Navigating without Vision: Principles of Blind Spatial Cognition

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Abstract

This chapter considers what it means to learn and navigate the world with limited or no vision. It investigates limitations of blindness research, discusses traditional theories of blind spatial abilities, and provides an alternative perspective of many of the oft-cited issues and challenges underlying spatial cognition of blind people. Several provocative assertions pertaining to visual impairment and spatial abilities are advanced that help to better understand navigation without vision, provide greater explanatory power relevant to many of the current debates, and offer some needed guidance on the development of new spatial learning strategies and technological solutions that will ultimately have a significant positive impact on the independence and quality of life of this demographic. An underlying and related theme of the chapter emphasizes the importance of 'space' in spatial cognition research, rather than vision as its principle mechanism. There is no debate that vision is an amazing conduit of spatial information, but it is also important to remember that it does not have a monopoly on space. Indeed, all of our senses encode spatial information to one degree or another, and as we will discuss, this commonality allows for equivalent performance on many of the same spatial behaviors, independent of whether they originate from visual or nonvisual perception.

1. Introduction

For most sighted people, navigating from place to place is a fundamental component of daily life, performed without much conscious thought or active attention (Merleau-Ponty 1962). If asked how they navigate, what information they use to support their behavior, or the consequences of what would happen if this ability was taken away, questions I have informally posed to many hundreds of people who visit the lab as experimental participants, the vast majority have never thought about the issues and have no immediate answers. Upon cognitive reflection, most people indicate a reliance on visual perception, although they rarely identify what visual cues they use. Vision is such an integral component of how most people perceive and move about in the world that unless we are discussing specific situations, e.g. navigating in caves or at night, or specific animals, e.g. the bat or the mole, the navigation process is synonymous with visual navigation. This naïve intuition is congruent with the dominant research focus, as the vast majority of spatial cognition studies deal with vision as the means of accessing, mentally representing, and acting in the world. This visuocentric focus is not without merit given the visual system's exquisite tuning for providing distal access to a large swath of the environment via a high bandwidth 'pipe' to the brain.

I recently dared a friend to walk independently from his house to the nearest supermarket when wearing a blindfold. The route to the store was on the same street within a few blocks. This is a person who loves a challenge and is willing to take a risk, but he gave up after walking less than one block because of fears of getting hurt, getting lost, walking into the road, looking 'helpless', and various other undefined but very real stressors. My friend is not an anomaly, the prospect of making such a trip completely without vision is incredibly daunting (if not impossible) to most sighted people: How would you determine where you are on the route or know when you have reached your destination? How would you avoid obstacles, not fall down stairs, or know when it is safe to cross a busy road? Performing such tasks without vision is incredibly scary to most sighted people. Indeed, a recent survey of 1000 sighted adults showed that they expressed more fear about going blind and the associated negative impact on their quality of life and independence than almost anything else that might happen to them, including paralysis, HIV/AIDS, cancer, stroke, heart attack, and deafness (American Foundation for the Blind 2007). I argue that this fear is more about the unknown and unimaginable than about reason and that this default response largely stems from: (1) people's misconception of the uniqueness of vision and (2) their inability to imagine ready solutions for how they would perform in its absence. At the end of the day, it is important to remember that navigating without (or with impaired) vision is not only possible, it is done effectively on a daily basis by millions of blind travelers. Indeed, there are plenty of examples of blind people who accomplish amazing spatial feats; for instance, climbing Mt Everest (Weihenmayer 2001), independently hiking the Appalachian Trail (Irwin and McCasland 1992), competitive speed skiing (Kurson 2007), and myriad other activities that most sighted folks never endeavor.

There has been much debate in the literature regarding whether or not some spatial behaviors are more difficult and less accurate for blind navigators compared to their sighted peers. While there are frequent anecdotes about the remaining senses of blind individuals being heightened, leading to super-human hearing or touch, this is largely fanciful and the prevailing view is of impoverished spatial performance based on nonvisual sensing. A fundamental argument advanced here is that the significant 'differences' in spatial abilities frequently ascribed to this demographic are misattributed as being about loss of vision instead of the real problems: insufficient access to navigation-critical information, poor training of spatial skills, and over-protective cultural values. The central thesis of this chapter is that to move beyond the focus of much of the past 70 years of research on blind spatial cognition, we need to embrace a paradigm shift. Rather than conceptualizing blindness as being about loss of vision, we need to think about vision loss as being about use of a different state space of nonvisual (or degraded visual) information. The research emphasis on studying performance differences between people with or without vision, or the role of previous visual experience and age of onset of vision loss, or the amount or type of visual impairment, misses the more important issue of understanding how key spatial tasks are supported using nonvisual sensing.

2. Blindness Terminology and Target Demographic

2.1. What is legal blindness and what are its causes?

Before delving into the domain of blind spatial abilities, it is important to first define some key terminology and concepts that are often misunderstood or unclear. For many people, the word blindness is synonymous with complete darkness. However, total blindness (generally caused by damage to the eye or peripheral visual channel but sometimes also caused from cortical damage) is the exception, accounting for only 5-10% of people who are legally blind (The Eye Diseases Prevalence Research Group 2004). The population of blind and visually impaired people (abbreviated to BVI in the remainder of this chapter) is heterogeneous, encompassing a broad range of visual conditions and abilities and falling along a continuum from mild low vision to total blindness. The term 'low vision' is inconsistently used but generally refers to any form of permanent visual impairment that affects daily function. In the U.S. legal blindness is a stricter statutory term used for establishing eligibility for benefits, with the clinical diagnosis referring to a central visual acuity of 20/200 or less in the better eye (with best possible correction) and/or a visual field of no more than 20 degrees.

Visual impairment generally manifests due to the reduction of three visual factors: (1) acuity loss, representing reduced visual clarity for resolving small details such as text or high-resolution images, (2) reduced contrast sensitivity, representing difficulty in discriminating the boundaries between objects and their backgrounds (e.g., a cement bench on a concrete sidewalk) or in distinguishing contours and edges, such as curbs or steps, and (3) visual-field loss, representing loss of central or peripheral vision. Visual challenges may also be caused by glare sensitivity, difficulty with light adaptation, reduced depth perception, and problems with color vision (see Legge 2007 for review). The relation of these factors to specific spatial deficits goes beyond the scope of this chapter but each can impose negative consequences on safe and efficient environmental learning and navigation performance.

2.2. Size of the BVI Population.

There are an estimated 12 million people in the U.S who have some form of permanent, uncorrected vision impairment, with 3.4 million having low-vision or being legally blind (Silverstone et al. 2000). Most vision loss is age-related, meaning that the incidence of visual impairment is sharply increasing owing to our rapidly aging population. With an estimated ten thousand people per day turning 65 until 2030 (Cohn and Taylor 2010), it is expected that people experiencing some form of visual impairment will double during this period to over 24 million (Silverstone, Lang, Rosenthal, and Faye 2000). Worldwide, the World Health Organization has estimated that there are 285 million people with vision impairment, 39 million being legally blind, and 246 million people with some form of low vision (World Health Organization 2011). These numbers are of societal concern, especially given our lack of knowledge about the relation of spatial aging and acquired blindness and the known trauma surrounding independent travel by people with age-related vision loss (Golledge 1993; Marston and Golledge 2003).

2.3. Traditional vs. Functional Classifications of Blindness.

The guiding tenet of this section is that most spatial research with blind individuals is based on two persistent practices that ultimately lead to unintended biases. The first relates to an over-constrained sample selection process focusing only on totally blind participants in experimental design / technology development. The second stems from an over-exaggerated emphasis of the importance of clinical measures and specific etiologies of blindness. While these practices have historical precedent, and are appropriate in many situations, they are not necessarily the best technique for studying and understanding blind spatial abilities or for developing information access technologies to support spatial learning and behavior. For these domains, the better approach in most instances is to adopt functional classifications of blindness based on the information access requirements of the person/group under investigation. As is discussed further in section 4.1, this approach is less concerned with categorizing the specific type or nature of blindness, focusing instead on what information is used, the modality(s) specifying this information, and the requirements of the behavior being supported. As such, these functional classifications are not fixed and may change based on the information requirements of the specific activity being performed (e.g., navigation vs. reading tasks) or even because of daily fluctuations in visual function (i.e., as occurs with many visual conditions due to changes in light level, weather, time of day, and other transient factors).

With respect to selection bias, the vast majority of research addressing spatial abilities of people who are blind (whether it be usability evaluations, behavioral experiments, or neuroscientific studies) only investigate the extremes of the visual continuum. That is, despite the well-known heterogeneity of causes leading to blindness and the huge range of visual impairment from mild to total vision loss, the preponderance of research only incorporates/compares sighted and totally blind participant groups (ideally with blindness being congenital). The rationale for this highly constrained sample selection is that comparisons between these two 'extremes' are 'pure' and are not contaminated by confounds introduced from residual vision or prior visual experience. While this emphasis may afford more experimental control and yield 'cleaner' data that is easier for researchers to analyze and interpret, it is neither representative of the underlying BVI population nor helpful in understanding the spatial abilities of the majority of BVI people across the broad spectrum of visual impairments. The fall-out of this practice, albeit unintended, is that our knowledge of 'blindness' is generalized to the population based on a small segment of totally blind people at the tail of the blindness distribution, while largely ignoring the 90-95% of legally blind individuals with residual functional vision.

Breaking from tradition, the focus of this chapter is on a broad subset of the legally blind demographic, ranging from people with only light perception or no residual vision (often colloquially called Totals) to legally blind people with residual functional vision but who still use mobility aids such as the long cane or dog guide during navigation and speech or braille to access printed information. This latter group, informally called 'Low-Partials', represents a much larger percent of legally blind individuals than 'totals' but are often stuck in a 'no man's land' of visual impairment research as they do not neatly fit into the traditional participant groups at the extremes of the visual continuum.

With respect to a bias for the medical model, while the Cause, Type, and Onset of Visual Impairment are certainly part of the puzzle for understanding blind spatial abilities, and evidence from the literature suggests that one or more of these factors correlates with differential performance on various spatial tasks, the findings are often contradictory and highly variable (see Schinazi, Thrash, & Chebat, 2016; Thinus-Blanc & Gaunet, 1997; and Ungar, 2000 for reviews). These factors represent low-hanging fruit that researchers study because they are easy to enumerate and readily fit into the symptom-based classification structure used in medical research. However, I argue that their explanatory power is often over-stated, as evidenced by the lack of consistency across participant groups and the heterogeneity of findings based on these factors reported in the extant literature [See Long and Giudice, 2010 for review). If the goal is to develop new gene therapies, advance theories of specific etiologies, perform surgeries, etc. then use of clinical diagnoses and careful characterization of pathology are the best techniques. However, if the goal is to understand blind spatial cognition and navigation, or to develop nonvisual spatial technologies, the better technique, as described here, is to evaluate functional characteristics of blindness and the information (or lack of information) that is available to support the spatial behaviors of interest.

To be clear, this is not an argument that functional classifications are the only way to categorize visual impairment or that clinical causes and specific etiologies are irrelevant in the study of blind spatial cognition. Loss of acuity, contrast sensitivity, and peripheral visual field, which in combination cover many forms of visual impairment, certainly change the manner that the surrounding environment is perceived (for discussion, see Fortenbaugh et al., 2008 and West et al., 2002). For instance, impoverished acuity and contrast sensitivity reduce the range and distinctiveness of environmental attributes/landmarks that are perceptible and central field loss can negatively impact the ability to read information or resolve fine detail. Likewise, peripheral field restrictions can increase the difficulty of perceiving the arrangement of landmarks over a wide visual angle or encoding large-scale environmental geometry/global configuration. These clinical measures should be considered as they can have a demonstrable impact on the time and effort required for accurate spatial learning and navigation. That said, the argument advanced here is that these factors are rarely the sole determinant of spatial abilities and in most cases, a functional classification relating these clinical measures to information-access needs will have greater explanatory power and ecological validity with respect to performance on spatial behaviors relevant to safe, independent, and efficient travel.

So, if not relying on the standard classification approaches, what alternative information-based functional metrics can be used for categorizing the broad swath of legally blind people that have usable residual vision? A key functional distinction can be made between people who rely on their residual vision as their primary mode of environmental access (e.g., high partials) and those who use vision as an augmentary / complementary information source but who rely on other modalities and tools as their primary sources of information access (e.g., low partials). Although there is no formal separation between these groups, something that has long vexed reviewers and clinicians, I have informally estimated from over 20 years working in this area that a reasonable acuity range encompassing people who are low-partial includes acuities between 20/500 and 20/2500. This group of people share many of the same information-access needs and use many of the same information-access tools as people with only light perception or total blindness. Two tools are discussed below that are useful in spatial research for characterizing functional visual impairment based on an information access classification.

BVI individuals who use a mobility aid during navigation (e.g., dog guide, long cane, or electronic device) represent a natural functional category of the blindness distribution that can be differentiated from the entire legally blind population based on a sample (1) who have determined that they have insufficient visual access to environmental information during navigation and thus would benefit from non-visual spatial supports and (2) who are likely active and independent travelers that want to maximize the available environmental information perceived to support the navigation process. Similarly, use of nonvisual screen-access technology, such as speech or braille output from a screen reader, also represents a good functional classification of vision loss with respect to information access. As with mobility aids, people who use this technology have determined that they are better served by a nonvisual information-access solution than from a visual (or magnified visual) interface. This decision speaks directly to their preferred manner of information encoding and processing. Taken together, people with residual vision who use both of these tools are functionally similar to people with no usable vision in that they share many of the same spatial challenges and have many of the same nonvisual information access needs. As such, these groups are discussed as a functional block in the remainder of this chapter. Note that this distinction does not mean that this group does not use their residual vision. To the contrary, most would likely indicate that whatever vision they have is quite useful. However, from a functional standpoint, it is used differently from legally blind people with significant residual vision (High Partials), those with low-vision (acuity >20/200), or sighted individuals. These groups tend to rely on vision (or visual magnification) as their principle modality of information access and use visual perception for guiding their spatial behaviors. As such, they are not the focus of this chapter.

2.4. Orientation and Mobility.

Most sighted people have never considered how they avoid obstacles, walk a straight line, or recognize landmarks. It is not something they consciously learned, it's just something they do. By contrast, the majority of BVI people who are competent, independent travelers have had specific training to teach them these skills. This is called Orientation and Mobility (O&M) Training, which has been a field of instructional practice and research study for many decades (Long and Giudice 2010). The distinction between orientation and mobility as relates to navigational behaviors is not fixed in the literature but, in general, mobility refers to the detection and avoidance of obstacles or drop-offs in the path of travel. Mobility training also involves teaching skills such as finding the curb and determining the correct alignment for crossing the street, as well as determining knowledge of intersection geometry, the state of the red/green signal based on traffic flow analysis, and awareness of nearby landmarks. Thus, access to complete mobility information would include knowledge relating to a person's direct path of travel as well as detection and interpretation of egocentric information relevant to their immediate travel environment.

A person may have good mobility skills, but they must also be able to know their current position and heading in the environment with respect to their goal and effectively update this information as they travel. These are called Orientation skills and their mastery enables a navigator to perform more complex spatial behaviors, such as integrating local information into a global understanding of layout configuration (e.g. cognitive map), determining detours or shortcuts, and re-orienting if lost. These skills are also critical for accurate wayfinding, which involves planning and determining routes through an environment, even if those routes have not been previously travelled (Golledge, 1999).

Performing mobility tasks, such as obstacle avoidance, can be done highly effectively using traditional mobility tools like the long cane or guide dog. However, these aids only convey information about objects in the direct path of travel and do not provide the user with meaningful information about the surrounding environment. This is somewhat analogous to what a sighted person might perceive if they walked around in a dense fog, where visibility was reduced to a five-foot radius. While the long cane or guide dog is extremely effective for revealing the presence of an open door jutting into a hall, these aids do not assist in detecting/reading the sign providing the room's name, for describing the room's size and layout geometry, or for keeping track of self-position or self to object relations during movement. Indeed, gaining access to this type of environmental information is often very difficult to obtain without vision, yet its availability is extremely important for effective decision making, environmental learning, spatial updating, and cognitive map development. As we will discuss in Section 7, navigational solutions that aim to extend the reach of standard mobility devices by informing the user about information beyond their immediate travel route and aiding in 'orientation' tasks constitute the most promising advancements in information access technology.

3. Models of Blind Spatial Abilities.

3.1. Overview.

Most models of blind spatial development start from the assumption that at least initially, the presence of vision endows sighted people with an advantage compared to their BVI peers. Where the models diverge is in the duration of this advantage, the role of experience, and whether nonvisual or reduced visual sensing can ultimately yield the same level of spatial behaviors as is possible from visual environmental access. The original formulation of these models, elaborated by Fletcher (1980) and underlying (explicitly or implicitly) most research on blind spatial cognition, includes the Deficiency, Inefficiency, and Difference theories (Fletcher 1980). These theories were recently extended to incorporate the Cumulative, Persistent, and Convergent Models, which better characterize interdisciplinary findings from the literature, diversity of BVI participants, and differences resulting from environmental scale (Schinazi et al. 2016). The three models (and their variants) are briefly summarized below.

3.2. The Deficiency (or Cumulative) Model.

This model argues that visual experience plays a critical role for accurate spatial learning, for the development of spatial representations, and for guiding spatial behaviors. The extreme interpretation of this view, advanced in the work of Von Senden (1932), argues that vision is necessary in this process and that even basic spatial concepts are not possible in people who have been blind from birth. As will be discussed throughout this chapter, there are myriad studies showing accurate cognitive map development and other complex spatial behaviors by BVI individuals, including congenitally blind, rendering this theory as an interesting historical artifact. Less extreme interpretations of this position maintain that spatial knowledge acquisition is slower and less accurate with blind people relative to their sighted peers, owing to lack of visual experience. Thus, from the standpoint of the Deficiency theory, although blind individuals may be able to acquire spatial knowledge from nonvisual sensing over time, their net gain from this experience affords less benefit than occurs with vision. As a result, the disparity between blind and sighted individuals should increase over time as a function of greater experience. Evidence supporting this view would need to show that spatial learning and experience has a differential effect on blind versus sighted people, which is not born out in the literature (See Schinazi et al. 2016 for discussion).

3.3. The Inefficiency (or Persistent) Model.

This view argues that any initial deficits imposed by a lack (or reduction) of vision persist across life in a constant manner, as experiences based on nonvisual sensing are inherently less accurate and effective for supporting spatial learning and behavior than is possible from visual perception. As a result, this view would predict that congenitally totally blind individuals would always be at a deficit compared to people with late-onset blindness or sighted individuals. Support for this theory, and the critical role of visual experience on spatial knowledge development, has been used to explain results from congenitally and early blind people who, as a group, tend to show worse performance on spatial tasks such as updating and cognitive map development, compared to people with late-onset blindness or low vision on the same tasks (Rieser 1989; Rieser, Guth, and Hill 1986). While this view would acknowledge that blind people could perform spatial tasks reasonably accurately, definitive evidential support must show that their performance would always be worse (consistently slower and less accurate) than their sighted peers on the same tasks. Furthermore, this disparity would persist across life, even with increased experience. Schinazi et al. (2016) point out that the majority of evidence used to support this theory is flawed, as it uses performance differences elicited at a given time, e.g. when the experiment was conducted, but then 'assumes' without empirical verification that any observed differences are constant across time. Troublingly, this assumption is not tested at different temporal epochs. Findings showing equivalent or superior performance by congenitally blind people compared to sighted individuals on the same spatial tasks would provide the strongest evidence against this theory. This outcome was observed in a study by Giudice, Betty, and Loomis (2011), where functionally equivalent updating performance was found between sighted and congenitally blind people after learning route-maps by touch. Indeed, even some of the studies that have been used to support this view include congenitally or early blind participants who exhibit superior behavior compared to late blind or visually impaired participants (Hill, Rieser, Hill, Halpin, and Halpin 1993; Rieser et al. 1986). Although congenital, total blindness or blindness that occurs at an early age may result in greater challenges on certain spatial tasks, the fact that this is not a categorical outcome and that this group can exhibit excellent spatial skills argues against the *Inefficiency/Persistent model.*

3.4. The Difference (or Convergent) Model.

This theory posits that while BVI people start life at a disadvantage relative to sighted individuals, any observed disparity decreases as a function of increasing experience. This view suggests that BVI people can ultimately obtain similar spatial competencies and reach similar performance levels to their sighted peers, albeit more slowly and from different information sources. The key factor here is the role of experience, not the loss of vision, but how this manifests or is measured is less clear. Schinazi et al. (2016) describe 'experience' as encompassing various scenarios, including repeated discovery of a known environment, rehearsal of a given activity or behavior, and the general development of spatial abilities that occur as a function of age. As these researchers correctly point out, the lack of longitudinal studies with BVI people makes it hard to accurately evaluate how experience might change spatial performance over time. Blind children have been found to exhibit challenges on non-route tasks requiring straight line pointing and cognitive-map development (Bigelow 1988; Ungar, Blades, and Spencer 1997). Providing tentative support for this theory, some studies with BVI adults have shown accurate performance on these tasks, suggesting a positive impact of experience, but others suggest reliable impairments (see Thinus-Blanc and Gaunet 1997 for review). Thus, it is hard to argue there is definitive support for the *Difference/Convergent Theory* or to accurately characterize the role of experience on spatial abilities, as these studies incorporated different participants, and the children who exhibited spatial deficits were not subsequently tested. It is also possible that the older adults who exhibited accurate performance were simply more highly 'spatial' and would have performed similarly well when they were younger. Although the critical factor advanced in this chapter explaining differences in BVI spatial abilities relates to accurate access to, and use of, spatial information rather than prolonged experience, The Convergent model is most congruent with the Spatial Information perspective that experience, especially when coupled with principled training, is an important factor. In support, studies have shown that performance on spatial updating tasks improves as a function of increased O&M training (see Long and Giudice 2010 for review) and that access to tactile maps improves subsequent spatial abilities (Blades, Ungar, and Spencer 1999; Ungar 2000). At a minimum, these data suggest a critical role of formal O&M training and the importance of nonvisual or multimodal spatial products that convey global spatial concepts and provide BVI individuals with access to spatial information that they may otherwise not be able to obtain.

4. Reconceptualizing Blindness and the Case for Space.

4.1. The problem of Visuocentrism.

A problem underlying all of the theories in section 3, as well as with much of the extant research addressing blind spatial performance more generally, is that there is an inherent visuocentric bias. That is, the focus is usually on how accurately task X can be done without vision or how performance on nonvisual task Y compares to the same task when done visually. There are two fundamental problems with this traditional approach:

1) It ignores the currency of nonvisual information processing. The research focus on elucidating what tasks/behaviors can and cannot be done without visual sensing misses the more important issue of understanding how nonvisual information (e.g. from audition, touch, and language) is best encoded, learned, and represented by BVI people (see Section 4.2).

2) A methodological bias for emphasizing differences over similarity. A fall-out of the visuocentric focus (even if unintended) is that most blindness-related research starts with the intent to elucidate differences between sighted and blind individuals: in their learning strategies, in their mental representations, in their neural substrates, and in their behavioral performance. A more positive and ultimately useful approach is to employ procedures that identify similarities between visual and nonvisual performance. When differences between BVI and sighted individuals manifest, additional research should be conducted to investigate the underlying reason rather than simply concluding that there are deficits in BVI spatial performance. A positive aspect of identifying spatial behaviors that are more challenging for BVI people compared to their sighted peers is that it provides empirical evidence to guide the development of information access technologies that provide compensatory cues to optimize performance (see Section 7).

Adopting this perspective requires a small but important ideological shift in the field of blind spatial cognition that redirects the traditional research focus on the presence or absence of vision and its role on experience to a more visually agnostic view that considers what it is about visual information that is conducive to supporting spatial learning and navigation. In other words, in order to truly understand blind/low-vision spatial abilities, and to develop useful learning strategies and information access technologies to remediate travel-related problems, we need more research on the role of nonvisual and multimodal information processing for supporting BVI spatial knowledge acquisition, representation, and behavior. From this view, the majority of challenges, differences, and problems cited in the literature regarding BVI spatial abilities are due to insufficient information access from nonvisual sensing or inadequate spatial problem-solving abilities, rather than vision loss per se. Different versions of this notion have been theorized in the past, although the visuocentric view persists. For instance, Ungar, Blades, and Spencer (1996) postulated that the spatial deficits frequently cited with BVI people are not due to lack of visual experience but arise because of insufficient nonvisual alternatives to support effective spatial coding strategies. They argue that observed differences can be ameliorated When explicit training is provided using coding systems that foster spatial learning and cognitive map development (e.g., through use of tactile maps). Improvements in BVI spatial behaviors observed after using these tools lend support for this argument (Ungar 2000). Millar (1988) has also argued that while nonvisual sensing may lead to differences between BVI and sighted individuals, there is nothing inherent in the experience of vision loss that limits the potential for BVI people to build up a complete and globally integrated representation of space (Millar 1988).

4.2. Space as the Common Denominator.

While vision is an excellent conduit of spatial information, it by no means has a monopoly on space. This thesis is based on the following two assertions: (1) The vast majority of visual information is really spatial information, and (2) The vast majority of spatial information can be conveyed through multiple sensory channels. Indeed, the perceptual modalities of audition and touch, as well as language, are all able to convey much of the same spatial information as vision. For instance, lines, edges, and surfaces, the distance and direction of entities, the relation between these entities, and the 3-D structure of space, are all spatial properties that can be specified to varying degrees through these other channels.

As a simple illustration, imagine the following scenario: You are standing at a table in your favorite pub. There is a fork, an empty square plate, and an open beer bottle on the table directly in front of you. The plate is about two inches from the edge of the table and the fork is on the table about two inches from the left edge of the plate. The bottle is on the table about two inches from the top right corner of the plate, at approximately the 1 o'clock position (see Figure 1). Whether you were to read this description, look at the arrangement, or close your eyes and feel the physical objects, it is trivial to imagine the relation between the three items in your head.

Figure 1. The above photo represents a sample scenario that can be interpreted through multiple modalities.

As you have now read the description and seen the Figure, your response to this informal experiment would be biased. However, I wager that if you read this description to a friend, or let them feel the arrangement with eyes closed, they could reach out and grab the bottle with equivalent speed and accuracy in both nonvisual scenarios as when done after visual perception. The important point here is that the spatial information is essentially the same, irrespective of the input source. The take-home message is that much of what is intuitively considered as 'visual' information is really 'spatial' information and can be specified through multiple sensory modalities, as well as other channels such as language, kinesthesis, and inertial sensing. At least from the standpoint of spatial cognition, blindness is far more about effective encoding, learning, and representation of these nonvisual sources of information than about the type or nature of visual impairment.

4.3. Functional Equivalence and Amodal Spatial Representations.

Whether or not it is explicitly stated as such, most theories of human spatial cognition consider vision as the sole/primary input and discuss memory representations in terms of visual-spatial structure. In contrast to this traditional view, a growing body of evidence has demonstrated that learning from combinations of different spatial inputs leads to highly similar behavioral performance on a range of spatial tasks, an outcome referred to as functional equivalence. For instance, functionally equivalent performance has been found for spatial updating of maps or target arrays after visual and haptic learning (Giudice, Klatzky, Bennett, and Loomis 2013; Giudice, Klatzky, and Loomis 2009; Giudice et al. 2011), updating after learning target locations from spatialized audio or spatial language (Avraamides, Loomis, Klatzky, and Golledge 2004; Loomis, Lippa, Golledge, and Klatzky 2002), and updating target locations after learning from visual, spatialized audio, and spatial language (Klatzky, Lippa, Loomis, and Golledge 2003).

There are at least three theoretical explanations that could account for functional equivalence of spatial behaviors:

1) The Separate but Equal Hypothesis attributes equivalent spatial performance across different inputs to the formation of sensory-specific, isomorphic spatial representations that support common behaviors. From this perspective, while the modality-specific representation may support equivalent behavior, one would expect that the time to access the different representations in memory or the processing latency required for executing spatial transformations on this representation once instantiated would differ between modalities. However, evidence showing equivalent latency and error data for performing judgments of relative direction (JRDs) after haptic and visual map learning argue against this explanation (Giudice et al. 2011). Indeed, this hypothesis has limited explanatory or predictive power, as it provides no fundamental principle to explain how sensory-specific representations would result in equivalent performance across modalities.

2) The Visual Recoding Hypothesis assumes that all inputs are recoded into a visually-based spatial format (Lehnert and Zimmer 2008; Pick 1974). From this view, functionally equivalent error performance would be explained by all input sources being converted into a common visual representation that is equally accessible in the service of action. However, reaction-time data between modalities would not be equivalent, as there should be a processing cost due to inefficiencies in the conversion process of nonvisual to visual representations (Newell, Woods, Mernagh, and Bulthoff 2005). Evidence against this theory comes from a study investigating learning of circular six-target arrays of either all visual, all haptic, or interspersed visual-haptic targets (Giudice et al. 2009). At test, participants performed JRDs requiring memory of start and end targets that were either learned intramodally (e.g. both start and end targets were haptic or visual) or learned cross-modally (e.g. the start target was haptic and the end target was visual, or vice versa). The finding of equivalent spatial updating performance for both error and latency across all conditions, and lack of any switching cost for the cross-

modal conditions, especially the latency data for trials involving haptic to visual JRDs, provides compelling evidence against the Recoding hypothesis. Further evidence against this hypothesis comes from experiments showing similar spatial updating performance between sighted and congenitally blind participants, the latter presumably not relying on a visually recoded image (Giudice et al. 2011; Loomis et al. 2002).

3) The Amodal Hypothesis explains functional equivalence as the result of different inputs building up into an amodal (sensory-independent) spatial representation in memory that is not tied to any sensory or cognitive input source. Assuming information is matched and learning is equated between inputs, this common spatial representation is postulated as supporting equivalent behavior.

Think back to the earlier scenario about the plate, fork, and bottle (depicted in Figure 1): If my prediction is correct, and you (or your friend) can reach with equivalent speed and accuracy for the bottle irrespective of the mode of learning, you are providing real-world support for the amodal hypothesis. In other words, the mental image you have in your head has accurately captured the spatial relations between the plate, bottle, and fork that you learned from vision, touch, or language, and has stored this information as a common spatial representation that is no longer tied to the sensory-specific information used during initial encoding. Importantly, this amodal spatial representation is equally able to support behavior, in this case, your ability to reach out and grasp your beer. In sum, given the limitations of the other two explanations, and the combined findings of the previously discussed studies that have worked to distinguish these three theories, the empirical evidence clearly supports the efficacy of the amodal hypothesis (see Loomis, Klatzky, and Giudice [2013] for a detailed review).

In order to provide an explanation for equivalent performance observed across modalities based on the amodal hypothesis, Loomis and colleagues introduced the notion of a spatial image, which is conceptualized as a transient three-dimensional working memory representation of external space around a person (Loomis et al. 2002). The spatial image can be built up from spatial perception, forged from spatial processes originating from spatial language or imagination, or formed from long-term memory (Loomis et al. 2013). Figure 2 provides a conceptual diagram of the amodal hypothesis and the role of spatial images.

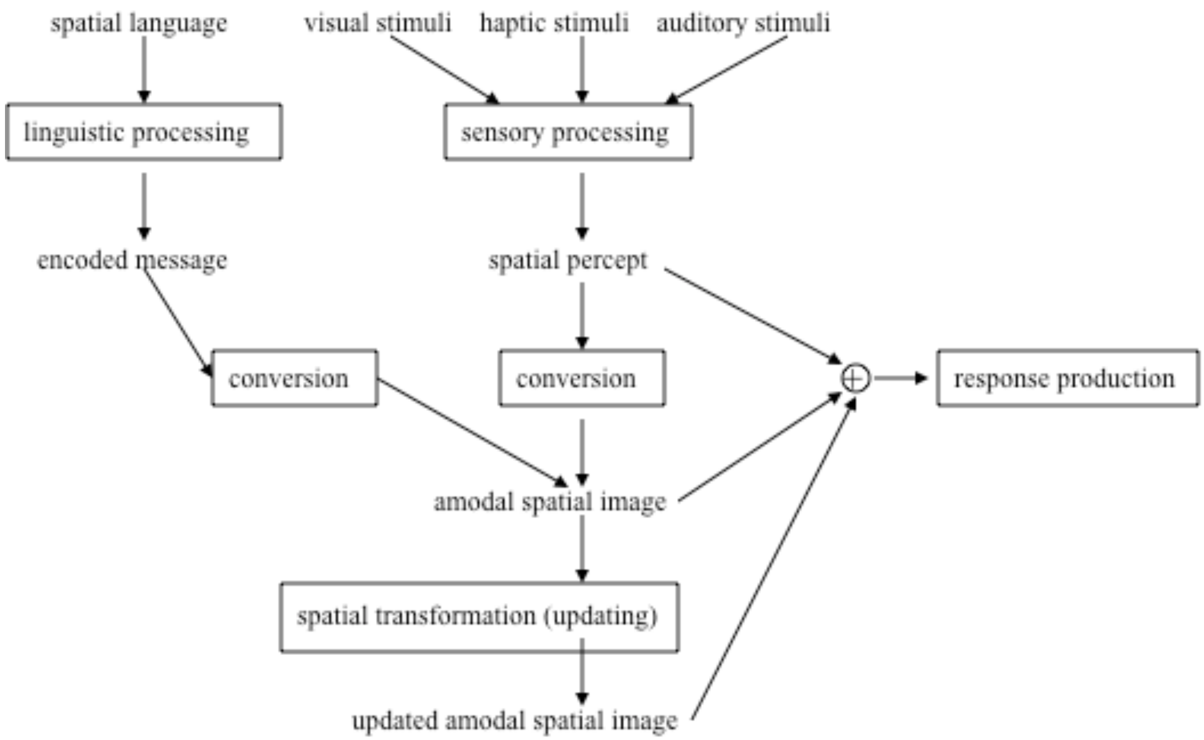

Figure 2. Functional block diagram for the conceptual framework of amodal representations described in the text. Sensory inputs from vision, hearing, and touch give rise to percepts as well as spatially congruent spatial images. When the stimuli are removed, the percepts cease, but the spatial images remain. Spatial images can also be created by language or instantiated from long-term memory. The lower section shows how both perceived and imagined self-motion can lead to a change in the observer's estimated position and orientation, which in turn can lead to spatial updating of the spatial image. The section on the right represents response production, which supports a wide variety of spatial judgments.

The amodal spatial image has similarities with other theories from behavioral science. For instance, Bryant's proposal of the spatial representation system incorporating a unitary mental format for auditory, linguistic, tactile, and visual inputs (Bryant 1997) and Jackendoff's conception of a common spatial representation/spatial mental model (Jackendoff 1987). Neuroscientific variants of the notion of amodal representations also exist. For instance, Pascual-Leone discusses the visual brain as not being ‘visual’, based on findings from neuroimaging studies demonstrating that Occipital regions traditionally considered to process sensory-specific visual information can be recruited for computation of similar stimuli from tactile inputs (see Pascual-Leone and Hamilton 2001 for a discussion). Other evidence of amodal spatial information processing in the brain comes from studies showing similar involvement of various ‘expert’ regions based on stimulation of multiple modalities. For instance, visual face perception is known to selectively innervate a brain area called the fusiform face area (Kanwisher et al., 1997; Kanwisher et al., 1998). Subsequent research showed that it was not the visual nature of faces that was important but their stereotypical spatial arrangement, as evidenced by similar neural involvement of this region for haptic face recognition in both sighted (Kitada, Johnsrude, Kochiyama, and Lederman 2009) and blind participants (Goyal, Hansen, and Blakemore 2006). Similarly, activation in the object-sensitive ventral visual pathway is not exclusive to visual processing, as was originally believed (Haxby et al., 1991) but has also been observed during auditory, haptic, and cross-modal object recognition (Amedi, Jacobson, Hendler, Malach, and Zohary 2002). Perhaps most germane to the topic of this chapter, a study investigating the Parahippocampal Place Area (PPA), a specialized brain area known for extracting the visuospatial structure of 3D scenes, found that this region was similarly involved for scenes that were learned from both vision and touch (Wolbers, Wutte, Klatzky, Loomis, and Giudice 2011). Further, blind and sighted participants revealed similar patterns for haptic scene apprehension, arguing against visual recoding. Taken together, this study supports the notion of an amodal spatial representation in the PPA based on neuronal populations that are preferentially tuned for spatial computation of 3-D geometric structure, irrespective of the sensory modality used during learning. Although more research is needed in this domain, a growing body of neuroscience evidence clearly shows convergence of auditory, linguistic, tactile, and visual inputs in common brain regions; for general reviews, see Amedi, von Kriegstein, Van Atteveldt, Beauchamp, and Naumer (2005) and Driver and Noesselt (2008). Considering the behavioral and neuroimaging studies discussed in this section, the evidence clearly demonstrates that when appropriate information is provided, both nonvisual and visual encoding can give rise to similar behavioral outcomes, as well as innervate the same regions of the brain. Importantly, these outcomes manifest for both sighted and BVI individuals, supporting the view that provided sufficient information, BVI people can function at the same level as their sighted counterparts.

Before moving on, an important caveat must be made to ensure that readers do not misinterpret the theory being advanced or the evidence used in its support. The argument is not that all information is equivalent between visual and nonvisual perception or that the brain simply processes 'information,' irrespective of its modal source or sensory processing mechanism. This naïve and over-simplified explanation is sometimes used to erroneously support the efficacy of sensory substitution devices (Loomis, Klatzky, and Giudice 2012).

Functional equivalence is only possible when (1) like information, i.e. spatial properties, are matched between inputs and (2) sufficient learning is allowed between the respective modalities being compared. On the other hand, we also perceive sensory-specific, non-spatial information that has no obvious analog in other modalities and thus is unlikely to yield functionally equivalent behaviors between inputs. For instance, vision and color, touch and surface compliance, audition and timbre, etc. all represent modality-specific properties with non-isomorphic information processing characteristics. In addition to differences in the type and nature of salient stimulus properties, the manner in which we apprehend information differs between the senses. For instance, the stereotyped hand movements and exploratory procedures that have been described as being most efficient for haptic perception (Lederman and Klatzky 1987) are very different from how we perceive visual cues through eye movements or auditory cues through head movements. Although spatial properties are largely invariant across multiple senses, the breadth and depth of access to this information varies widely between modalities. As will be discussed in the next section, consideration of this information disparity between the senses is imperative for understanding the similarities and differences of information processing between blind and sighted individuals.

5. Differences and Similarities of Navigating with and without Vision.

5.1. Overview.

If other spatial inputs can convey the same spatial information as vision, then why is there still so much debate about the accuracy of blind spatial behaviors compared to their sighted peers? The answer lies in the type and nature of spatial information that is salient to non-visual sensing/perception and how this information is used and represented in order to support spatial behaviors. This section will delve into two major differences in spatial cognition between sighted and BVI navigators:

1) The use of environmental information that differs in its availability, reliability, and consistency between visual and nonvisual perception.
2) The added demand of using effortful cognitive and attentionally-mediated resources required for blind navigation vs. unconscious and automatic perceptual processes underlying sighted navigation.

In order to fully appreciate BVI navigation or to design effective nonvisual information access technology supporting this endeavor, one must carefully consider both of these factors.

5.2. Visual vs. Nonvisual Information.

While sighted and BVI individuals may have the same navigational goals, and many expert BVI travelers can perform the same tasks equally as fast and accurately as their sighted peers, the sensory cues and information processing methods employed to perform these tasks are likely very different between the two groups. As mentioned at the onset of the chapter, most sighted people do not introspect on their navigation process, they simply rely on an accurate visually-guided perceptual-motor coupling to move through space. Although people also utilize internal acceleration cues, e.g. path integration, as well as access their cognitive maps to plan routes, update position in the larger unseen environment, and orient to places that are not accessible from their current view, the core information supporting these tasks is derived through visual access to the environment. The reason is simple: Vision provides simultaneous and rapid access to highly precise distance and direction information about the 3D position and inter-position of both nearby and distant visible landmarks, allows apprehension of geometric information about spatial structure, affords easy recognition of objects over a large field of view, and provides access to precise motion cues about changing self-to-object and object-to-object relations that occur during navigation. In principle, many of these cues can be conveyed through other senses, but in reality, much of this navigation-critical information is ambiguous, unreliably specified, or simply not available from non-visual sources of environmental access. For instance, hearing and touch convey far less information than vision about self-motion, self-to-object distances and directions, inter-object relations, and global spatial structure. Compared to vision, haptic perception affords access to only proximal, low-resolution information over a small field of view. It is limited to what can be felt within arm's reach (perhaps extended to a couple yards through use of a long cane), and information encoding is based on a limited number of contact points. As a result, many objects along a travel path are too large, too far away from the path, or too dangerous to touch. As a comparison of the limits of haptic information processing, the sensory bandwidth of vision has been estimated as being 500 times greater than touch (Loomis et al. 2013). Auditory perception provides more distal access to environmental information than touch and is omnidirectional, which affords benefits as an 'alerting' sense, but this information is often transient and provides less spatial precision in localizing the distance and direction of objects compared to vision (see Long and Giudice 2010 for a discussion).

As a thought experiment, imagine that you decide to take a walk from your hotel to a bakery you noticed on the next block. From the Hotel's door, you can simultaneously see a nearby trash can, several outside tables at an adjacent café, the traffic light at the corner about 100 feet down the sidewalk, and the colorful awning of the bakery you plan to eat at in the distance. In this scenario, BVI travelers might access the same information, but it would be derived from very different sources and perceived in a sequential and less gestalt manner. For instance, they might use echo location from their cane or foot steps to determine the position and distance of the trashcan as they pass, the sound of people eating to identify the location and direction of the tables at the café, the feel of texture changes from a tactile warning strip to indicate the presence of the intersection and the correct orientation to adopt for a safe street crossing, the auditory flow of passing cars to assess the state of the traffic signal, the smell of the bakery as a cue that they are nearing the destination, and, finally, sensing the shade of the awning to indicate that they have reached their desired location. Most sighted people make limited use of these nonvisual cues, but for a BVI navigator, these are the basic tools of the trade used for supporting daily travel.

Given the unreliability and under-specification of the sources of nonvisual sensing that BVI navigators use as their primary mode of environmental access, coupled with the greater effort needed to integrate this information with the complex sensorimotor contingencies underlying effective navigation, it is not surprising that blind individuals often show poorer and more variable performance than their sighted peers (see section 6). Irrespective of the extent of this variability, the known differences in the availability of spatial information between vision and its sister senses speak to the immediate need for more research and development of multimodal information-access technologies that provide augmenting, complementary, and redundant environmental cues to support BVI navigators (see Section 7).

5.3. Perceptual vs. Cognitive Focus.

Another major difference between sighted and blind navigation is the use of cognitive strategies vs. perceptual information. Where the perceptual-motor coupling of seeing and avoiding an obstruction to the path of travel is generally an effortless, unconscious process for a sighted navigator, a blind person's perception of the same obstruction occurs at much closer range, requires active detection and avoidance, and generally involves a more deliberate and effortful cognitive process (Bigelow 1991). This cognitive-perceptual distinction is particularly evident during spatial updating. For instance, a sighted navigator can directly monitor their movement with respect to environmental features in an automatic manner and can use distal landmarks as a reference to guide action. By contrast, blind travelers must depend to a greater extent on proximal cues and moment to moment monitoring of self-movement, meaning that spatial updating without vision involves significantly more attentional resources and cognitive effort than when performed with vision (Rieser et al. 1986).

This additional cognitive effort inevitably contributes to the increased stress of travel and decreased independence experienced by a large percentage of BVI people (Clark-Carter, Heyes, and Howarth 1986; Golledge 1993). Instead of thinking of a walk as a nice way to relax and zone out, for a blind traveler, a walk requires constant environmental awareness, attentional monitoring, and spatial problem solving: Is this intersection a straight crossing? Is there a turn arrow? Is that the shrub that means I turn right? Did I miss the brick wall indicating I should cross the street when I was answering that text? In short, while nonvisual sensing can support accurate navigation, the entire enterprise requires far more cognitive intervention and is generally far less relaxing than when done with vision.

6. Blind Spatial Cognition.

6.1. Overview.

There are a number of reasonably consistent findings that should be highlighted from the spatial cognition and navigation literature employing BVI participants. In general, if challenges are experienced by this demographic, they relate to spatial inference (e.g. determining shortcuts, detours, straight-line distances between off-route landmarks, etc.) or environmental learning of global structure and layout configuration (e.g. the information needed for accurate cognitive map development). This outcome makes intuitive sense: If you cannot see the relations between objects or landmarks, or how your location on a route relates to another location, it is hard to make reliable spatial inferences or build up an accurate global representation of the space (for an excellent review, see Thinus-Blanc and Gaunet 1997). The conjunction of proximal, serial, and uncertain spatial cues from nonvisual inputs with increased reliance on effortful spatio-cognitive processes discussed throughout this chapter has also resulted in many blind individuals having a poor understanding of some key spatial concepts, including spatial scale and frames of reference, as well as exhibiting difficulties in learning unfamiliar environments.

6.2. Spatial Scale and Frames of Reference.

Spatial scale is often discussed as being contracted for blind people (Hull 1997), which is at least partially due to nonvisual sensing being limited to proximal and spatially imprecise modes of environmental access. While the focus of this chapter is on navigation, spatial challenges for BVI people have been discussed in the literature at all spatial scales (see Schinazi et al. 2016 for review). Multiple conceptions of spatial scale have been elaborated through the years. However, a common categorization distinguishes space into four scales: figural space is smaller than the human body and is perceived without movement (e.g. pictures or 3D objects on a tabletop), vista space is larger than the human body but is also perceived from a single vantage point, allowing for head rotation (e.g. an indoor room or football field), environmental space represents larger scale and requires motion over time in order to be perceived (e.g. a large indoor mall or city), and geographical space represents the largest spatial extent, which cannot be apprehended through motion over time and must be perceived through symbolic models, such as maps (Montello 1993). This characterization is similar to Zubin's for-part model of space (Zubin 1989), except where Zubin describes categories based on absolute size, Montello's model of psychological space emphasizes a classification using functional properties based on projective size.

In general, fewer problems exist for BVI people at the figural/tabletop scale, which makes sense as information acquisition, learning, representation, and subsequent transformations supporting behavior is similarly available at this scale, e.g. feeling or seeing an object array, map, or 3D model. At the vista scale, greater challenges may arise, as it is harder and less accurate to perceive the relevant 'scene' elements from nonvisual information sources (see Section 5.2). BVI people often experience the greatest practical difficulties at the environmental scale, as nonvisual apprehension and integration of features beyond the travel route is challenging and requires far more spatiotemporal integration than when done from visual perception. Unfortunately, access to this information is particularly beneficial for supporting environmental learning and cognitive map development, which helps explain why BVI navigators frequently exhibit inaccurate performance on spatial inference tasks or demonstrate an under-specified representation of global spatial relations. Finally, at the geographic scale, BVI people are often at a particular disadvantage due to the dearth of external aids and spatial products available from nonvisual renderings. Although a common complaint nowadays is that people no longer are able to read a map or understand geographic relations, most have had the opportunity to do so, independent of whether they have availed themselves of this opportunity. By contrast, most BVI people have never experienced a tactile or auditory map of a large-scale environment, e.g. a city, country, or the world, and thus not only lack the knowledge to 'read' and interpret this information but also have a poor internalized conception of spatial relations and global structure.

The type and extent of different spatial reference frames BVI people use has also been debated in the literature. A spatial reference frame provides a context to specify a person's/object's spatial position relative to something else. In an egocentric (or self-based) frame of reference, information is perceived (or presented) in a relative coordinate system with the observer as the origin. That is, knowing direction, distance, or position of objects in the environment in relation to your position and orientation, e.g. “I am in front of Dave’s Supermart” or “turn left at Valerio Street.” By contrast, with an allocentric (or object-based) frame of reference, information in the environment is given independently of the observer’s perspective; that is, with respect to a fixed external point of reference. For instance, direction, distance, and position are specified in absolute coordinates, e.g. north-south, east-west.

There is a long-standing view that BVI people rely heavily on—or in the extreme case—are limited to using an egocentric frame of reference (see Millar 1994 for a detailed discussion). While this may be the case for many BVI people, owing to the greater ease of egocentric information-coding from nonvisual environmental exploration, it certainly is not the inevitable outcome. The solution to promoting nonvisual allocentric learning is providing BVI individuals with sufficient spatial information to perceive inter-object locations, teaching of spatial problem-solving skills to infer spatial relations, and encouraging use of behaviors that reinforce this knowledge and the development of accurate cognitive maps (Long and Giudice 2010).

6.3. Route vs. Survey Knowledge.

Although learning a route without vision may require effort to learn the relevant cues along the way, success is principally based on one’s ability to perceive and learn the correct segment distances and turn locations/angles, and the ability to perform accurate spatial updating during travel. Many studies have shown that BVI people have little problem with route learning/navigation, but tasks requiring spatial inference or knowledge of layout configuration are more difficult and error prone (see Thinus-Blanc and Gaunet 1997; Ungar 2000 for reviews). The conventional argument holds that congenitally and early-blind individuals tend to perform worse on these types of tasks than late blind or blindfolded-sighted people (Rieser, Hill, Talor, Bradfield, and Rosen 1992). For instance, congenitally blind people tend to rely more heavily on functional separations between known locations, e.g. a connecting route, rather than the straight-line, non-route direction between these places, the latter indicating a globally coherent representation (Lockman, Rieser, and Pick 1981). In familiar environments, such as navigating well-known city centers, buildings, or campuses, blind participants effectively traverse routes from place to place but are often prone to significantly greater error than their sighted counterparts on performing tasks requiring knowledge of global configuration, such as map production (Casey 1978) or pointing between locations (Espinosa, Ungar, Ochaita, Blades, and Spencer 1998; Passini and Proulx 1988; Rieser, Lockman, and Pick 1980). Similar disadvantages for learning and representing global structure have been observed in blind children (Bigelow 1991; Ungar et al. 1997). These results have led to the pervasive view that BVI individuals operate on under-developed, route-based, egocentric spatial representations rather than the traditional survey-like notion associated with allocentric-based cognitive maps (Millar 1994).

Although it may be tempting to attribute sub-par performance to a natural outcome of navigating without vision (and a lack of visual experience), this is clearly not the case. As any O&M instructor can attest, some blind people, even those who are congenitally and totally blind, possess excellent spatial abilities. Indeed, some of the most amazing blind travelers I have met are people with congenital or total blindness. In corroboration, there are a growing number of studies that show no reliable differences between blind and sighted performance on spatial updating, inference, wayfinding, and cognitive mapping tasks (Giudice 2004; Giudice et al. 2011; Loomis et al. 1993; Loomis et al. 2002).

6.4. Environmental learning and Strategy Selection without Vision.

As is obvious from the diversity of conflicting theories on blindness (see section 3), there is no consensus on the effect of vision loss on spatial abilities. While I think the role of experience emphasized in the Difference/Convergent Model best captures the totality of blind spatial cognition, it misses several key elements advanced throughout this chapter. First, one's nonvisual experience of the world depends on their ability to access relevant information from their surrounds. This speaks to the importance of using alternative sensory inputs to gather/encode information and efficient cognitive strategies to synthesize this information. On the encoding side, blind people must learn how to accurately and efficiently explore their environment in order to extract relevant information. This process has been shown to be hugely important as a developmental stage in blind children (Millar 1994; Ungar et al. 1997) but the underlying notion of adopting accurate exploratory techniques for information gathering needs also to be emphasized for older people who are losing their sight or those with poor spatial abilities. From the cognitive standpoint related to spatial information processing, representation, and mental manipulation, we need to develop more strategies that teach blind individuals how to perform accurate spatial problem solving. Given the lack of reliable and stable spatial cues from nonvisual sensing and the increased importance of cognitive vs. perceptual processing of environmental information, it is critical that BVI people are taught to use all available information in an intelligent and testable manner. We have called this spatial hypothesis testing (Long and Giudice 2010), relating to the process of evaluating the information gathered against known priors (e.g. sidewalks generally run parallel to streets, phone polls are usually between the street and sidewalk, elevators are most often near building entrances, etc.). Invoking such priors and performing simple spatial hypothesis testing with available information (e.g. using the cane to confirm that the current walking path is on the sidewalk and not the street), can go a long way to mitigate the spatial ambiguities imposed by nonvisual sensing. While discussing such issues in a chapter is simple, actually learning and mastering these skills can be a long, difficult, and frustrating endeavor. Indeed, this is the goal of O&M instruction. However, given the myriad spatial skills that must be taught to support daily navigation, training often does not sufficiently emphasize the problem solving/hypothesis testing component of blind spatial cognition. My own experience (corroborated through personal communication with many O&M instructors) has led me to two conclusions. First, the instructors universally acknowledge the critical importance of teaching shortcutting, detouring, and other spatial inference skills, as well as reinforcing wayfinding, off-route learning, and inter-object relations as key components of accurate cognitive map development. Second, they stress the limited resources and time they have with each client and the need to prioritize teaching of skills that promote safety and have the greatest functional utility to daily life. As such, instruction is strongly biased toward teaching accurate route navigation and promoting safe and efficient mobility (e.g. not running into obstacles, effective traffic flow analysis, and street crossing proficiency). The logic being that people need to be able to master getting from their house to the store, doctor, or other known location more than learning how to make shortcuts or point to off-route locations. Thus, in addition to the limitations of nonvisual sensing, this lack of formal training of complex spatial skills represents a significant challenge for BVI navigators. As will be discussed in the next section, there are many technological solutions that may play a role in solving this problem, but there is no substitute for explicit instruction on these tasks by O&M professionals.

What can be taken from this discussion is that important research questions remain about understanding what information supports these behaviors and what skills and techniques are being used by successful blind participants vs. those that exhibit deficits on these tasks? Addressing such questions requires: (1) developing empirically-motivated strategies supporting successful navigation and effective cognitive map development, (2) developing new techniques for teaching strategy selection, spatial problem solving, and how to effectively use different sources of nonvisual information access, and (3) developing new information-access technologies that assist with environmental awareness, spatial updating, and acquisition of global spatial knowledge.

While effectively learning and navigating large, unknown environments is likely the most difficult task faced by BVI travelers, using the intrinsic regularities of many built environments can greatly reduce the stress and cognitive effort of navigation (Strelow 1985). For instance, urban settings often are arranged on a grid system, residential environments usually have driveways which are perpendicular to the sidewalk, information desks are generally located near the door on the first floor of commercial buildings, etc. Since these elements tend to be stable and consistent across like environments, they can greatly improve the efficiency of navigating in a new place and can actually improve spatial reasoning abilities, as they facilitate tapping prior knowledge to interpret current perception. While it is frequently discussed, far more research is needed to identify the best exploratory strategies and instructional procedures for learning these environmental regularities and teaching spatial reasoning strategies.

Another technique which should be given more emphasis by researchers and O&M instructors is the use of exploration strategies that explicitly emphasize the relations between landmarks, independent of the functional connectivity between these points (i.e. route navigation). Presumably, the process of learning about inter-object relations and thinking about the space from a structural/configurational level vs. a purely functional/route perspective will benefit the development of more accurate cognitive maps by blind individuals. Although most research designs and training programs do not look at this issue, several studies have been conducted investigating the effectiveness of exploratory strategies for learning unfamiliar environments. The take-home message from these studies are that people who adopt multiple search strategies during exploration of rooms and open spaces and weight their search on movement patterns that facilitate linking of spatially discrete objects and known reference points, rather than simply following a fixed perimeter route, lead to the most accurate self-familiarization performance (Tellevik 1992; Gaunet and Thinus-Blanc 1996; Hill et al. 1993). When navigating large, unfamiliar spaces, such as street or corridor networks, an excellent technique for improving environmental learning and encouraging integration of spatial cues into a global understanding by BVI learners is to adopt training procedures that employ free exploration instead of route guidance. As part of my dissertation work, I had blind participants freely explore an unfamiliar building and find hidden target locations. At test, their task was to execute routes between these target locations (routes were never explicitly specified during training). The finding that over

50% of the correctly executed test routes had not been previously traveled during training clearly demonstrates that traversing fixed routes is not a necessary prerequisite for blind spatial learning (Giudice 2004). Participants in the same studies were also able to reproduce accurate models of the previously learned environments, providing clear evidence that the sensorimotor experience afforded by free exploration helps integrate multiple discrete locations into a globally coherent spatial framework.

In summary, the above studies provide important insight, as we know very little about how exploration strategies during self-familiarization of novel environments support spatial learning by BVI people. The findings showing accurate BVI performance on complex spatial tasks and similarity of performance between blind and sighted participants support the hypothesis that blind individuals can develop accurate spatial representations when using appropriate search strategies and when supported by sufficient environmental information. This research also highlights the need for greater focus on investigating how blind travelers interact with their environment and identifying what movement strategies and exploratory patterns they adopt for learning unfamiliar places.

7. Information Access Technology to Improve Spatial Cognition

7.1. Overview

There is a long history of people/companies developing information access technology (AT), also called assistive technology, and frequent publicity of new devices that seem promising at a superficial level. Unfortunately, most products never go beyond initial curiosity or actually reach the blind end-users for whom they were designed. Lack of commercial success and market acceptance is largely attributable to three problems:

1) The engineering trap: Referring to when devices are developed based on the naïve intuitions of the designer or are aimed at providing a solution to a non-existent problem (Giudice and Legge 2008). A good example is the host of devices developed since the

early 1960s for detecting and avoiding obstacles in the path of travel. The problem is that most of this AT does not provide significant information access advantages over the tried and true mobility aids of the long cane or dog guide, is expensive to purchase, and requires a steep learning curve to master. As such, these devices generally end up being more of a hassle than helpful. Adoption of human-centered design is particularly important for AT development as sighted designers frequently have many fears and misconceptions about blindness that may have little to do with the actual experience. Some simple user-centered solutions to the engineering trap that can provide invaluable feedback include: (1) conducting focus groups with potential BVI users based on realistic scenarios to assess phenomenological experience and input on design decisions, (2) performing usability evaluations with BVI participants interacting with prototypes, and (3) soliciting robust post-test input from these potential end-users about the pros and cons of the device.

2) Insufficient Knowledge: The design of most information-access technology is not sufficiently informed by knowledge of the perceptual and cognitive factors associated with nonvisual information processing. Where designers are accustomed to development of visual interfaces, they often have little knowledge of the theories or sensory-specific intricacies of nonvisual sensory perception. This can be particularly troublesome when developing sensory substitution devices, where information from one channel (e.g. visual input from a camera) is converted into output by another channel (e.g. auditory or tactile stimulation). The solution is to have a good understanding of each of the constituent modalities and of the sensory translation rules between them. It is not enough to simply implement an algorithm that converts visual information to some nonvisual output, this output must be natural and intuitive to be meaningful (see Loomis et al. 2012 for a review of these issues).

3) Insufficient specificity: Most AT is developed to serve as a general-purpose device. However, the better approach is to design the technology to address a specific need/problem faced by BVI people. As such, it should focus on conveying task-specific environmental information and the interface should support the user's ability to select the desired content and mode of output. Importantly, the technology should be capable of being incorporated into a person's daily life without undue burden. This includes its cost, its ease of learning, and its ability to complement rather than disrupt other activities and technologies.

7.2. Information Access Technology that Makes a Difference.

The basic research supporting functional equivalence of spatial behaviors and the development and accessing of an amodal spatial representation discussed earlier has important applications to AT design. These findings suggest that assuming the appropriate information is provided, nonvisual information access technologies can be used to support similar behaviors as are possible from visual interfaces. Corroborating this claim, research comparing learning of simulated building floor plans from information-matched visual and spatialized audio displays revealed equivalent learning of the space, as measured by a transfer task requiring wayfinding in the corresponding real building (Giudice and Tietz 2008).

What is needed is more R&D of technologies that promote environmental learning, provide real-time access to off-route information, and assist BVI users with key navigation operations such as spatial updating. Until recently, there were few options for providing blind navigators with this orientation information. However, the advent of commercially-available, speech-enabled GPS-based navigation devices, such as products from the Sendero group (senderogroup.com) and BlindSquare (blindsquare.com) represent a significant milestone in this domain. The advantage of these (and other similar systems) is that they convey information that is not available from primary mobility aids, such as information about nearby points of interest, street names, descriptions of intersection geometry, and dynamically-updated position and orientation information. The value of providing true orientation information that does not overlap with traditional mobility tools should not be under-estimated. Technology that can provide this information has the greatest potential for improving BVI navigation and reducing the fear and anxiety associated with independent travel in unknown environments.

A problem with all current GPS-based navigation systems is that they are limited to outdoor usage. While this affects sighted and BVI people alike, the lack of indoor navigation assistance is particularly challenging for BVI travelers as most existing navigation supports, such as signage, building maps, and you-are-here indicators are rarely available in a nonvisual format. Although formal evaluations are sparse, survey responses from a group of highly independent BVI travelers indicated frequent anxiety about travel to large unfamiliar buildings, and that they would be far more likely to independently travel to such locations if they could avail themselves of an accessible indoor navigation system (Riehle, Anderson, Lichter, Whalen, and Giudice 2013). This is an area of active research and the ultimate solution will likely incorporate multiple technologies, including some combination of digital beacons, inertial sensors, narrative and tactile maps, RFID tags, Wi-Fi positioning, and an accessible navigation app that likely resides on a smartphone or tablet (see Giudice et al. in press; Legge, Beckmann, Tjan, Havey, and Kramer 2013; Riehle et al. 2013 for initial incarnations of such systems).

Building on the claim that most problems of BVI navigation relate to insufficient information access, I posit that increased availability of tools and technologies that convey normally inaccessible spatial information will lead to corresponding improvements in spatial abilities. In support of this assertion, the use of tactile maps by blind individuals, both before and during travel, has been shown to facilitate spatial learning, navigation, and cognitive map development (Blades et al. 1999; Espinosa et al. 1998). These findings are extremely promising and suggest that technology development, whether it be haptic, auditory, language-based, or multimodal, should endeavor to convey information about spatial relations and global structure, as this confers the greatest benefit to BVI travelers in providing information that is not readily available from other sources of environmental access.

7.3. Designing for the Future: Where Is AT Going?

The advent of smaller, cheaper, and commercially-available technologies, coupled with increases in our understanding of blind spatial cognition, means that we are on the cusp of a new era of AT design. A number of factors/technologies to consider are discussed below.

Despite the myriad benefits of tactile maps, these spatial products are limited in that they are generally difficult and expensive to author, often include confusing symbols, and only provide a static representation of space. In addition, there is little standardization in the construction of tactile maps; from my discussions with tactile cartographers, the general approach is to follow their own convention based on their experience of what map elements, textures, symbols, etc. have worked in the past. Advancements in this domain should consider the pros and cons of adopting standards. More importantly, research with different haptic displays is extremely promising, as it allows for dynamic rendering of multimodal information and some incarnations can even be implemented on smartphones that the majority of BVI people already own; see Klatzky, Giudice, Bennett, and Loomis (2014); O'Modhrain, Giudice, Gardner, and Legge (2015) for reviews.

The success of accessible GPS devices speaks to the value of the information they provide. However, the commercial incarnations of these systems rely on spatial language descriptions. As language involves cognitive intervention to interpret, it requires more working memory capacity and cognitive load than perceptual interfaces, such as those based on vision, touch, or spatialized audio. In support, research studying route guidance between spatial language and a spatialized audio indicator showed that the latter was significantly less affected by a concurrent secondary distractor task (Klatzky, Marston, Giudice, Golledge, and Loomis 2006). Similar advantages for spatialized audio over spatial language were found for guidance along outdoor routes using an experimental GPS-based navigation system (Loomis, Golledge, and Klatzky 1998) and for cognitive map development (Giudice, Marston, Klatzky, Loomis, and Golledge 2008; Giudice and Tietz 2008). Although most accessible technologies rely on language as the mode of information exchange, the above results suggest that linguistic-based interfaces have some significant limitations. Thus, there needs to be a stronger emphasis in future AT development on incorporating perceptual interfaces implementing haptic, spatialized audio, or multimodal output.

Finally, recent research has shown an important role for game playing in spatial learning by blind young adults, as measured by both behavioral and neuroimaging tasks (Merabet, Connors, Halko, and Sanchez 2012). Importantly, game play in a simulated environment based on haptic and spatialized audio cues led to accurate environmental transfer to navigation in the corresponding physical space that yielded better performance than was found after formal O&M training (Connors, Chrastil, Sánchez, and Merabet 2014). As O&M instruction can be difficult and onerous for BVI youth, the prospect of complementing traditional instruction using a fun and 'cool' gaming context could have huge benefits on the design and implementation of future O&M training curricula.

8. Conclusion

The goal of navigation, irrespective of visual status, is to travel safely and efficiently between an origin and destination. However, the breadth and depth of environmental information available to sighted and blind individuals is very different. In this chapter, I have argued that the biggest challenges to blind spatial cognition are about insufficient information access rather than vision loss, but that availability of the right spatial information, being the common denominator of the senses, can level the playing field and ultimately lead to equivalent performance between sighted and BVI individuals. This argument fundamentally changes the way we think about blindness, the type of research that is needed, and the solutions that will have the broadest impact moving forward.

The chapter also discussed some of the problems related to how blindness is defined and interpreted. Arguments were provided supporting the claim that in order to truly understand blind/low-vision spatial abilities, and to develop useful learning strategies to remediate travel-related problems, the focus of research on the presence or absence of visual information, or the role of visual experience or particular etiology, must be redirected to consider spatial information from all sensory modalities. Solutions to blindness-related spatial challenges must start with a functional understanding of the underlying challenge in terms of what information could remediate the problem. Armed with this understanding, it will be far easier to develop new spatial strategies and information access technologies with the greatest impact. The take-home message of the chapter is to encourage readers to appreciate how spatial cues can be specified from different modalities, and to consider how blindness is more about effective use of this information than vision loss per se.

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