use their spatial memory to remember general vicinities in which items are located, but that other feedback (such as thumbnails or text) is required for the user to verify that their intended selection is correct.

UI Design Guideline 18 *While spatial memory can enable users to narrow down a likely region in which an item is located, extra cues such as textual labels can assist users to verify exact locations.*

Research Question 9 *Are there design approaches that can provide both memory-based expert performance and a fallback to other modes when retrieval fails?*

4.4.3 Auditory feedback and environmental factors

Some studies have investigated the effects of auditory cues on spatial abilities. Auditory feedback does contain a spatial dimension (when listening to a sound, we can often make a rough estimate of the direction and distance of the source) and this effect is often used in surround-

sound systems for movies and games, but results for aiding spatial retrieval in HCI have been mixed. Robertson et al.'s Data Mountain system [142] included auditory cues when document thumbnails were being dragged; controlling volume, panning and reverb levels to indicate spatial location. However, this was consistently ranked as the least helpful cue by participants.

Davis et al. [34] performed another study on the effects of audio in a virtual environment. Participants interacted with virtual rooms, with and without a distinctive auditory cue in each room. They then underwent a spatial recall test where they were asked to remember which objects were in each room, and a recognition test, where objects were shown and participants were asked which room they belonged to. Recognition was more successful when high-fidelity audio was present (compared to low-fidelity and no audio conditions), and recall was marginally better.

Other environmental factors have been shown to be important to learning. Tan et al. [167] showed that using physically large displays improved users' spatial memory and performance in other spatial tasks. In a separate study, Tan et al. [169] improved the learning of word pairs by creating an immersive environment and placing items in different spatial locations.

5

Conclusions

Supporting spatial memory in user interfaces is an important goal, both in terms of user performance and satisfaction. In this review, we investigated the psychological underpinnings of spatial memory, utilising models of both working memory and the development of long-term recall abilities. We then summarised and distilled empirical results on the observable properties of spatial memory. Finally, we looked at spatial memory from an HCI perspective, examining interfaces that affect spatial memory (either positively or negatively) and different methods of presenting spatial data.

Overall, our review provides strong evidence that spatial knowledge of controls and data enables rapid interaction and information retrieval, and allows users to focus more of their cognitive resources on the task at hand, rather than on the interface. Throughout the paper we identified guidelines for designers (summarised in Table 5.1), which we hope provide clear advice on how and when to design with spatial memory in mind. Similarly, we hope that our summary of the area, as well as methodological cautions (Table 5.2) and directions for future research (Table 5.3) prove a useful resource for scientists interested in the importance of spatial memory in user interfaces.

Table 5.1: A summary of UI design guidelines identified throughout the paper.

#	Page	Description	References
1	p. 21	Allow users to search items in parallel by reducing the blank space between items.	[80]
2	p. 22	Use categorisations and orderings to help novice users quickly find items.	[17, 161]
3	p. 22	When multiple groups of items are displayed simultaneously, provide salient labels for groupings to encourage hierarchical search.	[79]
4	p. 27	Users develop an accurate memory for the locations of frequently accessed interface items.	[62, 147]
5	p. 29	In training systems, forcing users to intentionally memorise item locations can increase long-term retention. However, such systems must be careful to provide an appropriate level of difficulty.	[26]
6	p. 30	Tailor the amount of effort required to interact in accordance with the goals of the system. Increasing effort can increase the effectiveness of training interfaces, while reducing effort can increase overall interface performance.	[26, 39, 48]
7	p. 39	Providing a spatial overview of an information space can improve users' ability to navigate to known locations, as well as reducing visual search.	[23, 142, 31, 165, 166]
8	p. 42	There is little evidence that 3D depth effects improve spatial memory for object layouts.	[28, 154]
9	p. 43	Broad, shallow hierarchies offer optimal navigation time for experts when item locations are predictable.	[22, 101, 147]
10	p. 46	Illustrate panning and zooming transitions with animation whenever possible.	[10, 11]
11	p. 48	Artificial landmarks can improve visual search in scrolling and fisheye interfaces. However, they should be used sparingly to avoid visual clutter.	[1, 139, 158]
12	p. 52	Using visual cues to make view distortions more explicit can increase spatial comprehension.	[188]
13	p. 53	Allowing users to customize the interface to their personal needs can increase satisfaction.	[44]
14	p. 54	Adaptive systems that frequently change item locations prevent users from developing a spatial knowledge of controls. Avoid this whenever possible.	[120, 44]
15	p. 55	Visual highlighting can speed up search for certain items, if it is done in a way that increases their saliency relative to the surrounding alternatives.	[46, 48, 56]
16	p. 56	Adaptive interfaces that move items are useful when the navigation cost to access an item is high, such as on small-screen devices.	[45]
17	p. 57	Interfaces can avoid disrupting spatial memory by keeping existing items spatially consistent relative to a salient frame of reference, such as the window border.	[148]
18	p. 60	Textual or iconic cues can assist users in verifying their selections.	[31, 90]

Table 5.2: A summary of methodological cautions identified throughout the paper.

#	Page	Description	References
1	p. 23	When examining spatial memory in visual interfaces, use visually homogeneous targets to avoid confounds caused by visual pop-out effects.	[58, 174, 173]
2	p. 25	When experimenting on interfaces that alter spatial locations, it is important to allow users enough time to develop expertise.	[17, 24]
3	p. 33	When spatial memory plays a role in an experiment, assess individual differences in participants' spatial abilities; participants can then be divided into a 'high spatial' group and a 'low spatial' group for later analysis.	[37, 71]
4	p. 34	HCI researchers should be cautious when generalising results of spatial memory experiments to all user populations.	[12, 53, 96, 106]

Table 5.3: A summary of research questions identified throughout the paper.

#	Page	Description
1	p. 12	How does interference affect spatial memory in user interfaces? Does learning the layout of one spatial interface compromise retrieval for another previously-learned spatial interface? Are there factors (e.g., similarity of locations or of icons) that affect this interference?
2	p. 12	How long does spatial memory for a user interface last? Is it as resilient to decay as other spatial memories from everyday life?
3	p. 16	Research is needed to investigate the value of boundaries and partitions when designing control layouts.
4	p. 27	Exactly how accurate is absolute spatial memory, and what is the interaction between retrieved approximate memory and local visual search? How does this change as a user progresses towards expertise?
5	p. 33	Research is needed to determine the upper limits of long-term retention, and characterise the decay of spatial memory over time.
6	p. 34	Research is needed to determine the effects of interfaces designed to exploit spatial memory on low spatial-ability users, and identify methods (such as ability-based interface customisation) that could mitigate these effects.
7	p. 57	How does interference affect spatial memory in user interfaces? Does learning the layout of one spatial interface compromise retrieval for another previously-learned spatial interface? Are there factors (e.g., similarity of locations or of icons) that affect this interference?
8	p. 59	More research is needed to determine whether having users manually place on-screen items benefits spatial learning for those items, compared to spending the same amount of time on normal interaction.
9	p. 60	Are there design approaches that can provide both memory-based expert performance and a fallback to other modes when retrieval fails?

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References

- [1] Jason Alexander, Andy Cockburn, Stephen Fitchett, Carl Gutwin, and Saul Greenberg. Revisiting read wear: analysis, design, and evaluation of a footprints scrollbar. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, pages 1665–1674, New York, NY, USA, 2009. ACM.
- [2] Gary L Allen, Alexander W Siegel, and Richard R Rosinski. The role of perceptual context in structuring spatial knowledge. *Journal of Experimental Psychology: Human Learning and Memory*, 4(6):617, 1978.
- [3] Jackie Andrade and Peter Meudell. Short report: Is spatial information encoded automatically in memory? *The Quarterly Journal of Experimental Psychology Section A*, 46(2):365–375, 1993.
- [4] Alan Baddeley. The episodic buffer: a new component of working memory? *Trends in cognitive sciences*, 4(11):417–423, 2000.
- [5] Alan Baddeley. Working memory: Looking back and looking forward. *Nature Reviews Neuroscience*, 4(10):829–839, 2003.
- [6] Alan D Baddeley. *Essentials of human memory*. Psychology Press/Taylor & Francis (UK), 1999.
- [7] Alan D Baddeley. The psychology of memory. *The Handbook of Memory Disorders*, page 1, 2003.
- [8] Alan D. Baddeley and Graham Hitch. Working memory. volume 8 of *Psychology of Learning and Motivation*, pages 47 – 89. Academic Press, 1974.

- [9] Patrick Baudisch and Ruth Rosenholtz. Halo: a technique for visualizing off-screen objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '03, pages 481–488, New York, NY, USA, 2003. ACM.
- [10] B.B. Bederson and A. Boltman. Does animation help users build mental maps of spatial information? In *Information Visualization, 1999. (Info Vis '99) Proceedings. 1999 IEEE Symposium on*, pages 28–35, 1999.
- [11] Benjamin B. Bederson. The promise of zoomable user interfaces. *Behaviour & Information Technology*, 30(6):853–866, 2011.
- [12] Michael J. Boivin. The effect of culture on a visual-spatial memory task. *The Journal of General Psychology*, 118(4):327–334, 1991. PMID: 1813596.
- [13] Gordon H. Bower. Analysis of a mnemonic device: Modern psychology uncovers the powerful components of an ancient system for improving memory. *American Scientist*, 58(5):pp. 496–510, 1970.
- [14] Lee R Brooks. Spatial and verbal components of the act of recall. *Canadian Journal of Psychology/Revue canadienne de psychologie*, 22(5):349, 1968.
- [15] Stefano Burigat, Luca Chittaro, and Edoardo Parlato. Map, diagram, and web page navigation on mobile devices: the effectiveness of zoomable user interfaces with overviews. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services*, MobileHCI '08, pages 147–156, New York, NY, USA, 2008. ACM.
- [16] Michael D. Byrne, John R. Anderson, Scott Douglass, and Michael Matessa. Eye tracking the visual search of click-down menus. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, CHI '99, pages 402–409, New York, NY, USA, 1999. ACM.
- [17] Stuart K Card. Visual search of computer command menus. *Attention and performance X: Control of language processes*, pages 97–108, 1984.
- [18] Stuart K Card, Thomas P Moran, and Allen Newell. *The psychology of human computer interaction*. Routledge, 1983.
- [19] M.S.T. Carpendale, D.J. Cowperthwaite, and F.D. Fracchia. Making distortions comprehensible. In *Visual Languages, 1997. Proceedings. 1997 IEEE Symposium on*, pages 36–45, 1997.
- [20] Elizabeth R. Chrastil and William H. Warren. Active and passive contributions to spatial learning. *Psychonomic Bulletin & Review*, 19(1):1–23, 2012.

- [21] A. Cockburn, P. Quinn, C. Gutwin, G. Ramos, and J. Looser. Air pointing: Design and evaluation of spatial target acquisition with and without visual feedback. *International Journal of Human-Computer Studies*, 69(6):401 – 414, 2011.
- [22] Andy Cockburn and Carl Gutwin. A predictive model of human performance with scrolling and hierarchical lists. *Human-Computer Interaction*, 24(3):273–314, 2009.
- [23] Andy Cockburn, Carl Gutwin, and Jason Alexander. Faster document navigation with space-filling thumbnails. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '06, pages 1–10, New York, NY, USA, 2006. ACM.
- [24] Andy Cockburn, Carl Gutwin, and Saul Greenberg. A predictive model of menu performance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '07, pages 627–636, New York, NY, USA, 2007. ACM.
- [25] Andy Cockburn, Amy Karlson, and Benjamin B. Bederson. A review of overview+detail, zooming, and focus+context interfaces. *ACM Comput. Surv.*, 41(1):2:1–2:31, January 2009.
- [26] Andy Cockburn, Per Ola Kristensson, Jason Alexander, and Shumin Zhai. Hard lessons: effort-inducing interfaces benefit spatial learning. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '07, pages 1571–1580, New York, NY, USA, 2007. ACM.
- [27] Andy Cockburn and Bruce McKenzie. Evaluating the effectiveness of spatial memory in 2d and 3d physical and virtual environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '02, pages 203–210, New York, NY, USA, 2002. ACM.
- [28] Andy Cockburn and Bruce McKenzie. Evaluating spatial memory in two and three dimensions. *International Journal of Human-Computer Studies*, 61(3):359–373, 2004.
- [29] A. Cooper. Mental rotation of random two-dimensional shapes. *Cognitive Psychology*, pages 20–43, 1975.
- [30] Fergus IM Craik and Robert S Lockhart. Levels of processing: A framework for memory research. *Journal of verbal learning and verbal behavior*, 11(6):671–684, 1972.
- [31] M Czerwinski, Maarten Van Dantzich, George Robertson, and Hunter Hoffman. The contribution of thumbnail image, mouse-over text and spatial location memory to web page retrieval in 3d. In *Proceedings of Interact*, volume 99, pages 163–170, 1999.

- [32] Rudolph P. Darken and John L. Sibert. Wayfinding strategies and behaviors in large virtual worlds. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '96, pages 142–149, New York, NY, USA, 1996. ACM.
- [33] Arindam Das and Wolfgang Stuerzlinger. Unified modeling of proactive interference and memorization effort: A new mathematical perspective within act-r theory. In *CogSci 2013*, 2013.
- [34] Elizabeth Thorpe Davis, Kevin Scott, Jarrell Pair, Larry F Hodges, and James Oliverio. Can audio enhance visual perception and performance in a virtual environment? In *Proceedings Of The Human Factors And Ergonomics Society 43rd Annual Meeting*, pages 1197–1201, 1999.
- [35] A Dix, J Finlay, G Abowd, and R Beale. Human–computer interaction, 1993.
- [36] Christian F. Doeller and Neil Burgess. Distinct error-correcting and incidental learning of location relative to landmarks and boundaries. *Proceedings of the National Academy of Sciences*, 105(15):5909–5914, 2008.
- [37] Marion Eals and Irwin Silverman. The hunter-gatherer theory of spatial sex differences: Proximate factors mediating the female advantage in recall of object arrays. *Ethology and Sociobiology*, 15(2):95 – 105, 1994.
- [38] Hermann Ebbinghaus. *Memory: A contribution to experimental psychology*. Number 3. Teachers college, Columbia university, 1913.
- [39] Brian D. Ehret. Learning where to look: location learning in graphical user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '02, pages 211–218, New York, NY, USA, 2002. ACM.
- [40] Digby Elliott and John Madalena. The influence of premovement visual information on manual aiming. *The Quarterly Journal of Experimental Psychology Section A*, 39(3):541–559, 1987.
- [41] David G Elmes. Interference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 14(4):668, 1988.
- [42] FL Engel. Visual conspicuity, visual search and fixation tendencies of the eye. *Vision Research*, 17(1):95–108, 1977.
- [43] Leah Findlater and Krzysztof Z. Gajos. Design space and evaluation challenges of adaptive graphical user interfaces. *AI Magazine*, 30(4):68–73, 2009.

- [44] Leah Findlater and Joanna McGrenere. A comparison of static, adaptive, and adaptable menus. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '04, pages 89–96, New York, NY, USA, 2004. ACM.
- [45] Leah Findlater and Joanna McGrenere. Impact of screen size on performance, awareness, and user satisfaction with adaptive graphical user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '08, pages 1247–1256, New York, NY, USA, 2008. ACM.
- [46] Leah Findlater, Karyn Moffatt, Joanna McGrenere, and Jessica Dawson. Ephemeral adaptation: the use of gradual onset to improve menu selection performance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, pages 1655–1664, New York, NY, USA, 2009. ACM.
- [47] Stephen Fitchett and Andy Cockburn. Accessrank: predicting what users will do next. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems*, CHI '12, pages 2239–2242, New York, NY, USA, 2012. ACM.
- [48] Stephen Fitchett, Andy Cockburn, and Carl Gutwin. Improving navigation-based file retrieval. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, New York, NY, USA, 2013. ACM.
- [49] Paul Morris Fitts and Michael I Posner. Human performance. 1967.
- [50] George Fitzmaurice and William Buxton. The chameleon: spatially aware palmtop computers. In *Conference Companion on Human Factors in Computing Systems*, CHI '94, pages 451–452, New York, NY, USA, 1994. ACM.
- [51] George W. Fitzmaurice. Situated information spaces and spatially aware palmtop computers. *Commun. ACM*, 36(7):39–49, July 1993.
- [52] George W. Fitzmaurice, Shumin Zhai, and Mark H. Chignell. Virtual reality for palmtop computers. *ACM Trans. Inf. Syst.*, 11(3):197–218, July 1993.
- [53] Mary Flaherty. The validity of tests of visuo-spatial skills in cross-cultural studies. *The Irish Journal of Psychology*, 18(4):404–412, 1997.
- [54] G. W. Furnas. Generalized fisheye views. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '86, pages 16–23, New York, NY, USA, 1986. ACM.

- [55] Diana Gagnon. Videogames and spatial skills: An exploratory study. *ECTJ*, 33(4):263–275, 1985.
- [56] Krzysztof Z. Gajos, Mary Czerwinski, Desney S. Tan, and Daniel S. Weld. Exploring the design space for adaptive graphical user interfaces. In *Proceedings of the working conference on Advanced visual interfaces*, AVI '06, pages 201–208, New York, NY, USA, 2006. ACM.
- [57] Krzysztof Z. Gajos, Katherine Everitt, Desney S. Tan, Mary Czerwinski, and Daniel S. Weld. Predictability and accuracy in adaptive user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '08, pages 1271–1274, New York, NY, USA, 2008. ACM.
- [58] Bradley S Gibson and Erin M Kelsey. Stimulus-driven attentional capture is contingent on attentional set for displaywide visual features. *Journal of Experimental Psychology: Human Perception and Performance*, 24(3):699, 1998.
- [59] Wayne D Gray and Wai-Tat Fu. Soft constraints in interactive behavior: The case of ignoring perfect knowledge in-the-world for imperfect knowledge in-the-head. *Cognitive Science*, 28(3):359–382, 2004.
- [60] Sean Gustafson, Patrick Baudisch, Carl Gutwin, and Pourang Irani. Wedge: clutter-free visualization of off-screen locations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '08, pages 787–796, New York, NY, USA, 2008. ACM.
- [61] Sean Gustafson, Daniel Bierwirth, and Patrick Baudisch. Imaginary interfaces: spatial interaction with empty hands and without visual feedback. In *Proceedings of the 23rd annual ACM symposium on User interface software and technology*, UIST '10, pages 3–12, New York, NY, USA, 2010. ACM.
- [62] Sean Gustafson, Christian Holz, and Patrick Baudisch. Imaginary phone: learning imaginary interfaces by transferring spatial memory from a familiar device. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*, UIST '11, pages 283–292, New York, NY, USA, 2011. ACM.
- [63] Carl Gutwin and Andy Cockburn. Improving list revisitation with listmaps. In *Proceedings of the working conference on Advanced visual interfaces*, AVI '06, pages 396–403, New York, NY, USA, 2006. ACM.
- [64] Robert H. Logie and David G. Pearson. The inner eye and the inner scribe of visuo-spatial working memory: Evidence from developmental fractionation. *European Journal of Cognitive Psychology*, 9(3):241–257, 1997.

- [65] Michel Habib and Angela Sirigu. Pure topographical disorientation: A definition and anatomical basis. *Cortex*, 23(1):73 – 85, 1987.
- [66] J.A.Y. Hall and Doreen Kimura. Sexual orientation and performance on sexually dimorphic motor tasks. *Archives of Sexual Behavior*, 24(4):395–407, 1995.
- [67] Diane F Halpern. *Sex differences in cognitive abilities*. Lawrence Erlbaum, 2000.
- [68] Wilfred J. Hansen. User engineering principles for interactive systems. In *Proceedings of the November 16-18, 1971, fall joint computer conference*, AFIPS '71 (Fall), pages 523–532, New York, NY, USA, 1971. ACM.
- [69] Lynn Hasher and Rose T Zacks. Automatic and effortful processes in memory. *Journal of Experimental psychology: general*, 108(3):356, 1979.
- [70] Nancy L. Hazen. Spatial exploration and spatial knowledge: Individual and developmental differences in very young children. *Child Development*, 53(3):pp. 826–833, 1982.
- [71] Mary Hegarty, Daniel R. Montello, Anthony E. Richardson, Toru Ishikawa, and Kristin Lovelace. Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence*, 34(2):151 – 176, 2006.
- [72] John M Henderson, James R Brockmole, Monica S Castelhana, Michael Mack, M Fischer, W Murray, and R Hill. Visual saliency does not account for eye movements during visual search in real-world scenes. *Eye movements: A window on mind and brain*, pages 537–562, 2007.
- [73] William E Hick. On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, 4(1):11–26, 1952.
- [74] William C. Hill, James D. Hollan, Dave Wroblewski, and Tim McCanless. Edit wear and read wear. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '92, pages 3–9, New York, NY, USA, 1992. ACM.
- [75] Ken Hinckley, Randy Pausch, and Dennis Proffitt. Attention and visual feedback: the bimanual frame of reference. In *Proceedings of the 1997 symposium on Interactive 3D graphics*, I3D '97, pages 121–ff., New York, NY, USA, 1997. ACM.
- [76] Harry Hochheiser and Ben Shneiderman. Performance benefits of simultaneous over sequential menus as task complexity increases. *International Journal of Human-Computer Interaction*, 12(2):173–192, 2000.

- [77] GJ Hole. Decay and interference effects in visuospatial short-term memory. *Perception*, 25(1):53, 1996.
- [78] Kasper Hornbæk, Benjamin B. Bederson, and Catherine Plaisant. Navigation patterns and usability of zoomable user interfaces with and without an overview. *ACM Trans. Comput.-Hum. Interact.*, 9(4):362–389, December 2002.
- [79] Anthony J Hornof. Cognitive strategies for the visual search of hierarchical computer displays. *Human-Computer Interaction*, 19(3):183–223, 2004.
- [80] Anthony J. Hornof and David E. Kieras. Cognitive modeling reveals menu search in both random and systematic. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*, CHI '97, pages 107–114, New York, NY, USA, 1997. ACM.
- [81] Andrew Howes, Stephen J. Payne, and Amelia Woodward. The trouble with shortcuts. In *CHI '00 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '00, pages 267–268, New York, NY, USA, 2000. ACM.
- [82] Janellen Huttenlocher, Larry V. Hedges, and Susan Duncan. Categories and particulars: Prototype effects in estimating spatial location. *Psychological Review*, 98(3):352 – 376, 1991.
- [83] Ray Hyman. Stimulus information as a determinant of reaction time. *Journal of experimental psychology*, 45(3):188, 1953.
- [84] Anne Igel and Lewis O Harvey. Spatial distortions in visual perception. *Gestalt theory*, 13(4):210–231, 1991.
- [85] Alexandra Ion, Y.-L. Betty Chang, Michael Haller, Mark Hancock, and Stacey D. Scott. Canyon: providing location awareness of multiple moving objects in a detail view on large displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 3149–3158, New York, NY, USA, 2013. ACM.
- [86] Toru Ishikawa, Hiromichi Fujiwara, Osamu Imai, and Atsuyuki Okabe. Wayfinding with a gps-based mobile navigation system: A comparison with maps and direct experience. *Journal of Environmental Psychology*, 28(1):74 – 82, 2008.
- [87] Laurent Itti and Christof Koch. A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, 40(10):1489 – 1506, 2000.

- [88] Hans-Christian Jetter, Svenja Leifert, Jens Gerken, Sören Schubert, and Harald Reiterer. Does (multi-)touch aid users' spatial memory and navigation in 'panning' and in 'zooming & panning' uis? In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, AVI '12, pages 83–90, New York, NY, USA, 2012. ACM.
- [89] Y. Jiang, J.H. Song, and A. Rigas. High-capacity spatial contextual memory. *Psychonomic Bulletin & Review*, 12(3):524–529, 2005.
- [90] William P. Jones and Susan T. Dumais. The spatial metaphor for user interfaces: experimental tests of reference by location versus name. *ACM Trans. Inf. Syst.*, 4(1):42–63, January 1986.
- [91] John Jonides and Steven Yantis. Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics*, 43(4):346–354, 1988.
- [92] Susanne Jul and George W. Furnas. Critical zones in desert fog: aids to multiscale navigation. In *Proceedings of the 11th annual ACM symposium on User interface software and technology*, UIST '98, pages 97–106, New York, NY, USA, 1998. ACM.
- [93] Victor Kaptelinin. Item recognition in menu selection: the effect of practice. In *INTERACT '93 and CHI '93 Conference Companion on Human Factors in Computing Systems*, CHI '93, pages 183–184, New York, NY, USA, 1993. ACM.
- [94] Bonifaz Kaufmann and David Ahlström. Revisiting peephole pointing: a study of target acquisition with a handheld projector. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*, MobileHCI '12, pages 211–220, New York, NY, USA, 2012. ACM.
- [95] Bonifaz Kaufmann and David Ahlström. Studying spatial memory and map navigation performance on projector phones with peephole interaction. In *Proceedings of the 2013 ACM annual conference on Human factors in computing systems*, CHI '13, pages 3173–3176, New York, NY, USA, 2013. ACM.
- [96] Judith M. Kearins. Visual spatial memory in australian aboriginal children of desert regions. *Cognitive Psychology*, 13(3):434 – 460, 1981.
- [97] John I. Kiger. The depth/breadth trade-off in the design of menu-driven user interfaces. *International Journal of Man-Machine Studies*, 20(2):201 – 213, 1984.
- [98] Doreen Kimura. *Sex and cognition*. MIT Press, 2000.

- [99] Donald L King, Farrasha L Jones, Ronald C Pearlman, Abraham Tishman, Cassandra A Felix, et al. The length of the retention interval, forgetting, and subjective similarity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28(4):660, 2002.
- [100] Ezra S Krendel and Jerome Wodinsky. Search in an unstructured visual field. *Journal of the Optical Society of America*, 50(6):562, 1960.
- [101] T. K. Landauer and D. W. Nachbar. Selection from alphabetic and numeric menu trees using a touch screen: breadth, depth, and width. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '85, pages 73–78, New York, NY, USA, 1985. ACM.
- [102] Mark W. Lansdale. Modeling memory for absolute location. *Psychological Review*, 105(2):351 – 378, 1998.
- [103] Eric Lee and James Macgregor. Minimizing user search time in menu retrieval systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 27(2):157–162, 1985.
- [104] B Leitheiser and D Munro. An experimental study of the relationship between spatial ability and the learning of a graphical user interface. In *Proceedings of the Inaugural Americas Conference on Information Systems*, pages 122–124, 1995.
- [105] Frank Chun Yat Li, David Dearman, and Khai N. Truong. Virtual shelves: interactions with orientation aware devices. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology*, UIST '09, pages 125–128, New York, NY, USA, 2009. ACM.
- [106] Leah L. Light and Elizabeth M. Zelinski. Memory for spatial information in young and old adults. *Developmental Psychology*, 19(6):901 – 906, 1983.
- [107] P.H. Lindsay and D.A. Norman. *Human information processing: An introduction to psychology*. Academic Press, 1977.
- [108] Gordon D Logan. What is learned during automatization? ii. obligatory encoding of spatial location. *JOURNAL OF EXPERIMENTAL PSYCHOLOGY HUMAN PERCEPTION AND PERFORMANCE*, 24:1720–1736, 1998.
- [109] Robert H. Logie. Visuo-spatial processing in working memory. *The Quarterly Journal of Experimental Psychology Section A*, 38(2):229–247, 1986.
- [110] Robert H. Logie, Gesualdo M. Zucco, and Alan D. Baddeley. Interference with visual short-term memory. *Acta Psychologica*, 75(1):55 – 74, 1990.

- [111] James MacGregor and Eric Lee. Menu search: random or systematic? *International Journal of Man-Machine Studies*, 26(5):627 – 631, 1987.
- [112] Eleanor A Maguire, Neil Burgess, and John O'SKeefe. Human spatial navigation: cognitive maps, sexual dimorphism, and neural substrates. *Current Opinion in Neurobiology*, 9(2):171 – 177, 1999.
- [113] Eleanor A Maguire and Lisa Cipolotti. Selective sparing of topographical memory. *Journal of Neurology, Neurosurgery & Psychiatry*, 65(6):903–909, 1998.
- [114] Sylvain Malacria, Gilles Bailly, Joel Harrison, Andy Cockburn, and Carl Gutwin. Promoting hotkey use through rehearsal with exposehk. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages 573–582, New York, NY, USA, 2013. ACM.
- [115] JeanM. Mandler, Dale Seegmiller, and Jeanne Day. On the coding of spatial information. *Memory & Cognition*, 5(1):10–16, 1977.
- [116] R A McCarthy, J J Evans, and J R Hodges. Topographic amnesia: spatial memory disorder, perceptual dysfunction, or category specific semantic memory impairment? *Journal of Neurology, Neurosurgery & Psychiatry*, 60(3):318–325, 1996.
- [117] Peter D McCormack. Coding of spatial information by young and elderly adults. *Journal of Gerontology*, 37(1):80–86, 1982.
- [118] Dwight P. Miller. The depth/breadth tradeoff in hierarchical computer menus. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 25(1):296–300, 1981.
- [119] Brenda Milner. Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin*, 1971.
- [120] J. Mitchell and B. Shneiderman. Dynamic versus static menus: an exploratory comparison. *SIGCHI Bull.*, 20(4):33–37, April 1989.
- [121] Weimin Mou, Frank Biocca, Charles B Owen, Arthur Tang, Fan Xiao, and Lynette Lim. Frames of reference in mobile augmented reality displays. *Journal of Experimental Psychology: Applied*, 10(4):238–244, 2004.
- [122] Weimin Mou, Timothy P McNamara, et al. Intrinsic frames of reference in spatial memory. *JOURNAL OF EXPERIMENTAL PSYCHOLOGY LEARNING MEMORY AND COGNITION*, 28(1):162–170, 2002.
- [123] Weimin Mou, Chengli Xiao, and Timothy P. McNamara. Reference directions and reference objects in spatial memory of a briefly viewed layout. *Cognition*, 108(1):136 – 154, 2008.

- [124] Moshe Naveh-Benjamin. Coding of spatial location information: An automatic process?. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13(4):595 – 605, 1987.
- [125] Moshe Naveh-Benjamin. Recognition memory of spatial location information: Another failure to support automaticity. *Memory & Cognition*, 16(5):437–445, 1988.
- [126] Thomas O Nelson, Seth Chaiklin, et al. Immediate memory for spatial location. *Journal of experimental psychology. Human learning and memory*, 6(5):529, 1980.
- [127] Allen Newell and Paul S Rosenbloom. Mechanisms of skill acquisition and the law of practice. *Cognitive skills and their acquisition*, pages 1–55, 1981.
- [128] Jakob Nielsen. *Usability Engineering*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1993.
- [129] Erik L Nilsen. Perceptual-motor control in human-computer interaction. Technical Report 37, Ann Arbor, Michigan: The Cognitive Science and Machine Intelligence Laboratory, The University of Michigan, 1996.
- [130] Kent L Norman. Spatial visualization—a gateway to computer-based technology. *Journal of Special Education Technology*, 12(3):195–206, 1994.
- [131] Kenton O’Hara and Abigail Sellen. A comparison of reading paper and on-line documents. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*, CHI ’97, pages 335–342, New York, NY, USA, 1997. ACM.
- [132] Kenton O’Hara, Abigail Sellen, and Richard Bentley. Supporting memory for spatial location while reading from small displays. In *CHI ’99 Extended Abstracts on Human Factors in Computing Systems*, CHI EA ’99, pages 220–221, New York, NY, USA, 1999. ACM.
- [133] Michel Pahud, Ken Hinckley, Shamsi Iqbal, Abigail Sellen, and Bill Buxton. Toward compound navigation tasks on mobiles via spatial manipulation. In *Proceedings of the 15th international conference on Human-computer interaction with mobile devices and services*, MobileHCI ’13, pages 113–122, New York, NY, USA, 2013. ACM.
- [134] Denise Cortis Park, J Thomas Puglisi, and Robert Lutz. Spatial memory in older adults: Effects of intentionality. *Journal of Gerontology*, 37(3):330–335, 1982.

- [135] Derrick Parkhurst, Klinton Law, and Ernst Niebur. Modeling the role of salience in the allocation of overt visual attention. *Vision Research*, 42(1):107 – 123, 2002.
- [136] Francesca Pazzaglia and Cesare Cornoldi. The role of distinct components of visuo-spatial working memory in the processing of texts. *Memory*, 7(1):19–41, 1999. PMID: 10645371.
- [137] Albert Postma and Edward De Haan. What was where? memory for object locations. *The Quarterly Journal of Experimental Psychology Section A*, 49(1):178–199, 1996. PMID: 8920102.
- [138] Philip Quinn and Andy Cockburn. The effects of menu parallelism on visual search and selection. In *Proceedings of the ninth conference on Australasian user interface - Volume 76*, AUIC '08, pages 79–84, Darlinghurst, Australia, Australia, 2008. Australian Computer Society, Inc.
- [139] Philip Quinn, Andy Cockburn, Indratmo, and Carl Gutwin. An investigation of dynamic landmarking functions. In *Proceedings of the working conference on Advanced visual interfaces*, AVI '08, pages 322–325, New York, NY, USA, 2008. ACM.
- [140] Roman Rädle, Hans-Christian Jetter, Simon Butscher, and Harald Reiterer. The effect of egocentric body movements on users' navigation performance and spatial memory in zoomable user interfaces. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces*, ITS '13, pages 23–32, New York, NY, USA, 2013. ACM.
- [141] Keith Rayner. Eye movements in reading and information processing: 20 years of research. *Psychological bulletin*, 124(3):372, 1998.
- [142] George Robertson, Mary Czerwinski, Kevin Larson, Daniel C. Robbins, David Thiel, and Maarten van Dantzich. Data mountain: using spatial memory for document management. In *Proceedings of the 11th annual ACM symposium on User interface software and technology*, UIST '98, pages 153–162, New York, NY, USA, 1998. ACM.
- [143] Ernst Z. Rothkopf. Incidental memory for location of information in text. *Journal of Verbal Learning and Verbal Behavior*, 10(6):608 – 613, 1971.
- [144] Roy A. Ruddle and Simon Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Trans. Comput.-Hum. Interact.*, 16(1):5:1–5:18, April 2009.

- [145] Sergio Della Sala, Colin Gray, Alan Baddeley, Nadia Allamano, and Lindsey Wilson. Pattern span: a tool for unwelding visuoŰspatial memory. *Neuropsychologia*, 37(10):1189 – 1199, 1999.
- [146] Krystian Samp. Designing graphical menus for novices and experts: connecting design characteristics with design goals. In *Proceedings of the 2013 ACM annual conference on Human factors in computing systems*, CHI '13, pages 3159–3168, New York, NY, USA, 2013. ACM.
- [147] Joey Scarr, Andy Cockburn, Carl Gutwin, and Andrea Bunt. Improving command selection with commandmaps. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12, pages 257–266, New York, NY, USA, 2012. ACM.
- [148] Joey Scarr, Andy Cockburn, Carl Gutwin, and Sylvain Malacria. Testing the robustness and performance of spatially consistent interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, New York, NY, USA, 2013. ACM.
- [149] Joey Scarr, Andy Cockburn, Carl Gutwin, and Philip Quinn. Dips and ceilings: understanding and supporting transitions to expertise in user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 2741–2750, New York, NY, USA, 2011. ACM.
- [150] R.A. Schmidt and T.D. Lee. *Motor Control and Learning: A Behavioral Emphasis*. Human Kinetics, 2011.
- [151] Andrew Sears, Julie A. Jacko, Josey Chu, and Francisco Moro. The role of visual search in the design of effective soft keyboards. *Behaviour & Information Technology*, 20(3):159–166, 2001.
- [152] Andrew Sears and Ben Shneiderman. Split menus: effectively using selection frequency to organize menus. *ACM Trans. Comput.-Hum. Interact.*, 1(1):27–51, March 1994.
- [153] Matthew J. Sharps and Eugene S. Gollin. Memory for object locations in young and elderly adults. *Journal of Gerontology*, 42(3):336–341, 1987.
- [154] Amy L Shelton and Timothy P McNamara. Multiple views of spatial memory. *Psychonomic Bulletin & Review*, 4(1):102–106, 1997.
- [155] Amy L Shelton, Timothy P McNamara, et al. Systems of spatial reference in human memory. *Cognitive Psychology*, 43(4):274–310, 2001.

- [156] Ben Shneiderman, Catherine Plaisant, Maxine Cohen, and Steven Jacobs. *Designing the User Interface: Strategies for Effective Human-Computer Interaction*. Addison-Wesley Publishing Company, USA, 5th edition, 2009.
- [157] Alexander W. Siegel and Sheldon H. White. The development of spatial representations of large-scale environments. volume 10 of *Advances in Child Development and Behavior*, pages 9 – 55. JAI, 1975.
- [158] Amy Skopik and Carl Gutwin. Improving revisitation in fisheye views with visit wear. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '05, pages 771–780, New York, NY, USA, 2005. ACM.
- [159] Randall B. Smith and Antero Taivalsaari. Generalized and stationary scrolling. In *Proceedings of the 12th annual ACM symposium on User interface software and technology*, UIST '99, pages 1–9, New York, NY, USA, 1999. ACM.
- [160] KATHLEEN SNOWBERRY, STANLEY R. PARKINSON, and NORWOOD SISSON. Computer display menus. *Ergonomics*, 26(7):699–712, 1983.
- [161] Benjamin L. Somberg. A comparison of rule-based and positionally constant arrangements of computer menu items. In *Proceedings of the SIGCHI/GI Conference on Human Factors in Computing Systems and Graphics Interface*, CHI '87, pages 255–260, New York, NY, USA, 1987. ACM.
- [162] MollyE. Sorrows and StephenC. Hirtle. The nature of landmarks for real and electronic spaces. In Christian Freksa and DavidM. Mark, editors, *Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science*, volume 1661 of *Lecture Notes in Computer Science*, pages 37–50. Springer Berlin Heidelberg, 1999.
- [163] Runa E Steenhuis and Melvyn A Goodale. The effects of time and distance on accuracy of target-directed locomotion: does an accurate short-term memory for spatial location exist? *Journal of Motor Behavior*, 20(4):399–415, 1988.
- [164] S. Tak and A. Cockburn. Enhanced spatial stability with hilbert and moore treemaps. *Visualization and Computer Graphics, IEEE Transactions on*, 19(1):141–148, 2013.

- [165] Susanne Tak, Andy Cockburn, Keith Humm, David Ahlström, Carl Gutwin, and Joey Scarr. Improving window switching interfaces. In *Proceedings of the 12th IFIP TC 13 International Conference on Human-Computer Interaction: Part II*, INTERACT '09, pages 187–200, Berlin, Heidelberg, 2009. Springer-Verlag.
- [166] Susanne Tak, Joey Scarr, Carl Gutwin, and Andy Cockburn. Supporting window switching with spatially consistent thumbnail zones: design and evaluation. In *Proceedings of the 13th IFIP TC 13 international conference on Human-computer interaction - Volume Part I*, INTERACT'11, pages 331–347, Berlin, Heidelberg, 2011. Springer-Verlag.
- [167] Desney S. Tan, Darren Gergle, Peter Scupelli, and Randy Pausch. Physically large displays improve performance on spatial tasks. *ACM Trans. Comput.-Hum. Interact.*, 13(1):71–99, March 2006.
- [168] Desney S. Tan, Randy Pausch, Jeanine K. Stefanucci, and Dennis R. Proffitt. Kinesthetic cues aid spatial memory. In *CHI '02 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '02, pages 806–807, New York, NY, USA, 2002. ACM.
- [169] Desney S. Tan, Jeanine K. Stefanucci, Dennis R. Proffitt, and Randy Pausch. The infocockpit: providing location and place to aid human memory. In *Proceedings of the 2001 workshop on Perceptive user interfaces*, PUI '01, pages 1–4, New York, NY, USA, 2001. ACM.
- [170] M. Tavanti and M. Lind. 2d vs 3d, implications on spatial memory. In *Information Visualization, 2001. INFOVIS 2001. IEEE Symposium on*, pages 139–145, 2001.
- [171] James A Thomson et al. Is continuous visual monitoring necessary in visually guided locomotion. *Journal of Experimental Psychology: Human Perception and Performance*, 9(3):427–443, 1983.
- [172] Michael Tlauka, Phill K. Donaldson, and Duncan Wilson. Forgetting in spatial memories acquired in a virtual environment. *Applied Cognitive Psychology*, 22(1):69–84, 2008.
- [173] Anne Treisman. Perceptual grouping and attention in visual search for features and for objects. *Journal of Experimental Psychology: Human Perception and Performance*, 8(2):194, 1982.
- [174] Anne M. Treisman and Garry Gelade. A feature-integration theory of attention. *Cognitive Psychology*, 12(1):97 – 136, 1980.

- [175] Michael Tsang, George W. Fitzmaurice, Gordon Kurtenbach, Azam Khan, and Bill Buxton. Boom chameleon: simultaneous capture of 3d viewpoint, voice and gesture annotations on a spatially-aware display. In *Proceedings of the 15th annual ACM symposium on User interface software and technology*, UIST '02, pages 111–120, New York, NY, USA, 2002. ACM.
- [176] Ying Tu and Han-Wei Shen. Visualizing changes of hierarchical data using treemaps. *Visualization and Computer Graphics, IEEE Transactions on*, 13(6):1286–1293, 2007.
- [177] BARBARA TVERSKY, JULIE BAUER MORRISON, and MIREILLE BETRANCOURT. Animation: can it facilitate? *International Journal of Human-Computer Studies*, 57(4):247 – 262, 2002.
- [178] Benton J. Underwood. Interference and forgetting. *Psychological Review*, 64(1):49 – 60, 1957.
- [179] Marieke van Asselen, Eva Fritschy, and Albert Postma. The influence of intentional and incidental learning on acquiring spatial knowledge during navigation. *Psychological Research*, 70:151–156, 2006.
- [180] J.M. von Wright, P. Gebhard, and M. Karttunen. A developmental study of the recall of spatial location. *Journal of Experimental Child Psychology*, 20(1):181 – 190, 1975.
- [181] Neil V. Watson and Doreen Kimura. Nontrivial sex differences in throwing and intercepting: Relation to psychometrically-defined spatial functions. *Personality and Individual Differences*, 12(5):375 – 385, 1991.
- [182] R. WILLIAM SOUKOREFF and I. SCOTT MACKENZIE. Theoretical upper and lower bounds on typing speed using a stylus and a soft keyboard. *Behaviour & Information Technology*, 14(6):370–379, 1995.
- [183] John T Wixted. The psychology and neuroscience of forgetting. *Annual review of psychology*, 55:235–269, 2004.
- [184] Jacob O. Wobbrock and Brad A. Myers. Enabling devices, empowering people: The design and evaluation of trackball edgewrite. *Disability and Rehabilitation: Assistive Technology*, 3(1-2):35–56, 2008.
- [185] Steven Yantis and John Jonides. Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human perception and performance*, 10(5):601–621, 1984.
- [186] F.A. Yates. *The Art of Memory*. A Phoenix book. University of Chicago Press, 1966.

- [187] Ka-Ping Yee. Peephole displays: pen interaction on spatially aware handheld computers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '03, pages 1–8, New York, NY, USA, 2003. ACM.
- [188] A. Zanella, M. S. T. Carpendale, and M. Rounding. On the effects of viewing cues in comprehending distortions. In *Proceedings of the second Nordic conference on Human-computer interaction*, NordiCHI '02, pages 119–128, New York, NY, USA, 2002. ACM.
- [189] Polle T. Zellweger, Jock D. Mackinlay, Lance Good, Mark Stefik, and Patrick Baudisch. City lights: contextual views in minimal space. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '03, pages 838–839, New York, NY, USA, 2003. ACM.