Perceiving Visual Properties of Indoor Layouts with Impaired Vision

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Dedication

To my wonderful grandmother, Carolyn Cudd, with whom I belong.

Abstract

Low vision is any visual impairment that affects everyday function and is not correctable with lenses (glasses or contacts). It results in a loss of details required for object recognition and space perception, which can lead to getting lost or disoriented, even in familiar environments. Visual accessibility is the use of vision to travel efficiently and safely through an environment, to perceive the spatial layout of key features, and to keep track of one's location. To construct a public space that facilitates visual accessibility, it is necessary to predict how well people with low vision can navigate within such spaces. Two topics are the focus of this thesis: i. the recognition of steps/ramps under different environmental conditions by subjects with low vision and those with normal vision wearing acuity-reducing goggles, and ii. spatial updating in real indoor spaces with limited visual and auditory input. The ability to recognize and safely utilize steps/ramps is an important component of visual accessibility. An overview of the thesis is provided in Chapter 1. Chapters 2, 3, and 4 discuss three related research projects.

Chapter 2 investigates two possible ways of enhancing step/ramp recognition for people with low vision: locomotion (walking) and visual floor texture. Normal vision subjects with artificially reduced acuity were evaluated on recognition accuracy. Locomotion enhanced performance, while floor texture detracted from it.

Chapter 3 explores the recognition of steps/ramps by people with heterogeneous forms of impaired vision. The effects of distance, target type, and locomotion were qualitatively

similar for low vision and normal vision with artificial acuity reduction. Recognition performance was significantly better at shorter distances and after locomotion.

Chapter 4 evaluates the spatial updating abilities of normally sighted subjects wearing acuity- and field-reducing goggles. Spatial updating is the ability to keep track of one's position and orientation in an environment. We measured the accuracy of distance and direction estimates, and learned that vision status influenced estimates of distance, but not estimates of direction.

Together, these studies provide insight into the visual accessibility of spaces for people with low vision, and suggest directions for future research.

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Chapter 1. Thesis Overview

Imagine you are visiting your doctor for a check-up in a large office building. How would you locate the reception area for check-in amongst all the other rooms in the building and make your way to the front desk? How would you locate obstacles, like steps or ramps, which may be in your path and use them as needed? For most of us, "I would use my vision" is the easy answer to these questions. However, these questions pose a more formidable problem for people with impaired vision because some aspects of indoor spaces are not visible to them.

In this thesis, I focus on the problem of visual accessibility for people with low vision. Low vision is any visual impairment that affects everyday function and is not correctable with lenses (glasses or contacts). It comes in many forms, involving combinations of loss of acuity, contrast sensitivity, and visual field. Visual accessibility is the use of vision to travel efficiently and safely through an environment, to perceive the spatial layout of key features, and to keep track of one's location. Figure 1.1 shows a bench viewed with normal vision, mild blur and severe blur. On a cloudy day, the bench is difficult to see with blurry vision, but when the sun is out, the high-contrast shadow cast by the bench makes it visible under all three visual conditions. This figure illustrates that the visual accessibility of the bench varies with vision status and lighting. There are two components of visual accessibility: obstacle avoidance and wayfinding. Obstacle avoidance is the ability to take the next step safely. Wayfinding is the ability to learn layouts, and plan and follow routes from place to place, while correctly updating one's

current position and heading. Some people with low vision deal effectively with obstacle avoidance by using a dog or white cane, but many choose to rely on their remaining vision (Ludt & Goodrich, 2002).
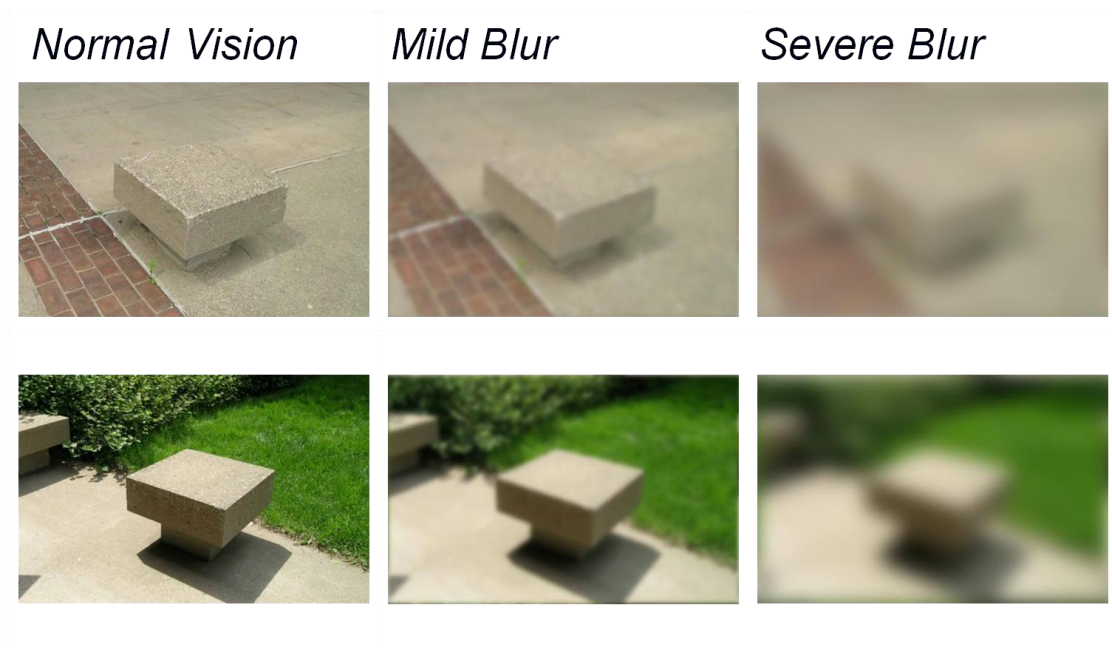
Figure 1.1. A bench on an overcast day (top row) and a sunny day (bottom row), shown under three different visual conditions (Normal Vision, Mild Blur, and Severe Blur). (Contributed by Chris Kallie.)

Wayfinding is a more difficult proposition because there is no technology as effective as a dog or cane to provide aid. To construct a public space that facilitates visual accessibility, it is necessary to predict how well people with low vision can navigate within such spaces.

Several million people in the United States have visual impairments serious enough to restrict their mobility. Currently, about 4.2 million Americans over the age of 40 have impaired vision (National Eye Institute, 2010). Of these, about 1.3 million are legally blind and another 2.9 million have milder low vision. Due to demographic trends, particularly the aging of the American population, these numbers are expected to increase substantially in the next decade (Eye Disease Prevalence Research Group, 2004).

Low vision results in a loss of details required for object recognition and space perception, which can lead to getting lost or disoriented. Reduced acuity, reduced contrast sensitivity, and reduced visual field size contribute to impairment. These three variables are considered in the studies in this thesis. Safety depends critically on the ability to reliably identify potential hazards from a distance, not just on the ability to maneuver around obstacles once they are recognized. Obstacle recognition at a distance is more visually demanding than preventing collision with nearby objects and surfaces (walls, etc.). Additionally, the varied and complex layouts of real spaces, the presence of mobile obstacles (e.g., other humans, bicycles and cars), and dynamic, multi-source lighting arrangements (overhead plus window lighting) place high demands on vision. Normal vision functions well across changes in lighting and other environmental variations because it is adept at extracting invariants such as object identity. When vision is reduced, the capacity to recognize objects and to construct an accurate representation of 3-D space may be lost. Objects, particularly those viewed at distance, become sensory blobs, without clear identity or distance cues.

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The considerable importance of environmental visual accessibility is underlined by the large literature indicating a relationship between vision status and falls or other accidents in the elderly. Studies have shown associations between reductions in binocularity, contrast sensitivity, acuity and field and the occurrence of falls and hip fractures in the elderly (Lord & Dayhew, 2001; Ivers, Cumming, Mitchell, & Attebo, 1998; Klein, Klein, Lee, & Cruickshanks, 1998). Poor vision is implicated in falls in specific environments, including nursing homes (Rubenstein, Josephson, & Osterweil, 1996) and on stairs (Archea, 1985).

In order to fully participate in modern society, it is vital to be independently mobile, whether one commutes by car, walking, biking, or public transportation. Vision loss can reduce mobility, and consequently lead to social isolation and economic disadvantage. Returning to our hospital example, in a best-case scenario, getting lost on the way to a doctor's appointment may result in only mild consequences, such as lateness, embarrassment from asking a passer-by for help, or a few bumps and bruises. However, a more serious long-term consequence can be a reduction in the number of subsequent independent travel attempts, which hampers work, recreation, and social opportunities. What can be done to enhance the navigation experience for people with impaired vision? The work contained in this thesis addresses this question by determining which environmental features people with impaired vision are able to see and use in navigation.

In the following chapters, I describe my research on three projects, which were conducted

as part of an interdisciplinary, multi-university project entitled "Designing Visually Accessible Spaces" (DEVA). The major goal of this project is to develop tools and methods that help architects and interior designers enhance the visual accessibility and navigability of complex indoor environments for people with impaired vision. The universal design principle seeks to maximize the utility of spaces for all people, regardless of age or disability. In the case of vision, this means designs in which key features of spaces (those important to its function, safety and mobility) are visually useful to the maximum number of people under the widest range of prevailing lighting conditions. Ultimately, we aim to develop a computer-based design tool in which spaces can be simulated with sufficient accuracy to predict the visibility of key landmarks or obstacles (e.g., steps or benches) under a variety of natural and artificial lighting conditions. At University of Minnesota, we have conducted psychophysical research with human subjects to find those aspects of physical spaces that are most salient for people with impaired vision. Empirical testing allows us to determine the relationship between the nature of a visual environment (geometry, materials, and lighting) and the effectiveness with which people with different types of degraded vision can perceive information relevant to mobility. Although real-world studies can be messy (confounding variables abound), real spaces present unique opportunities for empirical research. More controlled studies are also valuable, but real-world studies may produce results that translate more readily into guidelines for practitioners in low-vision clinics, who can then enhance the mobility of patients.

In the first published study from the DEVA project, Legge, Yu, Kallie, Bochsler, and Gage (2010), subjects with normal vision wearing blurring goggles were asked to detect and recognize deviations from a flat sidewalk—a step up or down, or a ramp up or down (see Figure 1.2). Viewing distance, sidewalk background (adjacent areas
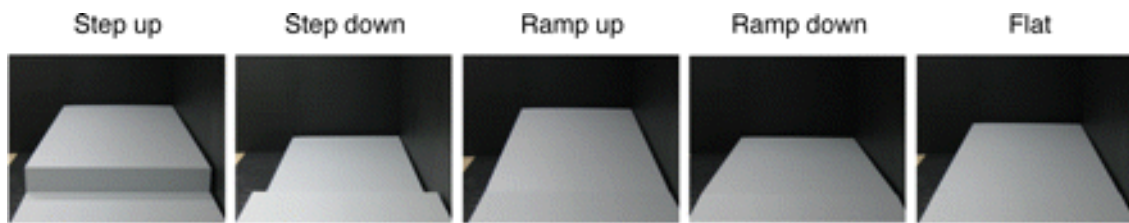
Figure 1.2. The five targets. (Reprinted from Legge et al., 2010.)

matched in gray or contrasting black), and lighting (diffuse overhead vs. side lighting from windows) were varied. Three crucial stimulus cues for recognizing steps and ramps were identified (see Figure 1.2)—luminance contrast at the transition point (edge of step or beginning of ramp), a geometrical shape cue (L-junction) on the bounding contour of a step down, and the height of the target against the background (high for step or ramp up, medium for flat, and low for step or ramp down).
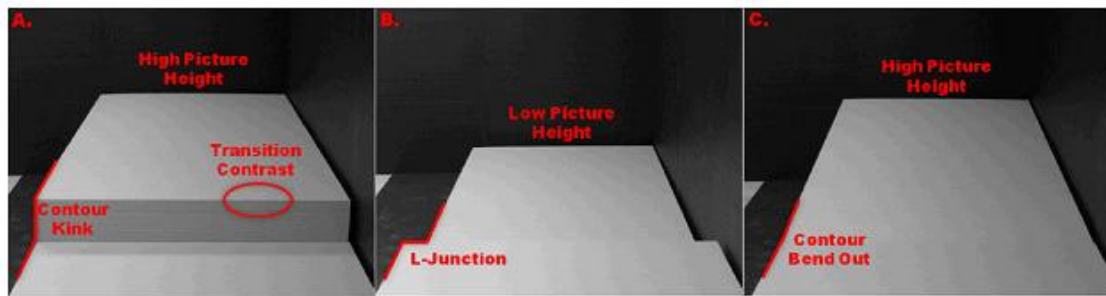
Figure 1.3. Cues for distinguishing ramps and steps. Panel A: The cues for Step Up include the luminance contrast marking the transition from sidewalk to riser, and a kink in the boundary contour of the sidewalk. Panel B: A cue for Step Down is the L-junction in the boundary contour of the sidewalk. Panel C: A cue for both Ramp Up and Ramp Down is the bend in the bounding contour associated with the transition from sidewalk to ramp. The bend out for Ramp Up is shown here, and there is a corresponding bend in for Ramp Down. An additional cue for all stimuli is the height in the picture plane, formed by the horizontal bounding contour between the far edge of the target panel and the wall behind it-high for Step Up and Ramp Up, low for Step Down and Ramp Down, and intermediate for the Flat target. (Figure and caption from Legge et al., 2010.)

The visibility of these cues depended on viewing distance, the severity of blur, and lighting. A step up was easier to recognize than a step down. This is unfortunate because missing a step down can lead to a serious fall down a flight of stairs, while missing a step up is usually less dangerous.

The present thesis extends the findings of Legge et al. (2010) by addressing two classes of tasks. One is the recognition of objects nearby in the environment (steps and ramps)

that can be essential to effective mobility. When not properly recognized, such objects are potential hazards. The second is the ability to perceive the spatial layout (size and shape) of the environment itself. Chapters 2 and 3 address the salience of local obstacles in the environment (steps and ramps) for simulated (Ch. 2) and real (Ch. 3) impaired vision. Chapter 4 takes a more global perspective, focusing on what people with simulated low vision can apprehend about the dimensions of a space and the distance and direction to landmarks in the space.

Subjects were either normally sighted people with artificially restricted vision or people with heterogeneous forms of impaired vision. Visual restrictions were produced by devices (blurring lenses, visual field-restricting tube) mounted in rubber goggles with one eye occluded (monocular viewing only). Monocular viewing is often a good parallel with low vision, because most people with low vision have a "better eye" that dominates performance. Documenting the psychophysical performance of subjects with normal vision under restricted viewing conditions has multiple advantages. From a practical perspective, normal vision subjects are easier to recruit and transport to the study location than people with impaired vision, due in part to the limited mobility that often accompanies visual impairment, as discussed earlier in the chapter. Visual performance can be used as a metric for quantifying "visual accessibility" for the conditions in question. For instance, a step down in a particular environment might have a detection distance of 30 ft under viewing condition A, 5 ft for viewing condition B, and 0 ft (never seen) for viewing condition C. Data from parametrically designed studies with well-

specified stimuli are critical to evaluate models for predicting detection and classification distances as well as spatial orientation. Lastly, the performance of subjects with normal vision under restricted viewing can provide a first-order prediction for performance of people with low vision. For instance, the detection distance of a target observed with normal vision with 10-fold contrast reduction could serve as a baseline prediction for the detection distance of a low-vision subject with a 10-fold reduction in contrast sensitivity. For some forms of impaired vision, simple models like this one may be adequate for accurately predicting performance.

It is important to validate findings with normally sighted subjects by testing people with actual low-vision conditions. There are various reasons why the results could be different with real low vision, including the effects of prior experience (age of onset of vision loss, time since vision loss), combined effects of different types of loss (such as contrast loss and field loss), co-morbid conditions, and other attributes of vision loss (e.g., problems of binocularity and glare).

Using the same experimental test space and apparatus as Legge et al. (2010), Chapter 2 investigates two possible ways of enhancing step and ramp recognition for people with low vision: locomotion and visual floor texture. Detecting and recognizing steps and ramps is an important component of the visual accessibility of public spaces for people with impaired vision. We hypothesized that locomotion and floor texture might facilitate the recognition of steps and ramps during low-acuity viewing. Visual texture on the

ground plane is an environmental factor that improves judgments of surface distance and slant. Locomotion (walking) is common during observations of a layout, and may generate visual motion cues that enhance the recognition of steps and ramps.

In two experiments, normally sighted subjects viewed steps or ramps through blur goggles that reduced acuity to either approx. 20/150 Snellen (mild blur) or 20/880 (severe blur). The subjects judged whether a step, ramp or neither was present ahead on a sidewalk. The sidewalk was a 4-foot-wide by 24.5-foot-long platform built in an indoor classroom; elevated 16 inches above the floor (see Legge et al., 2010 for details). A photo of the test space is shown in Fig. 2.1. In the texture experiment, subjects viewed steps and ramps on a surface with a coarse black-and-white checkerboard pattern. In the locomotion experiment, subjects walked along the sidewalk toward the target before making judgments. Surprisingly, performance was lower with the textured surface than with a uniform surface, likely because the texture masked visual cues necessary for target recognition. Subjects performed better in walking trials than in stationary trials, possibly because they were able to take advantage of visual cues that were only present during motion. We concluded that under conditions of simulated low acuity, large, high-contrast texture elements are not helpful, and can actually hinder the recognition of steps and ramps while locomotion enhances recognition.

Chapter 3 validates and expands on the results from Chapter 2 by exploring the recognition of steps and ramps by people with heterogeneous forms of impaired vision.

The primary goal was to assess the impact of viewing conditions and environmental factors on the recognition of these targets by people with low vision. A secondary goal was to determine if results from our previous studies of normally sighted subjects, wearing acuity-reducing goggles, would generalize to low vision.

Sixteen subjects with heterogeneous forms of low vision participated, with acuities ranging from approximately 20/200 to 20/2000. Subjects viewed a "sidewalk" interrupted by one of five targets: a single step up or down, a ramp up or down, or a flat continuation of the sidewalk. Subjects reported which of the five targets was shown, and percent correct was computed. The effects of viewing distance, target/background contrast, lighting arrangement and subject locomotion were considered. Performance was compared with a group of normally sighted subjects who viewed the targets through acuity-reducing goggles. Recognition performance was significantly better at shorter distances and after locomotion (compared with purely stationary viewing). As in Legge et al. (2010) and Chapter 2, the step up was more visible than the step down. The effects of distance, target type, and locomotion were qualitatively similar for low vision and normal vision with artificial acuity reduction. However, the effects of lighting arrangement and background contrast were only significant for subjects with normal vision.

In Chapter 4, our focus shifted from obstacle recognition to estimates of distance and direction derived from spatial updating. Spatial updating refers to the ability to keep track of one's position and orientation in an environment. Spatial updating involves two

distinct processes: learning, where the observer builds a cognitive model of the spatial structure of the environment, and reevaluating, where the observer modifies the model as they move (Reiser, 1999). It is a critical skill that allows humans to maintain a stable representation of the world. For instance, while walking along a city street, an observer understands that as she passes a building, it is now behind her, and as she turns to the right, the sign that was in front of her is now on her left. Some authors have posited that updating may occur automatically with self-movement (e.g., Farrell & Robertson, 1998; May & Klatzky, 2000) using paradigms that require observers to ignore a given movement during the updating task. In this framework, updating would involve path integration, in which velocity- or acceleration-based self-motion information is used to update spatial displacement. However, others (e.g., Waller, Montello, Richardson, & Hegarty, 2002) have shown that updating is not obligatory with body-movement when subjects are given explicit instructions to transform the image of a spatial layout, suggesting that there may be a higher-level cognitive component to spatial updating. People with impaired vision experience difficulty with spatial updating. They sometimes become disoriented, even in familiar environments. In Chapter 4, we asked how different forms of visual impairment affect spatial updating, and what role non-visual cues may play. To study the impact of visual impairment, normally sighted subjects wore goggles to simulate reduced acuity and severe field restriction. We reduced acoustic information in the environment by auditory noise masking. How are people with impaired vision hindered in spatial updating? Does visual (and auditory) perception of the size and shape of an indoor space facilitate spatial updating?

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To begin addressing these issues, we tested 32 normally sighted young adults in several sensory deprivation conditions- artificially reduced acuity (mild blur: 20/135, or severe blur: 20/900), severely restricted field (dia = 8 degrees), and blindfolded with or without environmental auditory cues. Most people with low vision have reduced acuity, and many have a restricted visual field. Severe field loss is thought to have a major impact on mobility. People with impaired vision may often rely on acoustic cues, so it is valuable to understand if these cues are useful for indoor navigation. Subjects were guided by an experimenter along short, three-segment paths in seven rectangular indoor spaces (6 rooms and one corridor). Turning angles were non-orthogonal and the lengths of the path segments ranged from 3 to 9 feet. Each path began at the entry to the space and the subject was instructed to drop a place marker (bean bag) at the end of the first route segment. At the end of the route, subjects estimated the length and width of the space, and the distances and directions to the entry point and place marker.

Simulated acuity reduction (mild and severe blur) did not influence judgments of space dimensions and the distances to the entry and place marker, while severe field restriction and no vision (blindfold condition) worsened these judgments, $p < 0.05$. The vision restrictions did not affect direction estimates of the entry and place marker, with mean absolute errors averaging 20 degrees. Presence or absence of auditory cues did not affect performance. These results suggest that visual perception of room context (size and shape) plays a vital role in distance judgments, but not direction judgments. Possibly, knowledge gathered about room dimensions can subsequently be employed to make

position judgments in a space. Artificial acuity reduction had little impact on spatial updating but severe field restriction produced errors in distance judgments equivalent to those made by blindfolded subjects. This suggests that severe field restriction may have a greater impact on spatial updating than severe acuity reduction. People with severe field restrictions, such as retinitis pigmentosa, may experience greater problems with spatial updating than people with low acuity but full fields.

In summary, the research described herein contributes to our understanding of how visual impairment influences obstacle detection and spatial updating in real indoor spaces. Two contributions made by this thesis include:

1. With both artificial visual restriction and actual impaired vision, walking through a space can enhance the visibility of obstacles (steps and ramps) within the space, while visual floor texture can detract from their visibility.

2. Vision status plays a key role in distance judgments, but not direction judgments, for subjects in a spatial updating task.

Chapter 2. Seeing Steps and Ramps with Simulated Low Acuity: Impact of Texture and Locomotion

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Overview

Purpose: Detecting and recognizing steps and ramps is an important component of the visual accessibility of public spaces for people with impaired vision. The present study, which is part of a larger program of research on visual accessibility, investigated the impact of two factors that may facilitate the recognition of steps and ramps during low-acuity viewing. Visual texture on the ground plane is an environmental factor that improves judgments of surface distance and slant. Locomotion (walking) is common during observations of a layout, and may generate visual motion cues that enhance the recognition of steps and ramps.

Method: In two experiments, normally sighted subjects viewed the targets monocularly through blur goggles that reduced acuity to either approx. 20/150 Snellen (mild blur) or 20/880 (severe blur). The subjects judged whether a step, ramp or neither was present ahead on a sidewalk. In the texture experiment, subjects viewed steps and ramps on a surface with a coarse black-and-white checkerboard pattern. In the locomotion

experiment, subjects walked along the sidewalk toward the target before making judgments.

Results: Surprisingly, performance was lower with the textured surface than with a uniform surface, perhaps because the texture masked visual cues necessary for target recognition. Subjects performed better in walking trials than in stationary trials, possibly because they were able to take advantage of visual cues that were only present during motion.

Conclusions: We conclude that under conditions of simulated low acuity, large, high-contrast texture elements can hinder the recognition of steps and ramps while locomotion enhances recognition.

Introduction

Obstacles on the ground or discontinuities in the ground plane, such as steps, pose hazards for people with low vision. Visual impairment is a risk factor for both falls and fractures in the elderly (de Boer Moll, Pluijim, Lips, Völker-Dieben, Deeg, & van Rens, 2004; Lord & Deyhew, 2001). Recognizing ground-plane irregularities, such as steps and ramps, is an important component of the visual accessibility of public spaces for people with impaired vision. Visual accessibility is the use of vision to travel efficiently and safely through an environment, to perceive the spatial layout of the environment, and to update one's location in the environment. A long-term goal of our research on visual accessibility is to provide a principled basis for guiding the design of safe environments for the mobility of people with low vision.

In Legge, Yu, Kallie, Bochsler, & Gage (2010), we investigated the impact on the detection of steps and ramps of environmental factors, such as target-background contrast and lighting arrangements, and also viewing conditions such as distance to target. Adults with normal vision, wearing acuity-reducing goggles, were tested in a windowless classroom using methods like those described in this paper. Among the results of the previous study, a step up was more visible with the acuity-reducing goggles than a step down. The effects of target-background contrast were greater than the effects of lighting arrangement. The empirical results were interpreted in the context of a probabilistic model of target-cue detection. Ongoing research in our lab is extending the findings to subjects with low vision.

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In the present study, we address the influence of two additional visual factors expected to enhance the recognition of ramps and steps under low-resolution viewing--surface texture and self-locomotion. Here, low-resolution viewing refers to viewing through acuity-reducing goggles (see Methods for details).

Texture is thought to provide information about the distance and orientation of surfaces (Gibson, 1950). Although computer graphics specialists have contributed much to our understanding of the image properties of real materials, with the goal of simulating such materials in virtual displays, there is a dearth of research on visual texture perception in real environments (Landy & Graham, 2004). However, some evidence demonstrates the impact of surface texture on real-world perception of target distance and surface slant (Sinai, Ooi, Teng, & He, 1998; Feria, Braunstein, & Andersen, 2003; Wu, Ooi, & He, 2004). These studies leave open the question of whether surface texture would help or hinder the recognition of steps, ramps, or other ground-plane irregularities.

In the real world, ground-plane surface textures often result from distributions of small elements, often with low contrast features, (e.g., grass, carpet weave, or a gravel path). With normal vision, such texture elements might be an effective source of information, but with low vision, they would often be invisible and unlikely to convey useful information. We hypothesized that surfaces with large, high-contrast texture elements would enhance the identification of steps and ramps with low-resolution viewing. If so, appropriately designed visual texture patterns on walking surfaces might facilitate safe

mobility for people with reduced acuity or contrast sensitivity. In Experiment 1, subjects viewed steps and ramps on a surface with a coarse black-and-white checkerboard pattern. Since the angular size of texture elements depends on viewing distance, we expected any benefits from texture to depend on acuity and viewing distance.

Motion perception tends to be resistant to blur and contrast reduction (McKee, Silverman, & Nakayama, 1986; Straub, Paulus, & Brandt, 1990; Jobling, Mansfield, Legge, & Menge, 1997), prompting our interest in motion cues for visual accessibility. While steps and ramps are usually static in the real world, escalators being an interesting exception (Cohn & Lasley, 1985) self locomotion (walking) provides a common source of retinal-image motion. It is ecologically relevant to study detection and recognition of obstacles during walking because people are often mobile when making such judgments. It is possible that self motion might enhance the visibility of low-contrast contours or yield information from motion parallax or other change-of-view cues to improve detection and recognition of ramps and steps.

In brief, we hypothesized that both surface texture and self-locomotion would enhance the recognition of ramps and steps with low-resolution vision.

General Methods

Stimuli and Procedure

A large, windowless, 33.25 by 18.58 ft (10.13 by 5.66 m) classroom in the basement of

the psychology building on the campus of the University of Minnesota was used as the

test space for all experiments. A schematic drawing is shown in Figure 2.1.
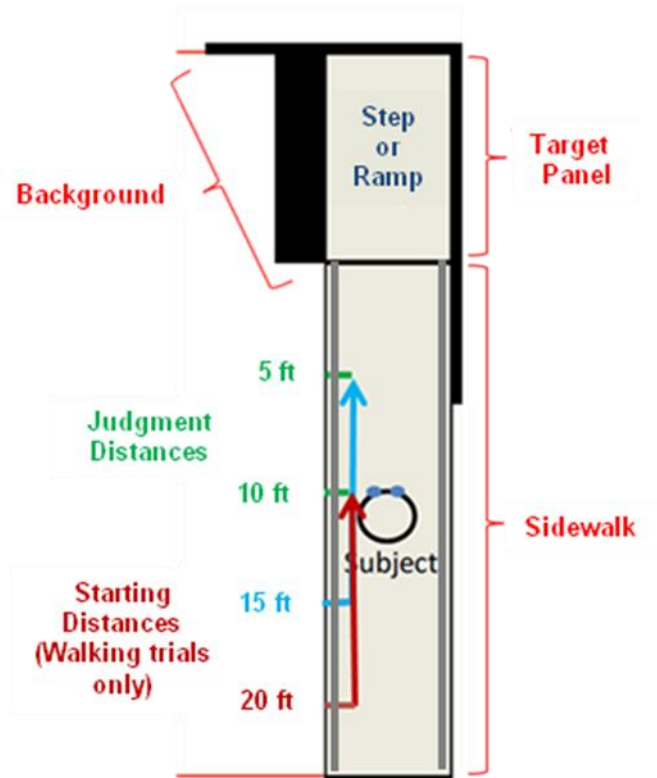
Figure 2.1. Schematic diagram of the test space, showing the target panel (upper left),

the sidewalk, the black background, the two stationary viewing locations in green (5 ft

and 10 ft), and the two starting locations for the walking trials in blue (15 ft and 20 ft).

The gray, metal railings were present for the walking trials only. With the omission of the

hand rails, the identical test space was used in Legge et al. (2010).

A uniform gray sidewalk (4 ft wide by 24.5 ft long; 1.3 m by 7.5 m) was constructed

using hardboard deck portable stage risers (Figure 2.1). This sidewalk was elevated 16 in

(0.4 m) above the floor. Five possible targets were shown at a fixed location on the

sidewalk's south end: a single step up or down (7 in height), a ramp up or down (7 in

change of height over 8 ft), or flat (see Figure 2.2). A 4 by 8 ft (1.2 m by 4.3 m) by 2 in

thick rectangular panel of expanded polystyrene (EPS), painted uniform gray, formed the

target. Sidewalk and target were also painted gray. Using motorized scissor jacks, the

target panel was adjusted by raising or lowering one or both ends of the panel above or

below the sidewalk.
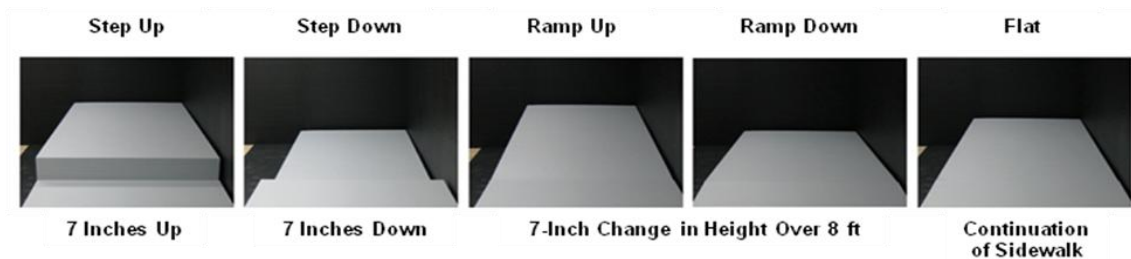
Figure 2.2. The five targets (shown with plain gray surfaces) were Step Up, Step Down,

Ramp Up, Ramp Down and Flat. The five targets are shown again with textured surfaces

in the top row of Figure 2.4.

The visual background for the targets was formed by the classroom floor, far wall, and

right-hand wall (see Figure 2.3). The walls were paneled with rectangular sections of

EPS, and the section of floor on the left of the target was covered with a wooden panel

(painted to match the background).

Overhead lighting was produced by four rows of three end-to-end 2 by 4 ft luminaries

(recessed acrylic prismatic 4 lamp SP41 fluorescent). This lighting produced a luminance

of approximately 77 cd/m^2 on white squares and 5 cd/m^2 on black squares in the texture pattern used in Experiment 1. The overhead illumination is representative of typical ambient room lighting. For more information about the test space and apparatus, please see Legge et al. (2010).

Effective acuity through the subject's dominant eye (determined with an aiming task) was reduced using either one or two Bangerter Occlusion Foils (see Odell, Leske, Hatt, Adams, & Holmes, 2008), mounted in a goggle frame. The foils were attached to one (mild blur) or both (severe blur) sides of a clear acrylic lens mounted in a welding goggle frame. See Figure 2.4 for examples of the effect of blur on target visibility. To reduce glare from illumination by the overhead fluorescent lights through the goggles, a cylindrical, black, acrylic viewing tube was attached to the goggles in front of the dominant eye. The tube reduced the field of view from about 48° to 33° (see Legge et al., 2010 for details). Effective acuity through the blur foils was determined by measuring each subject's acuity while wearing the blur goggles using the Lighthouse Distance Acuity chart. The mean acuity with mild blur was 20/152 (logMAR = 0.88) and with severe blur, 20/884 (logMAR = 1.65). Contrast sensitivity was also estimated psychophysically (Pelli-Robson chart, see Legge et al., 2010) as 0.8 (mild blur) and 0.6 (severe blur). Luminance was attenuated by approximately a factor of two through the blur foils.

Experiment 1 Methods

We compared ramps-and-steps recognition performance for a textured surface with similar recognition data for a uniform gray surface reported by Legge et al. (2010). The texture was a checkerboard pattern composed of large, high-contrast squares. The goal was to determine if visible texture would enhance the recognition of ramps and steps.

Participants

24 normally sighted young adults, ages 18-24 (M = 21.3 years), with mean acuity of 20/16 (logMAR = -0.097) and mean contrast sensitivity of 1.73 participated. Each subject completed the experiment in one session lasting from two to three hours. The experimenter obtained informed consent in accordance with procedures approved by the University of Minnesota's IRB.

Targets and Texture Pattern

The sidewalk and target were covered by linoleum flooring with a continuous texture of alternating black and white, high contrast (0.87 Michelson Contrast) squares (1 ft per side). An additional 4-ft-long by 7-in-wide narrow rectangle of black and white flooring was used to cover the riser for the Step Up target.

Procedure

Before each testing condition, subjects were shown the targets with normal viewing (no blur). This was done to equate their prior knowledge of the targets.

During each trial, the seated subject reported which of the five targets was shown (5-alternative forced choice) with a viewing time of 4 seconds. Subjects viewed the targets through the blurring goggles from three distances of 5 ft, 10 ft, and 20 ft (1.52, 3.05, and 6.10 m, respectively). To mask auditory cues associated with changing the target configuration, subjects wore noise-reducing earmuffs and listened to auditory white noise. Subjects were instructed to turn their head to face the right-hand wall between trials, preventing them from viewing the target adjustment.

Each subject completed 60 trials, two for each of the five targets, for two blur levels (mild and severe) and three viewing distances (5, 10, or 20 ft). See Figure 2.4 for the appearances of the targets with approximations of the mild and severe blur. Viewing distances are shown in Figure 2.1. Half of the subjects (N = 12) viewed the targets against a gray background and the other half viewed them against a black background (painted with Valspar interior satin dark kettle black acrylic latex). Since the contrast of the gray targets against the black background was higher (Michelson contrast = 0.82) than that against the gray background (0.25), it was hypothesized that subjects would perform with higher accuracy in the former condition. Within each background group (Black or Gray), trials were blocked by blur level and viewing distance.

Figure 2.3. Photo of the test space, with the sidewalk and Step Up target covered by textured surfaces. The overhead lighting is also shown.
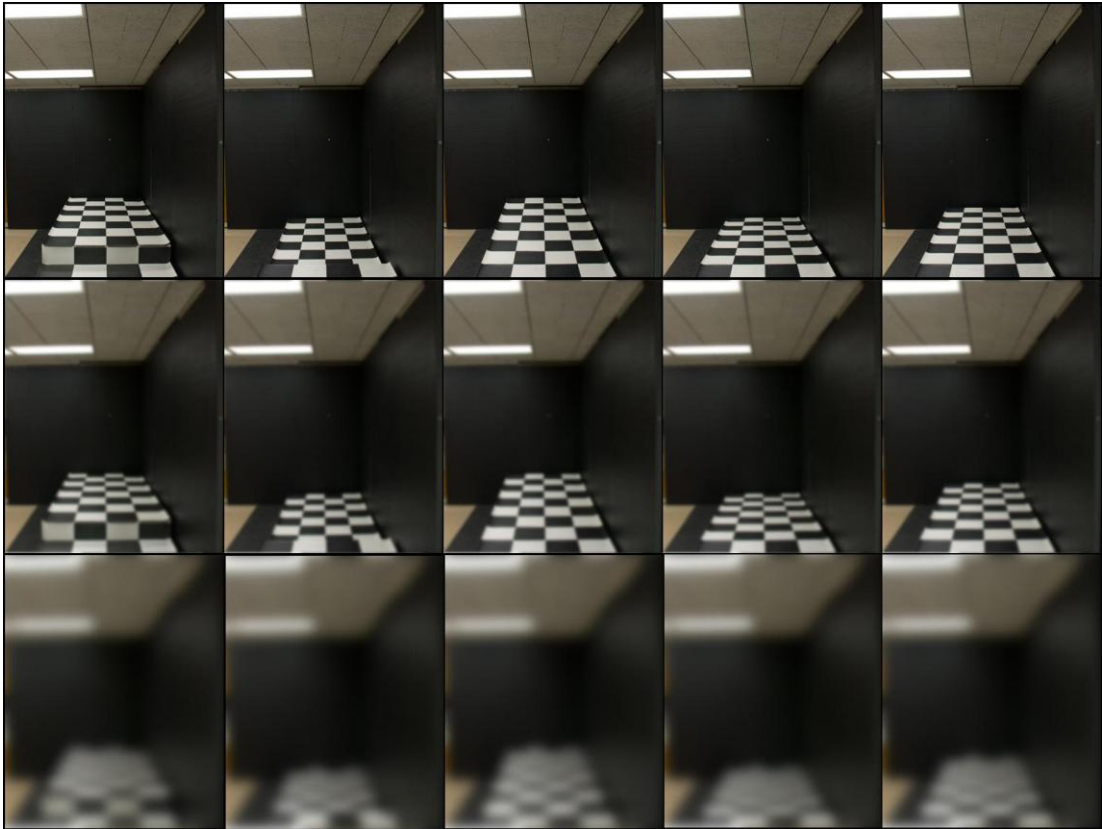
Figure 2.4. The targets are shown with full resolution (top), mild blur (middle), and severe blur (bottom). Here, the sidewalk has texture. The five targets, from left to right are: Step Up, Step Down, Ramp Up, Ramp Down, and Flat. The blurred images shown here are based on digital filtering and are not identical to images seen through the goggles.

Experiment 1 Results

In the presentation of results for Experiment 1, data for the uniform surface conditions come from the study of Legge et al. (2010), in which performance with the same black and gray backgrounds was compared. The size of the subject groups and testing conditions in the Legge et al. (2010) study were identical to the current study, apart from

the difference in surface pattern (texture vs. uniform). Accuracy for target identification (% correct) is reported. Chance accuracy was 20% because there were five targets.

To achieve normality of the group data, accuracy data were arcsine-transformed prior to statistical testing. We conducted a repeated-measures analysis of variance (ANOVA) on the transformed accuracy data, with three between-subjects factors—sidewalk type (Texture or Uniform), blur (Mild or Severe), and background color (Black or Gray)—and one within-subjects factor—viewing distance (5, 10 and 20 ft). T-tests, using a Bonferroni correction for multiple comparisons, were used in post-hoc testing. We hypothesized that texture would facilitate recognition of ramps and steps. However, contrary to expectation, the Uniform sidewalk groups performed slightly better overall (71% correct) than the texture sidewalk groups (67% correct), $p = .029$. The difference was greater with severe blur: the Uniform groups had 58% correct performed and the Texture groups had 47% correct, $p = .001$. With Mild blur, there was no significant difference between Textured and Uniform groups. The three-way interaction between sidewalk type, background color, and blur showed that Textured sidewalk was only significantly worse than Uniform sidewalk with Severe blur and the black background (F $(1, 23) = 11.34$, $p = 0.001$).

Figure 2.5 shows that performance was much better with mild blur (85% correct) than with severe blur (52% correct; F $(1, 88) = 242.83$, $p < .0001$). The high-contrast black background (88% correct) yielded better performance than the low-contrast gray

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background (78%) for the Uniform groups, p = .01 (see Legge et al., 2010).
Unexpectedly, there was no difference in performance between the black and gray
backgrounds for the Texture groups.

Performance varied with viewing distance (5, 10, or 20 ft) from the target (F (2, 88) =
19.72, p < .001). With Texture and Mild blur, performance was better at 10 and 20 ft than
at 5 ft, but with Gray and Mild blur, performance was best at 10 ft, p's < .03. For Severe
blur, performance was best at the shortest distance of 5 ft for both groups and declined at
longer distances, presumably due to acuity limitations, p < .001.
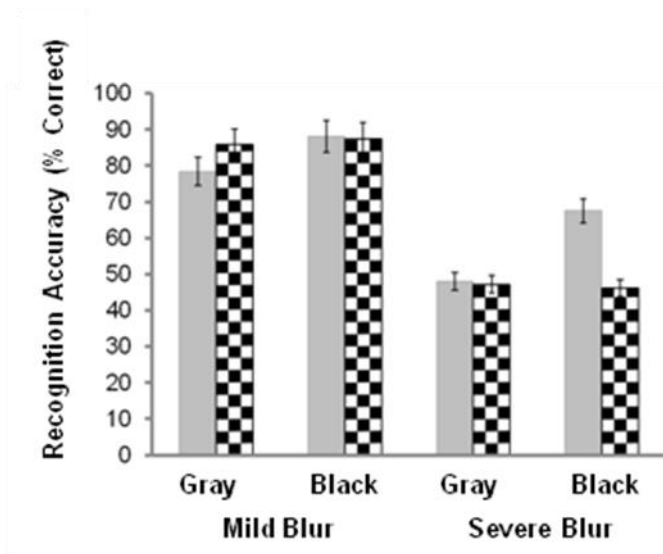
*Figure 2.5. Recognition performance (% correct) with black versus gray background
under blur. Error bars represent ± standard error.*
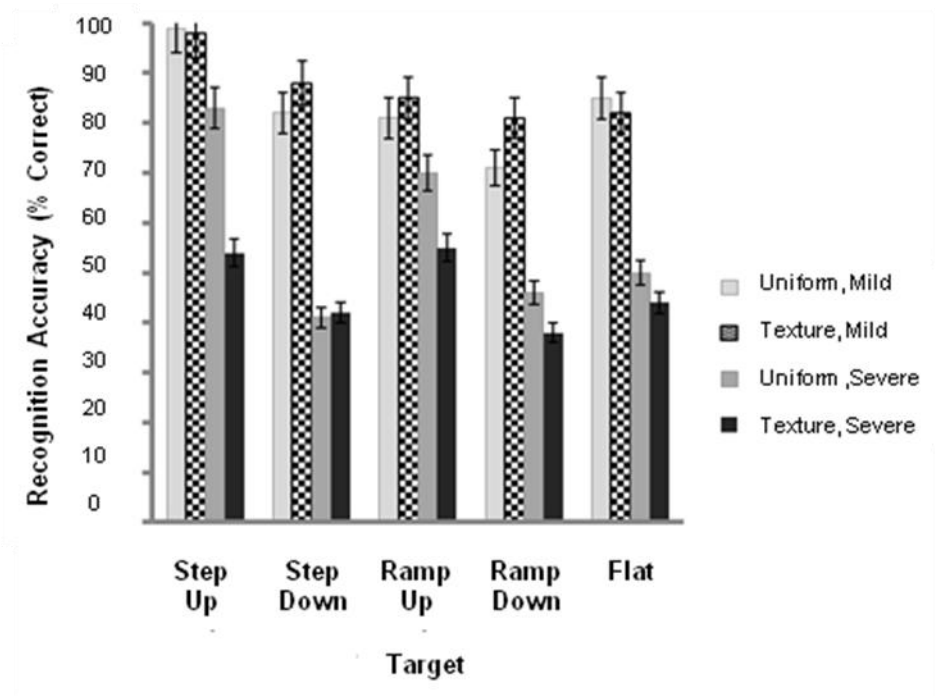
Figure 2.6. Recognition performance for the five targets. Error bars represent ± standard error.

Figure 2.6 shows that performance depended on the target (Step Up, Step Down, Ramp Up, Ramp Down, or Flat). Both Texture and Uniform groups performed better on Step Up than on Step Down, Ramp Down, or Flat, p's < .01. Similarly, both Texture and Gray groups performed better on Ramp Up than on Step Down, p's < .05. Overall, target accuracies for the texture study (Experiment 1) roughly correspond to those found with overhead lighting in Legge et al. (2010) when the corresponding conditions are compared (e.g., Black background & Mild blur at 10 ft).

Experiment 2 Methods

In this experiment, we compared recognition performance for a stationary condition and a walking condition. In the walking condition, subjects approached the targets along the sidewalk, stopping at the designated viewing distances (5 ft or 10 ft) to make their recognition decisions. The goal of this experiment was to determine if locomotion facilitated the recognition of ramps and steps.

Participants

18 normally sighted young adults ages 18-36 (M = 23.4 years), with mean acuity of 20/18 (logMAR = -0.046) and mean contrast sensitivity of 1.72 participated. Each subject completed the experiment in one session lasting from two to three hours. The experimenter obtained informed consent in accordance with procedures approved by the University of Minnesota's IRB.

Procedure: Walking versus Stationary

This experiment was like the Texture Experiment, with the following exceptions. Subjects made target recognition judgments from distances of 5 ft or 10 ft (but not 20 ft) either after stationary viewing or after walking 10 ft along the sidewalk from a greater distance to the same viewing locations. Weight-bearing railings were added to both sides of the sidewalk to enhance safety and subjects were asked to keep one hand on the left railing at all times during the experiment. Tactile markers were used to indicate the 5 ft, 10 ft, 15 ft and 20 ft distances.

In the stationary trials, subjects stood at the designated viewing distance and made their recognition decisions. In the moving trials, subjects walked 10 ft toward the target, stopped at the designated viewing distance, and made a recognition decision.

Testing was conducted with the same two surface patterns on the sidewalk (uniform and textured) used in Experiment 1. In both cases, the background was black. (See Figure 2.4 for examples.) Since our previous results (Legge et al., 2010) showed that the largest differences in performance among conditions were present with Severe blur, subjects were tested with only Severe blur.

Each subject completed 80 trials, two for each of the five targets, for two viewing distances (5 or 10 ft), two surface types (Uniform vs. Textured), and two movement conditions (Walking vs. Stationary). Within each surface type, trials were blocked by viewing distance and movement.

To determine whether walking trials were longer than stationary trials, we recorded three types of time measurements each for 10 trials (N = 4). Stationary trial time was the time taken in stationary trials from the experimenter's verbal signal for subjects to look at the targets until the subject made a recognition response. Average time for a stationary trial, 3.6 seconds, was close to the 4-second time limit in Legge et al. (2010). For the moving trials, total moving trial time was the time between the onset of walking and the subject's verbal recognition response. Walking time was the time from the onset of walking until

the subject stopped, not including any additional time before a verbal recognition response. Average total moving trial time was 8.2 seconds, and average walking time was 5.8 seconds.

For the walking trials, subjects were asked to wait until they arrived at the designated viewing location to give their response. They usually responded very soon after reaching this point (mean of 2.4 seconds) so most of the trial time was taken up with walking, rather than standing after the walk. Also, since subjects responded whenever they were ready during stationary trials, it is unlikely that requiring them to wait the average duration of a moving trial (~8 seconds) before giving their response would affect performance.

Experiment 2 Results

To achieve normality of the group data, accuracy data were arcsine-transformed prior to statistical testing. We conducted a repeated-measures analysis of variance (ANOVA) on the transformed accuracy data, with three within-subjects factors—locomotion (Walking or Stationary), sidewalk type (Texture or Uniform), and viewing distance (5 ft or 10 ft). The analysis revealed significant main effects of locomotion, $F(1, 18) = 51.90$, $p < .0001$; Sidewalk type, $F(1, 18) = 7.20$, $p < .01$; and viewing distance, $F(1, 18) = 9.96$, $p < .006$.
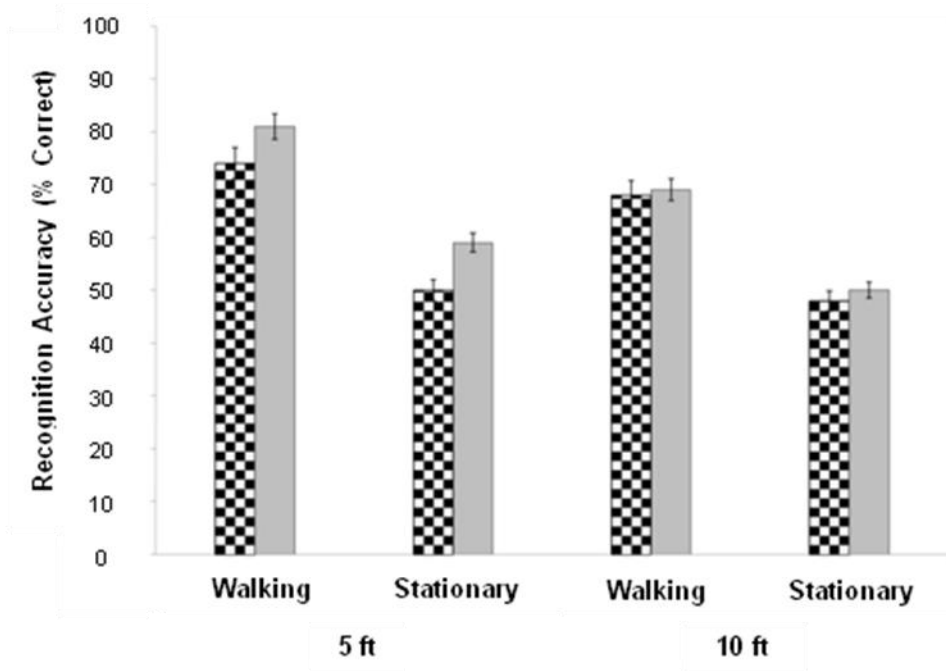
Figure 2.7. Comparison of walking and stationary recognition performance at 5 and 10 ft. Error bars represent ± standard error.

Subjects performed much better in the moving condition (74%) than in the stationary condition (52%). See Figure 2.7 for a comparison of Moving and Stationary performance with the Textured sidewalk and the Uniform sidewalk. As in Experiment 1, subjects performed better with the Uniform sidewalk (67.50% correct) than with the textured sidewalk (58%), $p < .01$. Subjects performed better at the 5 ft distance (66%) than at the 10 ft distance (59%), $p < .01$.

Discussion

The aim of these experiments was to determine whether surface texture and locomotion toward the target would enhance recognition of steps and ramps. Contrary to expectation,

surface texture detracted from performance. As hypothesized, locomotion towards a step

or ramp improved recognition compared with stationary observations. The Locomotion

experiment also replicated the findings of the texture experiment, showing that for severe

blur, recognition of steps and ramps was poorer with the texture pattern.

Why did the surface texture interfere with recognition performance? Texture contours

may mask some of the critical features for target recognition. Legge and colleagues

(2010) identified a set of cues useful for distinguishing among the five targets. Figure 2.8

illustrates these cues.
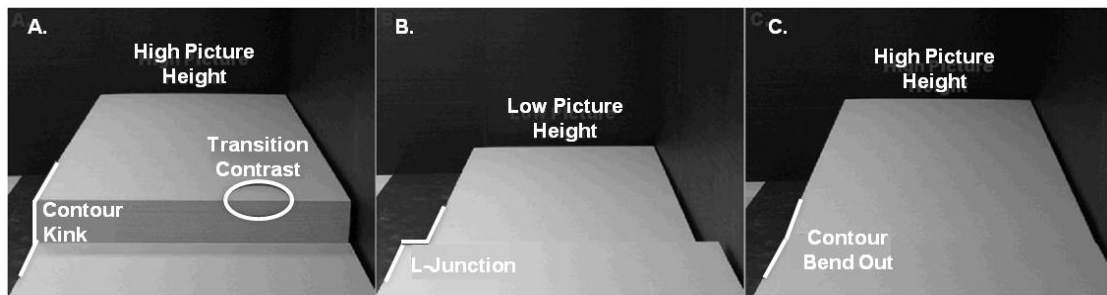
Figure 2.8. Cues for distinguishing steps and ramps. In panel A, the cues for the step up

target are shown. The transition contrast cue marks the transition between the riser and

the top of the target panel. The contour kink cue marks the "kink" in the boundary

contour of the sidewalk that is created by the step up. In panel B, the L-junction cue

marks the L-shaped boundary contour that is created by the step down. In panel C, the

contour bend out cue marks the subtle bend in the boundary profile of the sidewalk

created by a ramp up. A corresponding bend in cue marks the bend for ramp down.

Height in the picture plane, the horizontal bounding contour between the far edge of the

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target panel and the back wall, is an additional cue that can be used for all five targets.

Picture height is high for step up and ramp up, low for step down and ramp down, and

intermediate for the flat target. From Legge et al., 2010.

Legge et al. (2010) indicated that the transition contrast cue, diagnostic of Step Up, was

primarily responsible for good recognition of this target. But this transition contrast cue

appears to be less salient in the presence of the high-contrast texture edges (see Figure

2.9). The transition contrast cue is much more obvious with the uniform sidewalk than

with the checked sidewalk, particularly for severe blur.
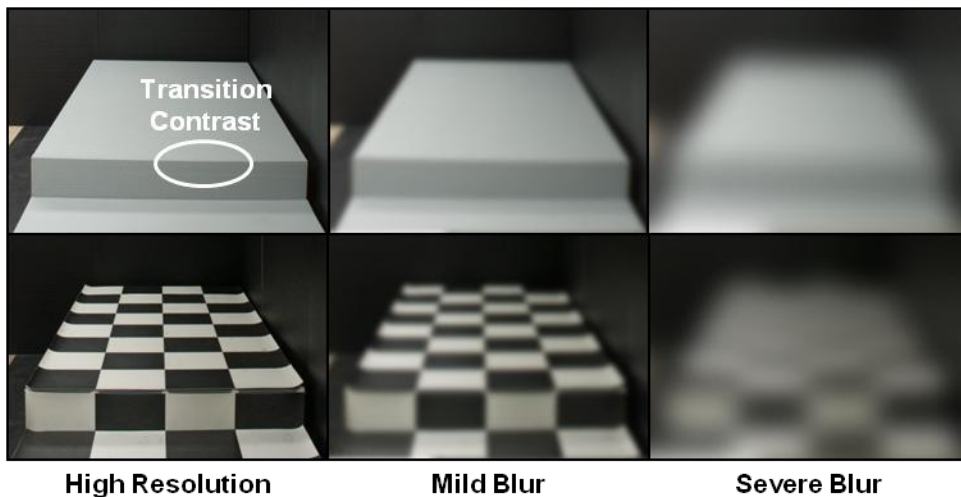
Figure 2.9. The Step Up target is shown in gray (top) and with the checked surface

texture (bottom) in a normal, high-resolution image (left) and with digital

approximations of the blur (mild, middle; severe, right).

The contour clutter produced by the horizontal and vertical contrast features of the texture pattern may reduce the salience or mask the subtle contours for the L-junction cue, which is diagnostic of Step Down (see Figure 2.10). The even more subtle bend-in and bend-out cues, for Ramp Down and Ramp Up, respectively, are also obscured with the textured sidewalk under conditions of severe blur. However, our results with a checkerboard pattern with strong orthogonal straight contours may represent a worst case scenario. Other coarse patterns, such as a diamond texture (contours rotated 45 degrees with respect to the step riser) or wide, black-and-white stripes might possibly produce better performance than the checkerboard texture. For example, stripes parallel to the bounding contour of the sidewalk would replicate the cues along this contour at the step or ramp transition possibly increasing target visibility.

High Resolution   **Mild Blur**   **Severe Blur**
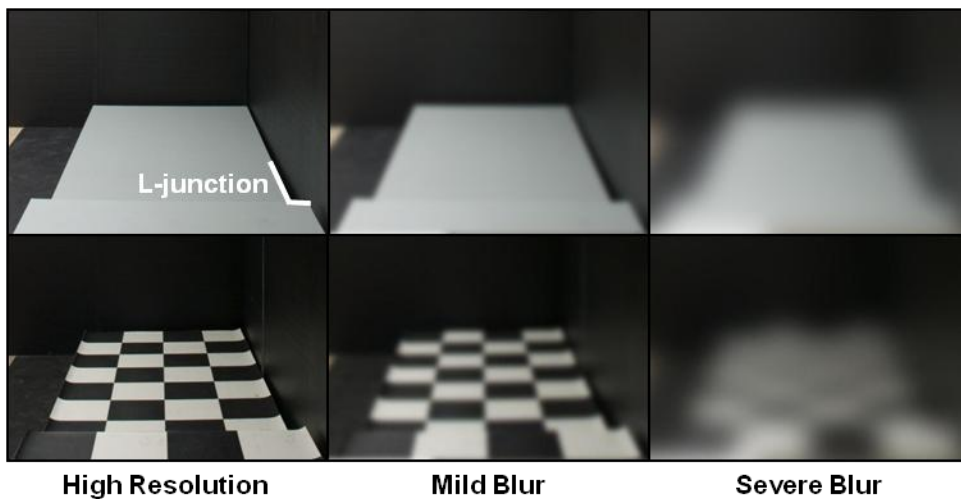
Figure 2.10. The Step Down target is shown with uniform surface (top) and textured surface (bottom), in high resolution (left) and with digital approximations of mild blur (middle); and severe blur (right). The masking of the L-junction by the texture contours

is more pronounced for the severe blur.

Why does locomotion enhance recognition of steps and ramps? Retinal-image motion could help in several ways. Motion parallax is known to improve depth discrimination in low vision and for normal vision under conditions of blur or low contrast (Jobling et al., 1997). In the present case, motion parallax might have facilitated detection of depth differences between the boundary contours for the sidewalk and target panel. But even in the stationary viewing condition, subjects were allowed to move their heads, so the parallax cue was potentially available in this condition as well.

A second possible cue is accretion and deletion of surface features as the viewpoint changes between a nearer surface and a more distant partially overlapping surface (Yonas, Craton, & Thompson, 1987). In our case, as the subject moved along the sidewalk toward the target, a little more of the lower surface came into view in the Step Down condition. This might explain the greater benefit of locomotion we observed for recognition of the step down. More generally, locomotion produces observations from a range of slightly different viewpoints. Perhaps the integration of the multiple views provides information not available from a single viewpoint.

A third possibility is that locomotion produces greater retinal image motion of informative image contours, enhancing their visibility. This might be especially significant for our severe blur condition because it is well known that contrast sensitivity

for patterns composed of low spatial frequencies is enhanced by abrupt temporal onsets or offsets (Legge, 1978).

The foregoing possibilities refer to enhancement of the visibility of cues by retinal-image motion. There is also evidence that the value of retinal-image motion in conveying 3D information about objects and surfaces is enhanced for active compared with passive observers, even when the visual input is identical (Wexler, Panerai, Lamouret, & Droulez, 2001). These authors propose that extra-visual movement-based information is incorporated into judgments of 3D structure.

While we expect the qualitative features of our results to generalize to people with reduced acuity associated with low vision, several caveats are in order.

First, the Bangerter blur foils reduce acuity and contrast sensitivity for normally sighted subjects, but are not necessarily representative of any particular form of low vision. For example, the contrast sensitivities through the blur foils associated with the two levels of acuity reduction (see Methods) are not well matched to the measured correlations of acuity and contrast sensitivity in low vision subjects (Kiser, Mladenovich, Eshraghi, Bourdeau, & Dagnelie, 2005). Our subjects differed from a typical group of low-vision subjects in other ways. Our subjects were young whereas most subjects with low vision are older. Our subjects had to deal with reduced acuity and contrast sensitivity whereas many people with low vision also experience visual-field loss. Our subjects undoubtedly

had much less experience functioning with low-resolution vision than a typical group of people with low vision.

Second, we studied monocular viewing to simplify the optical arrangements for our subjects, and to simplify potential extension of the findings to low vision. Many people with mild or severe low vision have unequal vision status (acuities and other visual characteristics) of the two eyes, with performance determined primarily by the better eye (e.g., Kabanarou & Rubin, 2006). In principle, stereopsis could be a useful binocular cue in recognizing ground plane irregularities. However, stereoacuity declines at low spatial frequencies and for unequal contrasts in the two eyes (Legge & Gu, 1989), which may imply weak or absent stereopsis in many cases of low vision.

Third, our subjects knew that one of the five targets was present in each trial, and where to look for it, but low-vision pedestrians navigating unfamiliar locations in the real world do not always know when and where obstacles will appear in their path. Such uncertainties pose challenges for mobility not present in our study.

We conclude that, contrary to our first hypothesis, a coarse texture pattern on the ground plane can hinder the visibility of ramps and steps under low-resolution viewing conditions. It is likely that contour associated with the texture pattern itself interferes with the visibility of pertinent cues for the ramps and steps. Consistent with our second hypothesis, we conclude that locomotion toward ramps and steps does enhance their

visibility. If our results generalize to people with low vision, our findings may prove

helpful in designing spaces to enhance visual accessibility. The findings may also be

helpful for rehabilitation specialists who can inform their low-vision clients about the

potential interfering effects of surface patterns or the advantages of locomotion in the

visual exploration of their surroundings.

Chapter 3. Recognition of Ramps and Steps by People with Low Vision

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Overview

Purpose: Detection and recognition of ramps and steps are important for the safe mobility of people with low vision. Our primary goal was to assess the impact of viewing conditions and environmental factors on the recognition of these targets by people with low vision. A secondary goal was to determine if results from our previous studies of normally sighted subjects, wearing acuity-reducing goggles, would generalize to low vision.

Methods: Sixteen subjects with heterogeneous forms of low vision participated—acuities from approximately 20/200 to 20/2000. They viewed a sidewalk interrupted by one of five targets: a single step up or down, a ramp up or down, or a flat continuation of the sidewalk. Subjects reported which of the five targets was shown, and percent correct was computed. The effects of viewing distance, target/background contrast, lighting arrangement and subject locomotion were investigated. Performance was compared with a group of normally sighted subjects who viewed the targets through acuity-reducing goggles.

Results: Recognition performance was significantly better at shorter distances and after locomotion (compared with purely stationary viewing). The effects of lighting arrangement and target/background contrast were weaker than hypothesized. Visibility of the targets varied, with the step up being more visible than the step down.

Conclusions: The empirical results provide insight into factors affecting the visibility of ramps and steps for people with low vision. The effects of distance, target type, and locomotion were qualitatively similar for low vision and normal vision with artificial acuity reduction. However, the effects of lighting arrangement and background contrast were only significant for subjects with normal vision.

Introduction

Low vision is any visual impairment not correctable with glasses or contacts that affects everyday functioning. As of 2004, there were about 3.3 million Americans over the age of 40 with impaired vision, with the number expected to increase to 5.7 million by 2020 (Eye Disease Prevalence Research Group). More than 90% of these individuals have functionally useful vision. Reduced mobility and associated social isolation and economic disadvantage are among the most debilitating consequences of low vision.

Visual impairment is a risk factor for both falls and fractures in the elderly (Lord, Sherrington, Menz, & Close, 2007; de Boer et al., 2004). Obstacles on the ground or discontinuities in the ground plane, such as steps, pose hazards for people with low vision. Most low-vision research on obstacle detection addresses the influence of three key measures of visual function— acuity, contrast sensitivity and visual-field status— on avoiding contact with obstacles while moving through a cluttered space. Typically, results have shown that acuity level is not very important for navigating through a cluttered space, while contrast sensitivity is somewhat important, and the total extent of the visual field is of major importance (Haymes, Guest, Heyes, & Johnston, 1996; Kuyk, Elliot, & Fuhr, 1998; Hassan, Lovie-Kitchin, & Woods, 2002). However, safety depends critically on the ability to reliably identify potential hazards from a distance, placing greater reliance on acuity (Ludt & Goodrich, 2002). An interesting example is the detection of crossable gaps in traffic at intersections (Geruschat, Fujiwara, & Wall Emerson, 2011; Hassan & Massof, 2012).

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Recognizing ground-plane irregularities, such as steps and ramps, is an important component of the visual accessibility of public spaces for people with low vision. Visual accessibility is the use of vision to travel efficiently and safely through an environment, to perceive the spatial layout of the environment, and to keep track of one's location and orientation. Many people with severe visual impairment deal effectively with obstacle avoidance using a white cane or guide dog. But the vast majority of people with milder forms of low vision rely on their residual vision. Orientation and mobility specialists have often noted the preference of people to rely on vision, sometimes to their detriment (Ludt & Goodrich, 2002).

Our previous work on subjects with normal vision wearing blur goggles to artificially reduce acuity has addressed the impact on visual accessibility of environmental factors likely to be important in real-world settings. These factors include target-background contrast and lighting arrangements, and also viewing conditions such as distance to target (Legge et al., 2010; Bochsler et al., 2012). A major aim of the present paper is to determine if these results generalize to people with low vision. A long-term goal of our research on visual accessibility is to provide a principled basis for guiding the design of safe environments for the mobility of people with low vision.

Legge and colleagues (2010) investigated the effects of lighting arrangement, target geometry, and target/background contrast on the recognition of ramps and steps by subjects with normal vision wearing blur goggles that reduced acuity to 20/135 (mild

blur) and 20/900 (severe blur). Subjects were tested in a windowless classroom (Figure 1) on five targets: a step up, a step down, a ramp up, and ramp down, and a flat continuation of the sidewalk. Stationary subjects made target-recognition decisions from viewing distances ranging from 5 to 20 ft. Among the results of this study, they showed that a step up was more visible with blurry vision than a step down. The effects of target-background contrast were greater than the effects of lighting arrangement. Performance was similar at 5 ft and 10 ft, but accuracy decreased at 20 ft.

In a subsequent study using similar methods, Bochsler et al. (2012) asked whether two additional visual factors— surface texture and self-locomotion— would enhance the recognition of ramps and steps under low-acuity viewing. Contrary to expectation, a coarse texture pattern on the ground plane detracted from performance. As hypothesized, locomotion towards a step or ramp improved recognition compared with stationary viewing.

In the present study, we address two questions. First, how do these same factors affect the recognition of ramps and steps by people with low vision? Second, do results obtained with normally sighted subjects with artificial acuity reduction generalize to low vision, thereby providing a useful surrogate for studying visual accessibility?

Methods

Participants

Sixteen subjects (Mean age = 49.19) with heterogeneous forms of low vision participated (see Table 3.1). All 16 participated in Exp. 1 and 2, but only 13 in Exp 3. Selection criteria included: i. subjects with moderate to severe low vision (logMAR acuity of approximately 1.0 or worse) to ensure that performance would not be at ceiling, and ii. subjects who we expected would be nimble enough to step up onto our elevated sidewalk (16 inch step) and undertake the walking in our locomotion experiment; this concern led us to limit the age range of subjects to those in their 60's or younger. We note that our subject sample, while not representative of the overall population of people with low vision, does have the roughly inverse linear relationship between logMAR acuity and log contrast sensitivity typical of other samples of low-vision research subjects (Kiser, Mladenovich, Eshraghi, Bordeau, & Dagnalie, 2005). Each subject completed the experiment in one session lasting from three to four hours, or two sessions of about two hours each. The experimenter obtained informed consent in accordance with procedures approved by the University of Minnesota's IRB.

The comparison group, from Legge et al. (2010), included 48 normally sighted young adults with a mean age of 22 years. See Table 3.2 in the Legge and colleagues manuscript for further details. These subjects wore blurring goggles, made from Bangerter occlusion foils, which reduced effective acuity to 20/135 (mild blur) or 20/900 (severe blur).

Subject	Gender	Age (yr)	Acuity (LogMAR Snellen)	Log Contrast Sensitivity	Field Loss	Diagnosis
A	m	50	1.28 20/ 381	0.75	None	Congenital cataracts
B	f	61	1.54 20/ 693	0.05	Per.	Optic neuritis, optic atrophy
C	m	42	1.46 20/ 577	0.4	Per.	Glaucoma
D*	f	34	1.04 20/ 219	0.8	None	Albinism
E	m	52	1.68 20/ 957	0**	Per.	Optic nerve atrophy
F*	m	58	1.1 20/ 252	1.65	Cent.	Stargardt Disease
G	f	60	1.54 20/ 693	0.15	Per.	Optic nerve atrophy
H*	f	32	1.2 20/ 317	0.5	Per.	Retinopathy of Prematurity
I	m	45	1.5 20/632	0.25	Per.	Retinopathy of Prematurity
J	m	63	2.18 20/ 3000	0**	None	Secondary corneal Scarring
K	f	19	1.7 20/ 1000	0**	Cent./ Per.	Corneal failure
L	m	39	1.86 20/ 1450	0.35	Per.	Glaucoma, Cataracts
M	f	66	1.44 20/ 551	0.15	Per.	Retinitis Pigmentosa
N	f	64	1.18 20/ 303	0.5	Cent.	Stargardt Disease
O	m	50	1.04 20/ 219	1	None	Sorsby disease
P	m	52	0.98 20/ 191	1.05	Cent.	Fuch's dystrophy
	Mean	**49.19**	**1.42 20/ 526**	**0.58**		

Table 3.1. Characteristics of 16 Visually Impaired Subjects.

* Subject participated in Experiments 1 and 2 only.

** At the testing distance of 1 m, these subjects were unable to read any letters on the

Pelli-Robson chart.
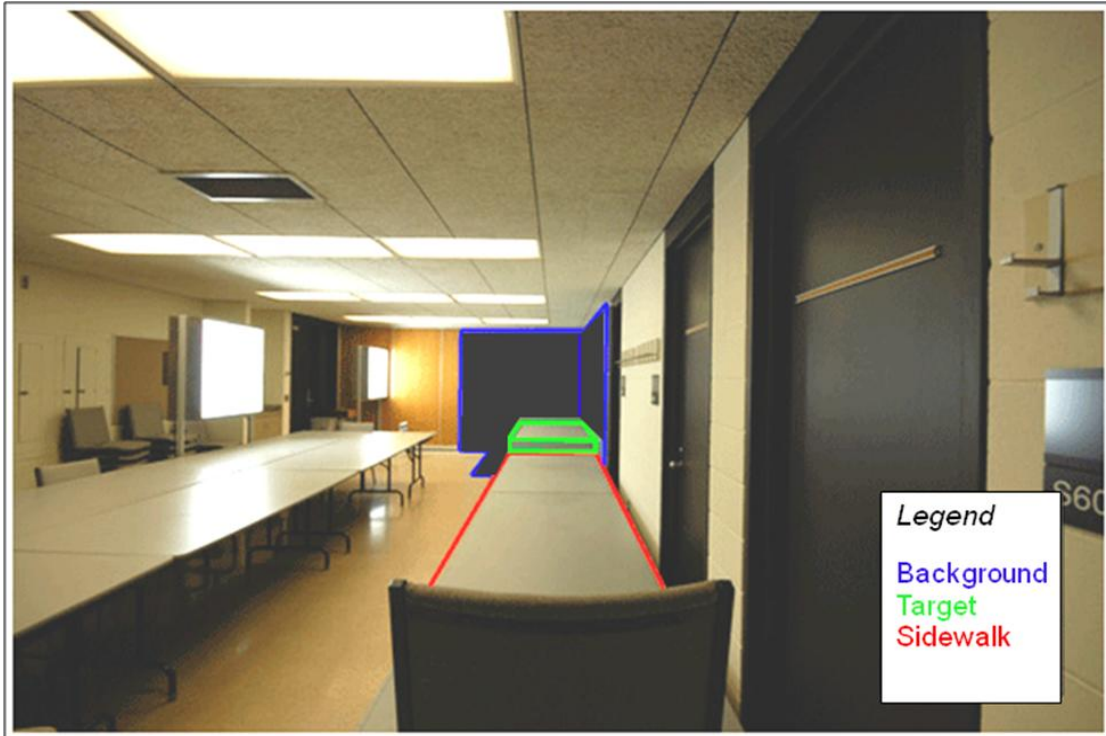
Figure 3.1. Photo of test space showing the black background, gray sidewalk, step up target and three lighting conditions. From Legge et al. (2010).

Stimuli

A large, windowless, 33.25 by 18.58 ft (10.13 by 5.66 m) basement classroom was used as the test space for all experiments (Figure 3.1). A uniform gray sidewalk (4 ft wide by 24.5 ft long; 1.3 m by 7.5 m) was constructed using hardboard deck portable stage risers. This sidewalk was elevated 16 inches (0.4 m) above the floor. Five possible targets were shown at a fixed location on the sidewalk's south end: a single step up or down (7 inch height), a ramp up or down (7 inch change of height over 8 ft), or flat (see Figure 3.2).

Step Up	Step Down	Ramp Up	Ramp Down	Flat
7 Inches Up	7 Inches Down	7-Inch Change in Height Over 8 feet		Continuation of Sidewalk

Figure 3.2. The five targets were step up, step down, ramp up, ramp down and a flat continuation of the sidewalk. From Legge et al. (2010).

A 4 by 8 ft by 2 in thick rectangular panel of expanded polystyrene (EPS), painted uniform gray, formed the target (see Figure 3.1). Using motorized scissor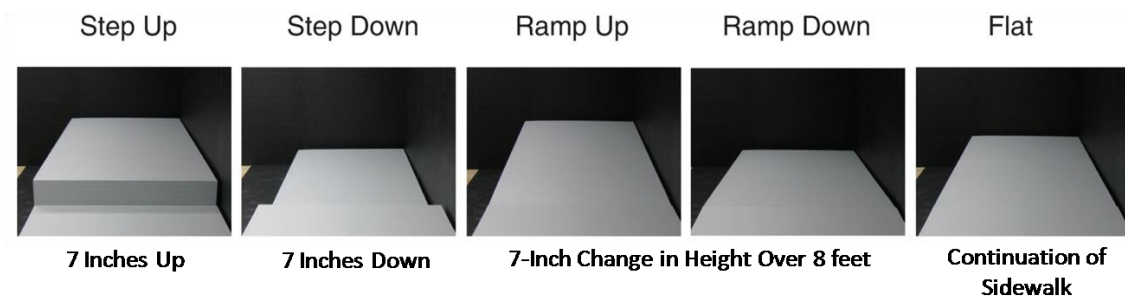 jacks, the target panel was adjusted by raising or lowering one or both ends of the panel above or below the sidewalk. The visual background for the targets was formed by the classroom floor, far wall, and right-hand wall. The walls were paneled with rectangular sections of EPS, and the section of floor on the left of the target was covered with a wooden panel (painted to match the background). Overhead lighting, representative of typical ambient room lighting, was produced by four rows of three 2 by 4 ft luminaries. For more information about the test space and apparatus, please see Legge et al. (2010).

Task and Procedure

Subjects participated in three experiments assessing the effects of target/background contrast and viewing distance (Experiment 1), lighting arrangement (Experiment 2), and locomotion (Experiment 3). Prior to testing, the subjects were familiarized with the targets; they inspected the targets close up and were encouraged to feel the contours of

the junction between target and sidewalk. During testing, subjects viewed the targets from three distances of 5 ft, 10 ft, and 20 ft.

During each trial, the subject reported which of the five targets was shown (5-alternative forced choice). Responses were used to calculate percent correct and to compose confusion matrices.

Subjects were instructed to turn their head to face the right-hand wall between trials, preventing them from viewing target setup. They were given a viewing time of 4 seconds. This time period was selected to provide subjects with sufficient time to turn to look at the target, but not excessive time for prolonged inspection. To mask auditory cues associated with changing the target configuration, subjects wore noise-reducing earmuffs and listened to auditory white noise.

In Experiment 1, subjects viewed the gray targets against a gray (contrast = 0.25) or black (contrast = 0.82) background with standard overhead room lighting. It was hypothesized that subjects would have better recognition performance in the higher-contrast condition. For each of the contrast conditions, subjects viewed the targets from three distances (5 ft, 10 ft, & 20 ft), completing four trials per target (5 targets) for a total of 60 trials. Trials were blocked by viewing distance. Based on the results of Legge et al. (2010), we hypothesized that the low vision subjects in the present study would perform better at the shorter distances of 5 and 10 feet than at 20 feet and better with the high-contrast black

background than the lower-contrast gray background.

In Experiment 2, there were two different lighting arrangements (Figure 1). A light box simulated a window to the near left (Near Window) or far left (Far Window) of the subject. Subjects completed 40 trials (2 windows x 5 targets x 4 trials per target) at a distance of 10 feet. Within each window lighting condition (near and far), the trials for the different targets were randomized. Performance for the two window lighting conditions was compared with the corresponding data for overhead lighting in Exp. 1. Legge et al. (2010) found that subjects with artificial acuity reduction performed better in the Far-Window condition, probably because this window condition enhanced contrast that highlighted the borders of the target panel. Accordingly, we hypothesized that low vision subjects in the present study would perform better with Far Window than Near Window lighting.

In Experiment 3, recognition performance for a stationary condition and a walking condition were compared. In the stationary condition, subjects made their recognition decisions while standing 10 feet from the target. In the walking condition, subjects started at 20 feet. They walked toward the targets along the sidewalk, stopping at the designated viewing distance of 10 feet to make their recognition decisions. Weight-bearing railings were added to both sides of the sidewalk to enhance safety and to guide the subjects. The goal of this experiment was to determine if locomotion facilitated the recognition of ramps and steps. Walking and stationary trials were randomly interleaved,

with four trials per target in each condition, for a total of 40 trials. Bochsler et al. (2012) used the same paradigm to measure the influence of locomotion on the performance of normal subjects with acuity-reducing goggles. They addressed the difference in time per trial for walking and stationary trials and concluded that it was unlikely to influence the results.

Results

Experiment 1: Effects of Visual Acuity, Background Contrast, and Target Type.

Figure 3.3 shows the overall recognition accuracy for the sixteen low-vision subjects in Exp. 1. The values are based on data combined across distance and background conditions and are plotted as a function of acuity. The individual letter symbols correspond to the subject designators in Table 3.1. For comparison, mean performance levels for normally sighted subjects wearing acuity-reducing goggles for the same conditions are replotted as blue symbols (from Legge et al., 2010). As expected, low-vision performance tended to decrease with lower acuity (larger logMAR values). Most of the low-vision data points lie above the line depicting the performance of the goggle-wearing normal subjects. A T-test on the difference scores between the Low Vision points (red) and the Blur Goggles line showed that low-vision subjects significantly outperformed estimated levels of the normally sighted goggle wearers, $p < .05$. Subjects "j" and "n" are exceptions to the general finding that low-vision subjects outperform the subjects with normal vision. J's acuity lies outside the range of the goggle measurements. After "j" and "n" are removed from the analysis, low vision observers significantly

outperform subjects with normal vision wearing goggles by an even greater margin.
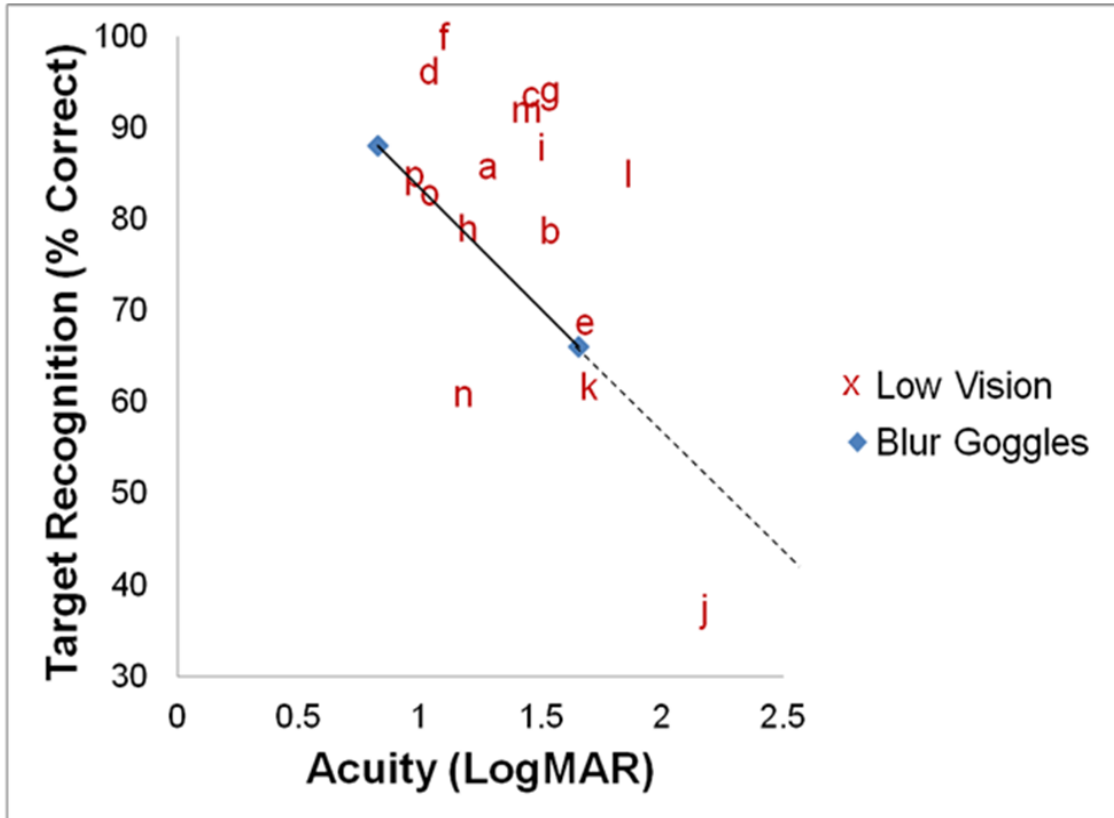
Figure 3.3. Relationship between acuity and target recognition performance. Low-vision data are compared with data from normally sighted subjects wearing acuity-reducing goggles. Letter symbols for the low-vision subjects correspond to the entries in Table 3.1. The dashed line represents extrapolation of the straight-line fit to the data for the normally sighted subjects.

We conducted a repeated-measures analysis of variance (ANOVA) on the arcsine-transformed accuracy data, with three within-subjects factors—viewing distance (5, 10, or 20 ft), target type (Step Up, Step Down, Ramp Up, Ramp Down, and Flat), and

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target/background contrast (low or high). The analysis revealed significant main effects of viewing distance, F (1, 15) = 8.36, p < .01; and target type F (1, 15) = 19.96, p < .0001, but not target/background contrast. There was no interaction between viewing distance and target type. T-tests, with a Bonferroni correction for multiple comparisons, were used in post-hoc testing.

Figure 3.4 shows that both low vision subjects and those with normal vision wearing blur goggles performed better at the shorter distances (5 & 10 ft) than the longest distance (20 ft), p < .01. Both normal and low vision subjects showed no significant difference in performance between 5 ft and 10 ft.
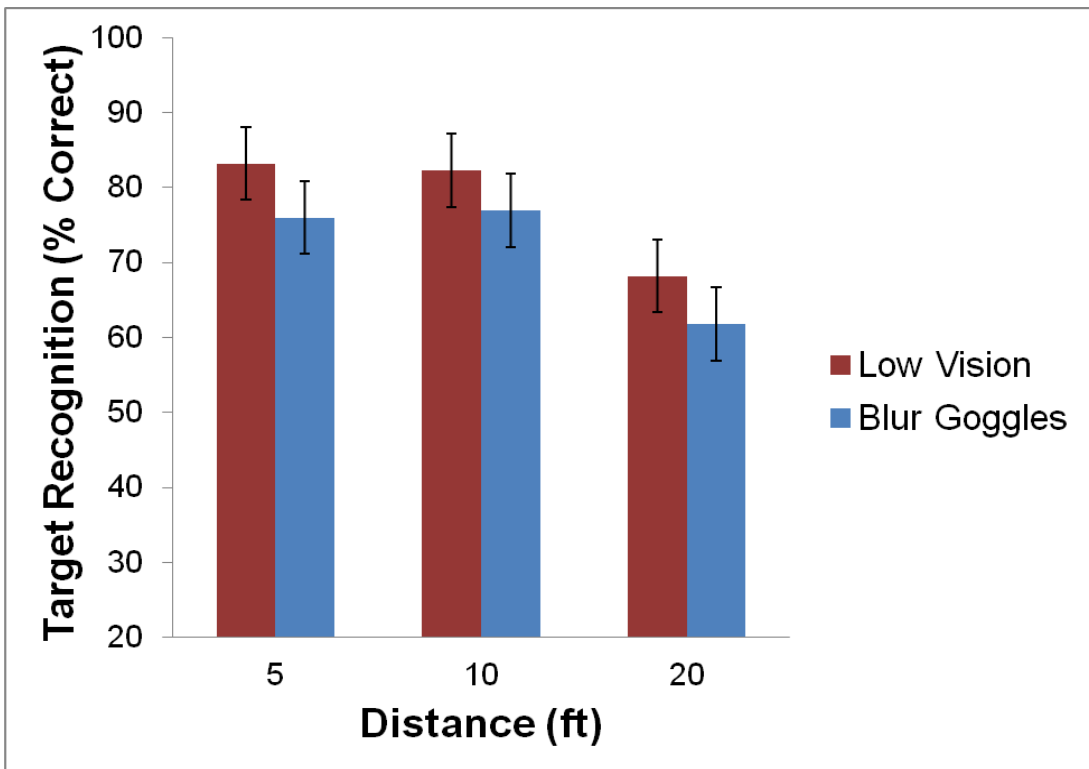
Figure 3.4. Mean performance at three distances (5, 10, & 20 ft). Low-vision data are compared with data from normally sighted subjects wearing acuity-reducing goggles (combined across blur conditions). Goggle data are replotted from Legge et al. (2010). Error bars represent ± 1 S.E.

Figure 3.5 shows confusion matrices for subjects with normal vision wearing blur goggles (top matrix) and for the low vision subjects in this study (bottom matrix). The pattern of results is similar in the two matrices. The diagonals of the matrices, shown in bold, represent correct responses. The order of target performance, from best to worst, was the same for the low vision group and those wearing the blur goggles: Step Up, Step Down, Ramp Up, Flat, and Ramp Down (Pearson correlation of 0.88 for the on-diagonal elements). A Step Up was more recognizable than a step down for both groups (p < .01),

perhaps because of the high contrast between the top of the step and the riser. See Table 1

in Legge et al. (2010) for detailed contrast measurements on all five targets.

A. Normal Vision Wearing Goggles		Subject Response (%)				
		Step Up	Step Dn	Ramp Up	Ramp Dn	Flat
	Step Up	**89.9**	1.3	5.4	0.8	2.6
	Step Dn	1.2	**67.6**	3.7	14.4	13.2
Target	Ramp Up	1.9	2.7	**68.8**	4.1	22.7
Presented	Ramp Dn	1.6	8.7	3.9	**63.2**	22.6
(%)	Flat	2.4	5	14.2	9.7	**68.5**
B. Low Vision		Subject Response (%)				
		Step Up	Step Dn	Ramp Up	Ramp Dn	Flat
	Step Up	95.3	0.6	2.0	0.3	2.2
	Step Dn	0.7	**86.4**	2.3	8.2	2.4
Target	Ramp Up	2.9	0.9	**79.3**	2.6	13.8
Presented	Ramp Dn	0.3	6.1	3.1	**72.9**	17.6
(%)	Flat	1.1	3.5	6.8	12.3	**76.7**

Figure 3.5. Confusion matrices showing the percentage of responses for each of the five target types. Diagonal values represent correct recognition performance and off-diagonal values represent confusions. A. Values for subjects with normal vision wearing blur goggles (Table 3 from Legge et al., 2010) and are based on 18 trials per target across 48 subjects (864 trials per target). B. Values for the low vision subjects in this study, based on 14 trials per target across 16 subjects (224 trials per target).

Similarities exist between the off-diagonal cells of the matrices as well. For both low vision (LV) and goggle-wearing normal vision (NV) groups, the highest-percentage off-

diagonal cells occurred when the subject viewed the Ramp Down target and confused it

for Flat (NV = 22.6%, LV = 17.6%), or viewed the Ramp Up target and confused it for

Flat (NV = 22.7%, LV = 13.8%). The most evident departure in the pattern of responses

between normal and low vision occurred for the step down target; normally sighted

subjects often responded with Flat when presented with Step Down (13.2%), while

subjects with low vision only did so rarely (2.4%).

Experiment 2: Effect of Lighting Arrangement.

We conducted a repeated-measures analysis of variance (ANOVA) on the arcsine

transformed accuracy data, with lighting condition (Overhead, Near Window, or Far

Window) as the within-subjects factor. Like the subjects with normal vision wearing blur

goggles, subjects with low vision performed better with far window lighting than with

overhead or near window lighting (Figure 3.6). However, this difference was only

significant for the subjects with normal vision wearing blur goggles ($p < .05$).
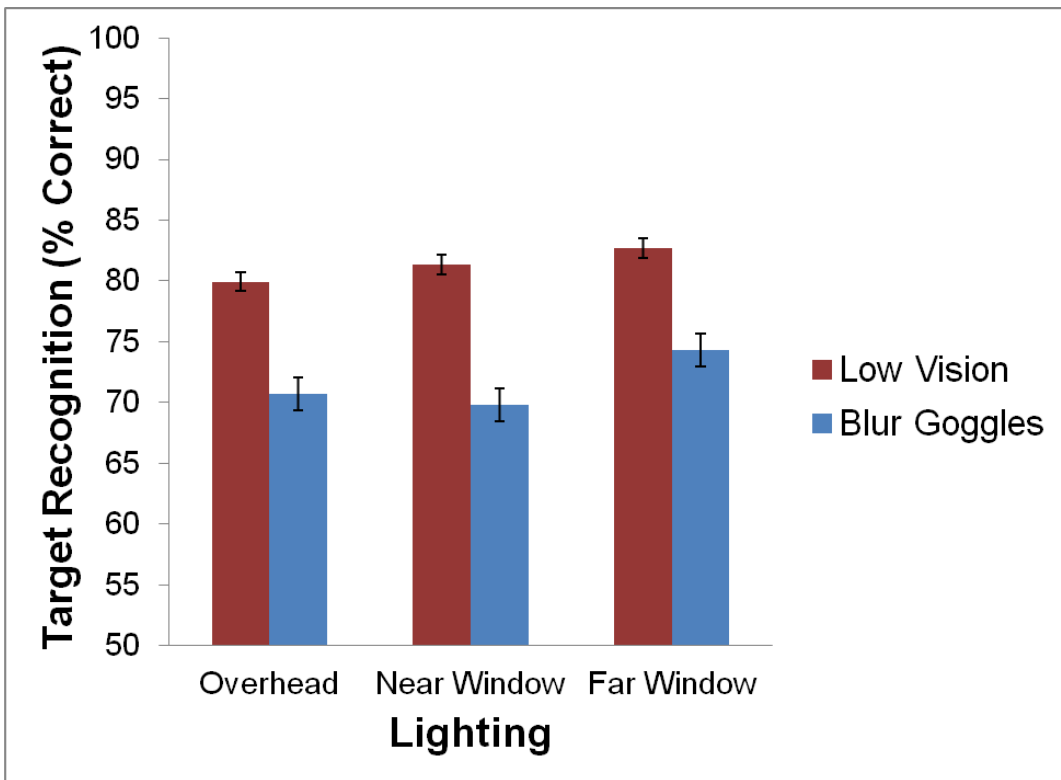
Figure 3.6. Performance for the three lighting arrangements (Overhead, Near Window and Far Window). Low-vision data are compared with data from normally sighted subjects wearing acuity-reducing goggles (combined across blur conditions). Goggle data are replotted from Legge et al. (2010). Error bars represent ± 1 S.E.

Experiment 3: Effect of Locomotion.

A paired samples T-test comparing performance in Walking and Stationary conditions showed that low vision subjects recognized ramps and steps significantly more accurately in locomotion trials (81% correct) than in stationary trials (68% correct), $p < .01$ (Figure 3.7). Similarly, goggle-wearing subjects with normal vision performed better after walking (74%) than in the stationary condition (52%; Bochsler et al., 2012).
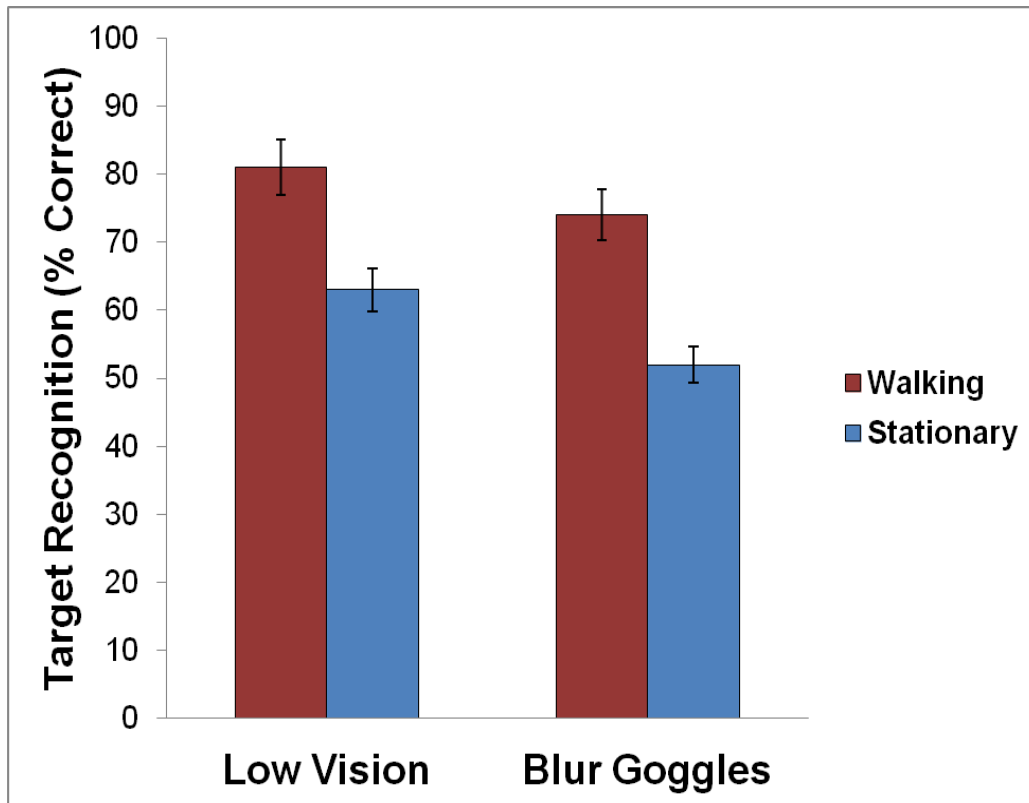
Figure 3.7. Performance in Walking and Stationary trials. Subjects with low vision are compared to those with normal vision wearing blur goggles in Bochsler et al. (2012). Error bars represent ± 1 S.E.

The order of target performance from best to worst was similar for the stationary and walking conditions (Figure 3.8). In both conditions, low-vision and normally sighted subjects performed best on the same three targets, in the following order: Step Up, Step Down, and Ramp Up. In the description of results for Exp. 1 above, we pointed out that the difference in visibility for the five targets showed this same ordering for the low-vision subjects and the goggle-wearing normal subjects (diagonals of Figure 3.5, A & B).
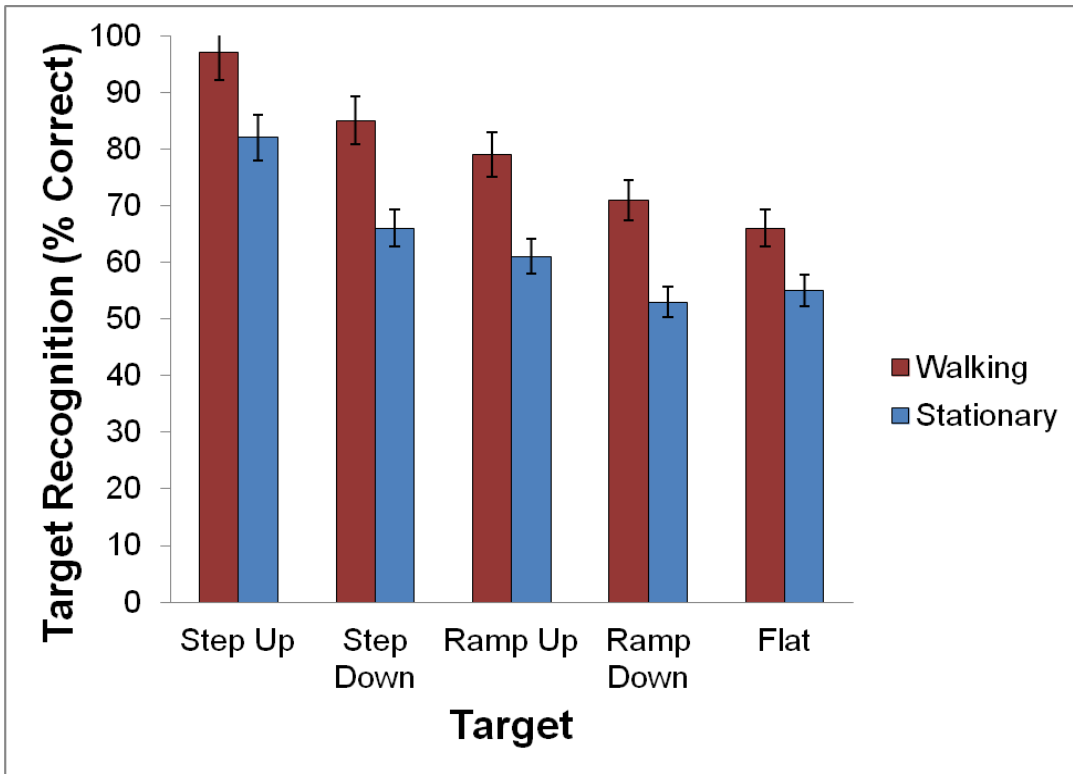
Figure 3.8. Target performance in walking trials compared to stationary trials. Error bars represent ± 1 S.E.

In summary, locomotion and viewing distance strongly influence performance, while background contrast and lighting arrangement have weaker effects. Subjects with low vision outperformed subjects with normal vision wearing blur goggles.

Discussion and Conclusions

In this study, low-vision subjects outperformed normally sighted subjects who wore acuity-reducing goggles. People with low-vision may recognize objects better because they have more experience functioning visually under low-resolution conditions. But we cannot exclude the possibility that the poorer performance of the normal subjects is

related to the optical properties of the goggles.

Experiment 1 revealed that performance declined with increasing viewing distance and acuity, as hypothesized. In Legge et al. (2010), we pointed out that some of the cues useful for recognizing ramps and steps (such as the L-junction in the edge contour of Step Down) are likely to place demands on acuity, and would exhibit the dependencies on distance and acuity we observed. See Legge and colleagues (2010) for a more detailed description of cues.

Surprisingly, target/background contrast did not significantly influence the performance of these low-vision subjects. Although some of the subjects had very low contrast sensitivity (Table 3.1), most of them may have had sufficient contrast sensitivity to detect the targets, even in the low-contrast condition. Another study from our lab, Kallie, Legge, & Yu (2013) tested recognition performance with blurry vision for other high visibility targets (cylinders and boxes). Consistent with the present study, the higher-contrast target under most conditions (cylinder) was more salient with low-acuity vision than the lower contrast target (box).

The effect of lighting arrangement was weaker than expected. Experiment 2 showed that subjects with low vision performed best with Far Window lighting, but this effect was only significant for normally sighted subjects wearing blur goggles. Perhaps this null result is due to the narrow range of lighting conditions tested here, compared to the wide

variety present in the real world. Consistent with the present study, Kallie et al. (2013) found no effect of lighting arrangement on convex object detection.

In Experiment 3, we learned that locomotion through an environment may enhance the visibility of obstacles for people with low vision. In particular, walking provided a strong advantage for Step Down, the most dangerous target to miss! Eighty-five percent of low vision subjects successfully identified step down after walking, while only 66% did so with stationary viewing.

Why does locomotion enhance recognition of steps and ramps for people with low vision? Three possible cues from motion include motion parallax, accretion and deletion of surface features, and enhanced retinal image motion. Motion parallax is known to improve depth discrimination in low vision and for normal vision under conditions of blur or low contrast (Jobling, Mansfield, Legge, & Menge, 1997). Accretion and deletion of surface features as the viewpoint changes between a nearer surface and a more distant partially overlapping surface may also provide useful information (Yonas, Craton, & Thompson, 1987). Locomotion may produce greater retinal image motion of informative image contours, enhancing their visibility. This might be especially significant for people with very low acuity because it is well known that contrast sensitivity for patterns composed of low spatial frequencies is enhanced by abrupt temporal onsets or offsets (Legge, 1978). See Bochsler et al. (2012) for a more detailed description of motion cues. The qualitative effects of viewing distance, target type and locomotion were similar for

the low vision subjects and subjects with normal vision wearing blur goggles. Although low-vision subjects did not exhibit the significant effects of target/background contrast and lighting arrangement found with the normally sighted subjects, these effects were relatively weak for both groups. Together, these findings suggest that subjects with normal vision wearing blur goggles can provide a convenient test bed for studying visual accessibility. However, caution should be exercised in generalizing results from goggle-wearers to low vision, and ideally, goggle studies should be replicated with low vision subjects.

While we expect the qualitative features of our results to generalize beyond our specific sample of subjects and testing conditions, we mention two caveats. First, our sample of low-vision subjects was unrepresentative in focusing on moderate and severe low vision, and on subjects in their 60's or younger. A broader sampling of low-vision subjects might conceivably yield some differences in performance. Second, our subjects knew that one of the five targets was present in each trial, and where to look for it. In a more natural context, low-vision pedestrians traveling in unfamiliar locations do not necessarily know when and where obstacles will appear in their path. Such uncertainties pose challenges for mobility not present in our study.

Even so, these results provide evidence that people with low vision may perform better on obstacle recognition tasks when actively walking through an environment, rather than passively viewing obstacles from a sitting or standing position. Researchers in visual

accessibility may want to design active tasks for low vision subjects for the most ecologically relevant results. We suspect that orientation and mobility instructors who work with low-vision clients already incorporate visual-cue selection during active mobility into their training protocols.

Chapter 4. Indoor Spatial Updating with Reduced Auditory and Visual Information

Overview

Purpose: Spatial updating refers to the ability to keep track of one's position and orientation in an environment. How are people with impaired vision hindered in spatial updating? Does visual (and auditory) perception of the size and shape of an indoor space facilitate spatial updating?

Methods: To begin addressing these issues, we tested 32 normally sighted young adults in several sensory deprivation conditions— artificially reduced acuity (mild blur: 20/135, or severe blur: 20/900), severely restricted field of view (dia = 8 degrees), and blindfolded with or without access to environmental auditory cues. Most people with low vision have reduced acuity, and many have a restricted visual field. Severe field loss is thought to have a major impact on mobility. People with impaired vision may often rely on acoustic cues, so it is valuable to understand if these cues are useful for spatial updating. Subjects were guided by an experimenter along three-segment paths in seven rectangular enclosed indoor spaces. Turning angles were ± 30, 45, or 60 degrees and the lengths of the path segments ranged from 3 to 9 ft. Each path began at the entry to the space and the subject was instructed to drop a place marker (bean bag) at the end of the first route segment. At the end of the route, subjects estimated the length and width of the space, and the distances and directions to the entry point and place marker.

Results: Nature of the visual deprivation (but not access to auditory cues) affected performance on estimating space dimensions and the distances to the entry and place marker. Subjects performed significantly better with both mild and severe blur than in the blindfolded and field restriction conditions. But vision status did not affect direction estimates of the entry and place marker, subjects' had mean absolute errors in direction close to 20 degrees, regardless of the sensory condition.

Conclusions: These results suggest that visual perception of room context (size and shape) plays a role in distance judgments, but not direction judgments. Artificial acuity reduction had little impact on spatial updating but severe field restriction produced errors in distance judgments equivalent to those made by blindfolded subjects, raising the possibility that people with very narrow fields may have as much trouble making distance estimates as people who are blind.

Introduction

The ability to navigate to a desired destination depends on spatial updating, the ability to keep track of one's position and orientation while moving through an environment (Klatzky, Loomis, Beall, Chance, & Golledge, 1998). During free movement in a space, humans and non-human primates can account for the distance and direction of self-movement (Klier & Angelaki, 2008). Studies have shown that people are able to update direction and distance to multiple reference points in the environment at once (Loomis, Klatsky, & Giudice, 2013)!

Research on mammalian spatial behavior has uncovered three characteristics of spatial updating: it is egocentric, dynamic, and limited to a small subset of the information available in the environment (Wang & Spelke, 2002). Although one can update multiple locations in an environment at once (Loomis et al., 2013), this key set of locations is still a tiny fraction of those present in one's environment. Using an egocentric reference frame means representing locations in the environment in relation to oneself as a reference point. On the other hand, in an allocentric reference frame, locations are represented with respect to one-another, regardless of one's location. Spatial updating can be characterized as dynamic because sensory input changes from moment to moment as one moves through a space. Furthermore, the perceptual and cognitive representation of one's location changes along with the sensory input. Even so, Horn and Loomis (2004) showed that spatial updating of targets located behind a subject can be accomplished almost as well as updating of targets in front.

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There are two distinct, but interrelated, methods for spatial updating, termed path integration and piloting (Loomis et al., 1993). The difference between these two methods is the source of the information used in updating. Piloting depends on external visual or auditory landmarks (environmental context) for spatial updating. In contrast, path integration depends on proprioceptive, vestibular, and optic/ acoustic flow information about self-motion to do updating. Unlike piloting, path integration does not rely on environmental context information. In the present study, we asked subjects to make distance and direction judgments in indoor spaces. If subjects used piloting to accomplish these tasks, we anticipated that restricting visual input would make judgments less accurate. However, if they used only path integration, visual restriction would not affect performance.

Spatial updating is multimodal, utilizing incoming sensory (vision, hearing, touch), proprioceptive and vestibular signals, and contributions from areas of the brain responsible for language and long-term memory (Loomis et al., 2013). Loomis, Lippa, Klattzky, and Golledge (2002) showed that when the precision of sensory encoding is equated, the modality of the input does not impact spatial updating performance. To specify target locations, they presented blind and blindfolded sighted subjects with either a sound from a loudspeaker or spatial language (e.g., "2 o'clock, 16 ft"). Updating performance was almost the same for the two modalities, indicating that spatial updating is multimodal. Tcheang, Bulthoff, and Burgess (2011) came to the same conclusion after studying path integration in darkness.

What perceptual and neural mechanisms play a role in spatial updating? Studies on rats suggest that spatial updating is maintained by locations in the receptive field that shift when the direction that the animal is pointing changes (O'Keefe & Dostrovsky, 1971). In rats, a special type of hippocampal cell called "place cells" becomes active when the animal is located in a specific area, called the "place field". "Grid cells", another cell type in the entorhinal cortex involved with spatial cognition, fire when the rat is in multiple locations in a grid-like pattern (Barry, Ginzberg, O'Keefe, & Burgess, 2012). Place cells probably combine signals from grid cells (and other cell types), but it is still unclear how this occurs (Zhang et al., 2013). In monkeys, parietal cortex neurons participate in the updating of visual information (Duhamel et al., 1992a). Functional MRI data from human subjects also demonstrate that spatial updating occurs in the parietal cortex (Merriam, Genovese, & Colby, 2003).

Vision is the dominant sense in humans, and when visual information is available, it plays an important role in spatial updating. One research group compared spatial updating in differently-shaped virtual-reality environments: trapezoidal, rectangular, square, and circular (Kelly, McNamara, Bodenheimer, Carr, & Reiser, 2008). A circle of 12 posts was located in the center of each environment. Subjects were tasked with remembering the location of a target post while walking to a sequence of other posts. Subjects performed equally well in trapezoidal, rectangular and square rooms, but performed worse in a circular room. The authors posited that the better performance in angular environments was due to the subject's ability to remember room shape (and use it

to locate a post of interest).

Information from muscles and joints (proprioception) and the vestibular system during movement is also important for spatial updating and may even take precedence over vision under certain conditions (Campos et al., 2010). Chance, Gaunet, Beall, & Loomis (1998) investigated the role of vestibular and proprioceptive inputs in path integration. Subjects travelled through virtual mazes using "Walk mode", where they walked through the experimental room, or "Visual Turn mode", where they used a joystick to make turns. At the end of a maze, subjects reported the directions to target objects encountered in the maze. Performance in the Walk mode was significantly better than in the visual turn mode, suggesting that vestibular and proprioceptive information contributes to direction estimates in spatial updating.

In one study, the respective roles of optic flow and vestibular/proprioceptive information were explored in a path integration task (Kearns, Warren, Duchon, & Tarr, 2002). Subjects were tested on a triangle completion task in a virtual environment, using a joystick to make turns (Experiments 1 and 2), or walked through a real environment (Experiment 3). Subjects successfully performed path integration with optic flow information alone, but when vestibular/proprioceptive information was available, it appeared to dominate.

Vestibular and proprioceptive information is especially critical for blind and low-vision

pedestrians, who navigate with little or no visual input. Walking without vision produces more accurate performance on indicating a target object's direction than imagined walking, providing evidence that proprioceptive information gleaned from walking is useful for spatial updating (Reiser, Guth, & Hill, 1986). A number of studies have demonstrated that spatial updating can still occur during locomotion without vision (e.g., Loomis, Fujita, Da Silva, & Fukusima, 1992). When the performance of blindfolded sighted, adventitiously blind and congenitally blind subjects was compared on spatial updating tasks, there were only slight differences between the groups, and these differences varied with the task (Loomis et al., 1993). Like sighted subjects, subjects who have been blind since the first year of life can update locations specified by 3-D sound or by spatial language (Loomis et al., 2002). These results indicate that spatial updating ability does not depend strongly on prior visual experience. In contrast, Rieser, Hill, Talor, Bradfield, and Rosen (1992) compared spatial structure judgments by people with a wide variety of visual capabilities. They tested people who were blind from birth, those who lost broad-field vision in childhood, those with early or late acuity loss, and those with late field loss. People who had been blind from birth, or lost broad-field vision in childhood performed less accurately than people in the other categories, suggesting that broad-field visual experience enhanced the accuracy of judgments of distance and direction.

Blind spatial updating typically occurs automatically during locomotion (Ferrell & Thomson, 1998). Spatial updating during blind walking is not pre-planned beforehand,

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while vision is still available. Instead, it seems to happen automatically via online position updates. However, automatic updating can be overridden by deliberate cognitive processing. Blindfolded subjects walked to one of four previously viewed targets via a second location. Subjects in the "updating" condition were asked to walk to the real position of the target, while those in the "ignoring" condition were asked to imagine that they were still at the starting point and walk from there to the target. In the ignoring condition, they were still able to accurately walk to a previously seen target if they were given sufficient time to respond.

Although spatial updating without vision has been extensively studied, different types of visual and auditory restriction have not been compared in the same study. In the present study, we limited the visual and auditory information available to subjects during a spatial updating task in seven different ways. Furthermore, we investigated whether information about the environmental context (such as size and shape of a space) enhances the accuracy of spatial updating. Real-world indoor spaces (such as a grocery store, office building, or restaurant) are typically rectangular, but the dimensions vary widely. Accordingly, we used rectangular spaces with a variety of sizes and aspect ratios. The boundaries of the space may act as a context, enhancing spatial updating by helping subjects to estimate distances and directions within the space. If visual context is helpful in spatial updating, then we anticipate that visual deprivation will reduce the accuracy of spatial updating.

The current investigation is part of a multi-disciplinary project— called Designing Visually Accessible Spaces— focused on understanding and enhancing visual accessibility for people with impaired vision. Visual accessibility is the use of vision to travel efficiently and safely through an environment, to perceive the spatial layout of key features in the environment, and to keep track of one's location in the environment. In previous psychophysical work on this project, we focused on factors affecting the visibility of local features present in indoor spaces, such as steps, ramps, columns, and box-shaped objects (Legge, Yu, Kallie, Bochsler, & Gage, 2010; Bochsler, Legge, Kallie, & Gage, 2012; Bochsler, Legge, Gage, & Kallie, 2013). These studies involved both normally sighted subjects with artificial acuity reduction and low vision subjects. We investigated the effects of acuity, viewing distance, lighting arrangement and target contrast on the visibility of these objects.

In the current study, we have focused on global features of a real, indoor space. We asked how different forms of visual impairment affect spatial updating, and what role non-visual cues may play. To study the impact of visual impairment, normally sighted subjects wore goggles to simulate reduced acuity and severe field restriction. We reduced acoustic information in the environment by auditory noise masking. Our interest in low vision leads us to consider the implications of our results for spatial updating by people with impaired vision.

Methods

Participants

Thirty-two normally sighted students at the University of Minnesota, Twin Cities

participated. Mean acuity on the Lighthouse Distance Acuity chart was 20/15.9 (logMAR

= -0.10) and mean contrast sensitivity (Pelli-Robson chart) was 1.98. Each subject

completed the experiment in one session lasting one to two hours. The experimenter

obtained informed consent in accordance with procedures approved by the University of

Minnesota's IRB.

Stimuli

Subjects participated in seven different visual and auditory conditions. (A detailed

description of each condition follows.) Three conditions— the Field Restriction and

reduced acuity conditions (Mild & Severe Blur)— were monocular, with the other eye

occluded. Noise-reducing earmuffs with earphones playing auditory white noise were

worn to mask acoustic cues, except in the Preview and No Visual/Auditory Input

conditions. The volume was kept loud enough to mask most environmental noise, without

causing discomfort.

The first condition was Normal Vision— Facing Forward. Subjects used their normal,

binocular vision, including any habitual corrections (glasses or contacts). They were not

permitted to look back at the entry point or "target" location. This forced them to use

spatial updating information gathered along the path, rather than just making a visual

point-to-point estimate at the end of the path. The experimenter monitored the subjects' gaze direction.

The second was Mild Blur. In this condition, acuity through the monocular, blurring goggles averaged 20/135 on the Lighthouse Distance Acuity Chart. One Bangerter Occlusion Foil (Odell, Leske, Hatt, Adams, & Holmes, 2008) was attached to one side of a clear acrylic lens and mounted in a welding goggle frame. This acuity level was selected to represent mild visual impairment.

In the third condition, Severe Blur, two Bangerter foils were used on either side of an acrylic lens in the same pair of goggles to blur vision to approximately 20/900. This acuity level was selected to represent severe visual impairment.

In the fourth condition, Severe Field Restriction, the subject's visual field was restricted to 8° using a cone mounted on a second pair of goggles. Previous studies have shown that limited field of view influences mobility in people with low vision who are walking (Black, Lovie-Kitchin, Woods, Arnold, Byrnes, & Murrish, 1997; Kuyk, Elliot, & Fuhr, 1998) or driving (Wood & Troutbeck, 1992). The field size of 8 degrees was chosen because it is small enough to affect navigation, but large enough to permit access to some visual input.

The fifth "Preview" condition was without vision (blind) but with prior knowledge of the

space plus acoustic cues. In blind walking studies, normally sighted subjects often view a target and then estimate the distance to the target by walking the distance blindfolded (e.g., Loomis et al., 1992). Subjects can accomplish this task fairly accurately, perhaps because the preview gives them an opportunity to create a spatial representation ("spatial image") of the space. However, this situation has not been compared to "no preview" blindfolded performance in the normally sighted. We anticipated that the spatial image generated during the preview would boost performance above non-visual performance. The experimenter provided the preview by allowing the subject to view the space binocularly from the entrance for ten seconds. The subject was not permitted to walk around in the space during the preview.

In the sixth condition, Auditory Only, subjects had access to solely auditory information (no vision). The test spaces were generally quiet. Sounds that were typically present included the experimenter and subject's footfalls, the voices of the experimenter and subject (after completing the route), the building ventilator, and occasional footfalls and/or voices in the hallway outside the space.

Subjects had No Visual or Auditory Input in the seventh condition. They wore a blindfold to eliminate visual input and earmuffs with earphones playing masking white noise to minimize auditory input.

For practical reasons, we used monocular blur and field reduction goggles, but binocular

normal vision and blindfold. This is because it would have been difficult to match the foil orientations on two Bangerter filters. Also, it is difficult to simulate a narrow visual field binocularly due to the problem of binocular overlap. Since many people with low vision have one better eye, or only one useful eye, we felt that monocular goggles were a reasonable compromise. However, it is possible that our results do not generalize to some varieties of visual impairment.

The experiment took place in seven different rectangular spaces in one building on the University of Minnesota, Twin Cities campus. Six were rooms and the seventh was a hallway. To represent the size-variation of spaces in a typical office building, we chose spaces with a substantial range of sizes and rectangular aspect ratios (including offices, classrooms, and corridors). Room sizes and dimensions are listed in Table 4.2. The spaces were a mix of classroom, meeting, and office space, and they contained typical furniture (see photos in Fig. 4.2). The most frequently encountered items were chairs, tables, bookshelves, and windows. All the spaces had overhead fluorescent lights. Three rooms had carpeted floors; the other four had light-colored linoleum flooring.

A customized walking path was devised for each space. Since we wanted to use a consistent set of path specifications, some of the paths that fit in larger spaces would not fit in the smaller spaces. Some of the spaces contained large obstacles, such as couches and bookshelves, so paths needed to be designed to avoid them. It is possible that some combination of room and route may have influenced performance. We tried to design the

routes so that both short- and medium-length routes were in smaller rooms, but the longest route (where all three segments were nine feet) would only fit in a large room. As a consequence, the route did provide some information about the size of the space, because the space must at least be large enough to contain it.

All paths were constructed using the same set of parameters, but the path was different for each room to prevent the subject from memorizing them. Subjects were exposed to one of the seven visual conditions in each room. For counterbalancing purposes, each subject was assigned to one of four groups (N = 8 per group). All members of a group did the same sequence of conditions in the same sequence of rooms. The four orders were chosen to ensure that each condition occurred in a variety of room sizes, so that room size was not confounded with condition.

In each space, the experimenter led the subject along a three-segment path. The subject held onto one end of a two-foot-long, half-inch diameter wooden rod and the experimenter guided them by the other end. Three tape marks on the floor of the space provided the experimenter with the position and orientation to line up the subject at the end of each segment. Path segments were always three, six, or nine feet long. Turning angles were limited to ± 30, 45, and 60 degrees. See Figure 4.2 for path examples. The subject dropped the target (bean bag) at the end of the first segment and responded to questions from the experimenter at the end of the third segment. In our analysis, the subject's estimates of distance and direction to the starting point and target were

compared to the true distances and angles. These were calculated with an Excel program that represented each segment as a vector and used trigonometry to determine the angle and direct distance of interest.

We included updating with respect to the target marker (bean bag), as well as the entrance point, because it represented a point within the space, only partway along the route. Previous work has suggested that people remember geometrical properties of a space (like the doorway starting point) better than objects in the space (like the bean bag; Wang & Spelke, 2000). Thus, we were interested to learn whether subjects' estimates relative to the start were more accurate than those relative to the bean bag.

Before the experiment began, an experimenter entered each of the spaces to turn on the room lights and moved any objects in the way of the path. When necessary, they placed strips of colored tape on the floor to mark the ends of the three path segments. A meter stick was used to measure the distances. Each strip of tape was carefully placed at the correct degree orientation using a large paper 360-degree circle, with the relevant angles marked. To make sure that the marks remained in consistent positions, they remained permanent or semi-permanent whenever possible. In three of the spaces, the same tape marks remained in place throughout the experiment; in two of the spaces, the tape marks were removed occasionally for cleaning by the custodial staff; and in the last two meeting spaces, the tape marks had to be replaced every time.

Task and Procedure

First, the experimenter explained the procedure, informing subjects that they would visit seven spaces in the building under different visual and auditory conditions. The subject was told that they would walk along different routes and, at the end, be asked to indicate the distance and direction to the starting location (doorway) and a target location (the beanbag dropped at the end of the first route segment). They would not be allowed to turn around during the walk or repeat any segments of the route. Subjects were also asked to estimate the size of each room they visited. They were told to estimate the length of the side with the door in it first, and then the length of the side angled 90 degrees away from the door side.

Next, the experimenter explained how the subject would report their answers. Distances were reported in feet, except when a subject was more familiar with meters. To report direction, subjects used a modified version of the four-quadrant verbal response measure introduced by Philbeck, Sargent, Arthur, and Dopkins (2008). They were shown a diagram to illustrate the measure and told to imagine two axes running through their body, one from straight ahead to straight behind and one from left to right (see Figure 4.1). The diagram showed a person in the center of a circle made up of four quadrants. The two quadrants ahead of the subject were labeled "front left" and "front right", while the two in back were labeled "back left" and "back right". The experimenter explained that zero for the front two quadrants was straight ahead, while zero for the back two quadrants is straight behind. Ninety degrees was always directly to the right or left of the

subject. The experimenter instructed the subject to imagine a line projecting from themselves to a location in the environment (starting point or target). They were told to report the location of this line by stating one of the four quadrants and an angle between one and ninety degrees (within the chosen quadrant). For example, the subject might estimate: "the starting point is in the left back quadrant at 45 degrees". To make sure that subjects were not confusing left and right, or misspeaking, they were asked to confirm the intended quadrant with a hand gesture. This usually entailed gesturing behind them to the left or right since they were not permitted to turn around or look back after reaching the end of the route.
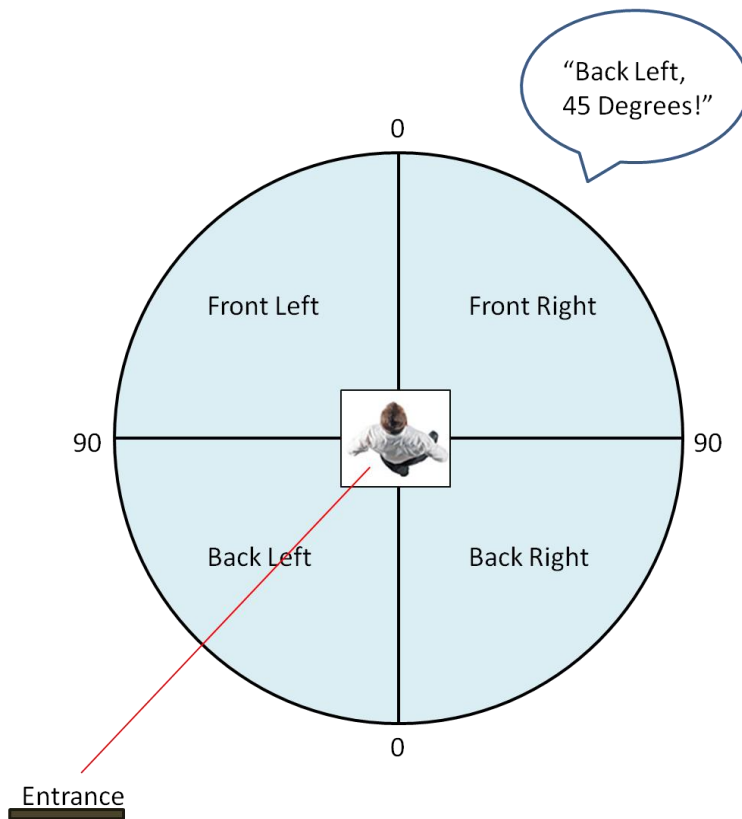

Figure 4.1: The diagram we used to explain the four-quadrant verbal response measure

of direction to subjects.

Before beginning the experiment, subjects completed two practice trials: one with normal vision and audition (no visual restriction or earmuffs), and one with the blindfold and earmuffs. Successful completion of the practice trials confirmed that the subject understood the verbal reporting procedure, the nomenclature for room dimensions, and the path-following procedure.

If the subject did not have any questions about the procedure, the experiment began. The experimenter led the subject to the seven spaces. Before opening the door of a space to begin a trial, the experimenter ensured that the subject's visual/auditory condition (earmuffs and/or simulated visual impairment) was in place. The subject began each trial at the doorway of the space, facing directly into the space, holding the rod in their right hand and the bean bag in their left hand. The experimenter always guided the subject along the route with the rod, even when the subject was participating in the Normal Vision, Facing Forward condition, and watched the subject to make sure they did not look back. When the experimenter and subject reach the end of each route, the subject remained facing forward with the visual/auditory condition in place while they gave their responses.
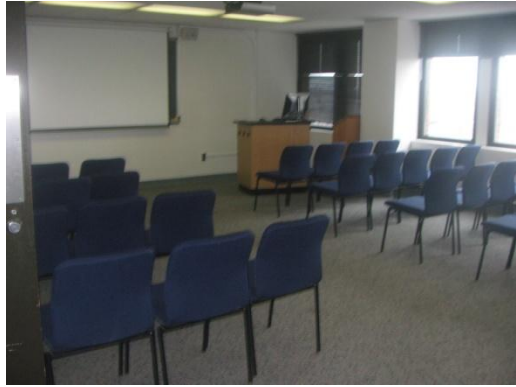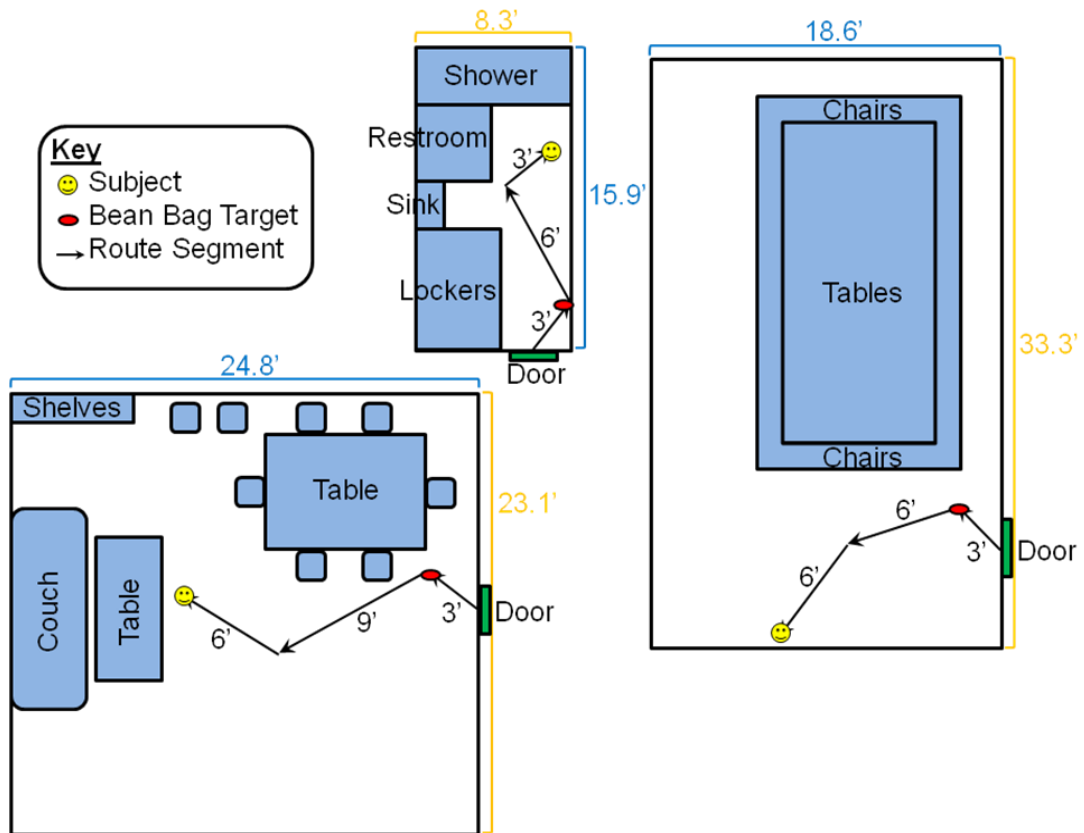
Figure 4.2. The seven spaces.

Figure 4.3. Three example routes. The Egocentric dimension is shown in blue and the

Exocentric dimension is shown in yellow.

After the experiment was concluded, subjects completed two control tasks. The goal was to determine the subject's free viewing performance. For the room dimensions control task, the experimenter brought the subject back to each of the seven rooms used in the experiment. The subject was instructed to stand in the doorway, look around at the room for ten seconds with full vision, and then estimate the room dimensions. In the localization control task, subjects were led along five paths located in one room. Unlike in the Normal Vision, Facing Forward condition, where subjects walked the route looking straight ahead, they were allowed to look around with their normal vision as they walked along the paths and look back while making their judgments. As before, they were asked to estimate the distance and direction to the target and starting point.

Results

We analyzed these data with a focus on the accuracy of the subject's distance and direction estimates. We compared the distance estimates to the actual distances. A ratio of the subject's estimated distance over the real measurement is shown in the following tables and graphs. Numbers less than 1 indicate underestimation. Numbers greater than 1 indicate overestimation. To determine direction accuracy, we converted the subject's response in the four-quadrant method (ex: back left, 10 deg) to an absolute difference score in degrees. The .05 level was adopted as the criterion for statistically significant results (P < .05).

The following analyses are divided into three sections. The first describes analyses

related to the space dimensions, the second describes analyses related to the estimates of distance to starting point and target, and the third describes analyses related to the estimates of direction to starting point and target.

Space Dimension Estimates

First, we addressed how accurately subjects estimated the dimensions of a space under each of the visual conditions (see Table 4.1). To avoid confusion, we refer to the length of the wall with the door in it as the "Exocentric" dimension and the distance from the door to the facing wall as the "Egocentric" dimension (Fig. 4.3).[1]

For each space dimension (Exocentric and Egocentric), we performed a one-way, repeated measures ANOVA with Sensory Condition as the independent variable. Both the Exo and the Ego ANOVAs showed that there were significant differences between two or more of the sensory conditions (Exocentric: $F(1, 31) = 9.22$, $p = 0.021$; Egocentric: $F(1, 31) = 6.82$, $p = 0.041$). Both ANOVAs showed no significant difference between Full Vision (Control), Normal Vision— Facing Forward, Mild Blur, and Severe Blur conditions. These four conditions were subsequently combined into one baseline condition, to enhance the power of our analysis. Then the baseline condition was compared to each of the other three conditions for each dimension. Pairwise t-test (with a Bonferroni correction for multiple tests) showed that three conditions— Severe Field Restriction, Auditory Only, and No Visual/Auditory Input— had significantly worse

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[1] This terminology would be most appropriate with reference to the entry of the space. Subjects clearly understood that they were expected to estimate the room dimensions (not the distances to the walls from their current location) at the time of reporting.

performance than baseline (p's < 0.05).

In summary, Figure 4.1 and Table 1.1 show that acuity reduction (Mild and Severe Blur conditions) did not differ from Normal Vision (Control). Second, Field Restriction and blindfolding (Auditory Only and No Visual/Auditory Input conditions) resulted in significantly larger underestimates. Third, estimates in the Auditory Only condition were no better than those in the No Visual/Auditory Input condition. Lastly, subjects performed poorly in the Preview condition compared to the Full Vision or Normal Vision— Facing Forward conditions.

In the No Visual/Auditory Input condition, where underestimates are largest, the mean Exo ratio is 0.49 and the mean Ego ratio is 0.77. A person deprived of visual and auditory input who is navigating in a real space may underestimate its size. When people lack visual and auditory information about the size of a space, they may base their guesses on prior experience with similar spaces (e.g., rooms in an office building). Proprioceptive and vestibular input from walking the route may set a lower bound for room size estimates.

Visual Conditions	Exo Dimension (± S.E.)	Ego Dimension (± S.E.)
Full Vision (Control)	0.85 ± .007	0.98 ± .010
Normal Vision-Facing Forward	0.83 ± .010	0.93 ± .022
Mild Blur	0.88 ± .018	0.92 ± .017
Severe Blur	0.77 ± .011	0.82 ± .018
Field Restriction	0.59 ± .023	0.65 ± .021
Preview	0.70 ± .019	0.76 ± .015
Acoustic Cues Only	0.56 ± .020	0.62 ± .022
No Visual/Aud. Input	0.49 ± .021	0.71 ± .022

Table 4.1. Means of the ratios of estimated dimension extent to true extent under different visual/auditory conditions.
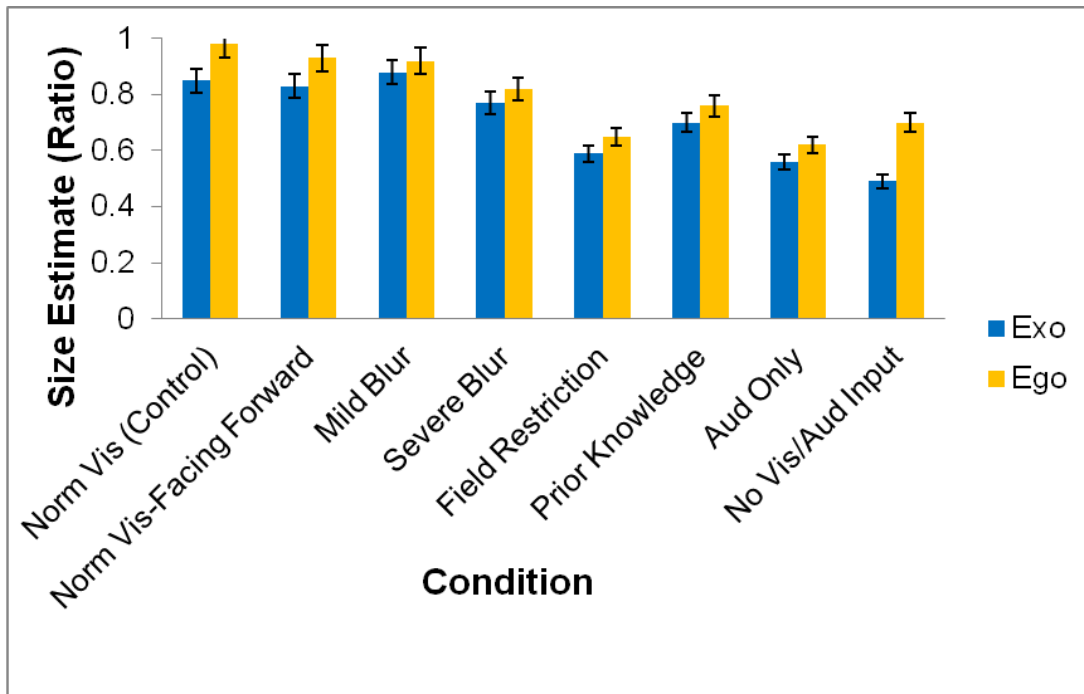

Figure 4.4. Accuracy of space dimension estimates, broken down by sensory condition,

shown as a ratio of the estimated size divided by the real size.

Subjects underestimated both space dimensions, but more so for the exocentric (Exo) dimension than the egocentric (Ego) dimension (see Figure 4.5). A pairwise t-test (with a Bonferroni correction for multiple tests) showed that subjects were significantly more accurate (ratios closer to 1.0) at estimating the egocentric distances than the exocentric distances ($p = 0.022$). If we look at the conditions individually, we find that there are significant differences between the accuracy of the two dimension estimates for three of them: Full Vision, Normal Vision— Facing Forward, and No Visual/Auditory Input. The other four conditions trend towards better performance on the Ego dimension. This suggests that subjects may have a prior bias toward guessing that rooms are narrower in the Exo dimension than the Ego dimension.

In a visual interval matching experiment, Loomis, Fujita, Da Silva, & Fukusima (1992) found a similar difference. They asked subjects to match a distance interval in depth to an equal-appearing frontal interval. Both of these were exocentric distances, but the depth interval had the same orientation as our Egocentric distance and the frontal interval had the same orientation as our Exocentric distance. Subjects adjusted the depth interval to be 1.61 times larger than the frontal interval. Their subjects perceived the same distance as smaller in the frontal plane than in depth. Our subjects' more pronounced underestimates of the exocentric distances implies that they also perceived a distance in the frontal plane (Exo) as smaller than the same distance in depth (Ego).

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Next, we considered whether the size of the space influenced the accuracy of dimension judgments (see Table 4.2). In the table, spaces are listed from smallest to largest area. The real Exo and Ego dimensions of the space and the subjects' estimated dimensions are compared. Subjects' estimates are also shown as ratios (estimated size/ real size).

Space #	Real Dimensions (ft) Exo by Ego (Area)	Estimated Dimensions (ft) Exo (Ratio)	Ego (Ratio)
1	8.3, 15.9 (131.2)	7.3 (0.88)	15.1 (0.95)
2	4.8, 45.2 (214.8)	4.1 (0.87)	40.7 (0.90)
3	16.8, 20.8 (350.2)	12.8 (0.76)	16.9 (0.81)
4	24.8, 23.1 (572.6)	17.4 (0.70)	13.7 (0.78)
5	33.2, 17.5 (582.5)	20.3 (0.61)	12.6 (0.72)
6	33.3, 18.6 (617.8)	19.2 (0.60)	15.0 (0.81)
7	31.6, 24.4 (771.0)	14.8 (0.47)	12.9 (0.53)

Table 4.2. Accuracy of space dimension estimates in different sized spaces. Ratios are of estimated size divided by the real size.
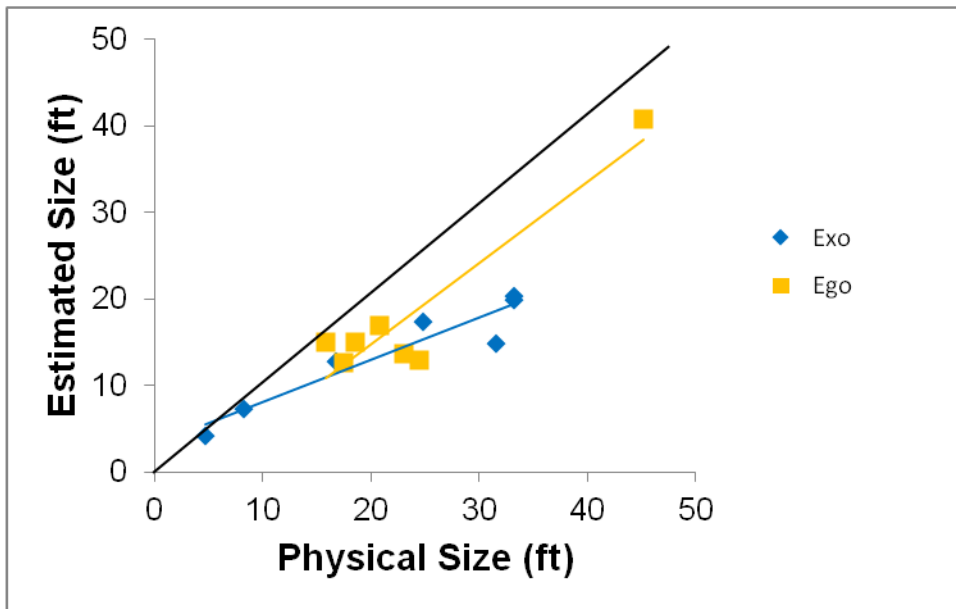
Figure 4.5. Mean subject estimates are plotted against the physical space dimensions.

The black line represents accurate performance.

In Figure 4.5, the slope of the Ego regression line is much closer to 1.0 (0.94), than the slope of the Exo line (0.49). However, the slope and correlation for the ego dimension is driven primarily by the value 45.2 ft. This was the extent of a long, narrow hallway space (Space 2 in Table 4.2), with the small Exo value (4.8 ft) indicating the narrowness of the hallway. When this Ego value is removed, the range of ego dimensions is severely compressed (15.9 ft to 24.4 ft) and the correlation between subjects' estimates and the Ego distances was not statistically significant.

To ensure that subjects in our No Visual/ Auditory Input condition truly lacked access to visual or auditory information, we compared the correlations between physical and estimated room size in this condition and the baseline condition. Without sensory input,

we would expect to find low (near zero) correlations between the physical and estimated room sizes. On the other hand, we would expect relatively high correlations when subjects had good vision (baseline condition). Indeed, there was no significant correlation between physical and estimated space size for the No Input condition (correlations were -0.13 for Exo and 0.04 for Ego). However, there were significant correlations between physical and estimated room size for the baseline condition (0.66 for Exo and 0.73 for Ego).

Estimates of Distance to the Starting Point and Target

We examined the distance and direction to starting point (doorway) and target (bean bag) judgments (see Table 4.3). As with the space dimension estimates, subjects underestimated the distances to the starting point and target (see Figure 4.6). For both judgments, one-way, repeated measures ANOVAs with Sensory Condition as the independent variable were significant (Distance to start: $F (1, 31) = 5.46$, $p = 0.041$; Distance to target: $F (1, 31) = 8.13$, $p = 0.012$). As before, there was no significant difference between the control condition (Full Vision) and three other conditions (Normal Vision- Facing Forward, Mild Blur, & Severe Blur), so these were combined into one baseline condition. This baseline condition was compared to each of the other three conditions.

The estimates for distance to starting point and target (Figure 4.6) look similar to the space dimension estimates (Figure 4.4). The same general findings apply. First, acuity

reduction (Mild and Severe Blur conditions) did not differ from Normal Vision (Control). Second, Field Restriction and blindfolding (Auditory Only and No Visual/Auditory Input conditions) resulted in significantly larger underestimates. Third, for both the starting point and target estimates, distance judgments in the Auditory Only condition were no better than those in the No Visual/Auditory Input condition.

There was no systematic difference between the distance ratios for the starting point and those for the target. However, there was one notable difference between starting point and target results. For the distance to the starting point, pairwise t-test (with a Bonferroni correction for multiple tests) showed that three conditions— Field Restriction, Auditory Only, and No Visual/Auditory Input— had significantly smaller ratios (worse performance) than the baseline ratio of 0.86. For the distance to the target, a fourth condition (Preview) was added to this list.

Visual Condition	Distance to Start (Ratio)	Distance to Target (Ratio)
Full Vision (Control)	0.89	0.91
Normal Vision, Facing Forward	0.85	0.85
Mild Blur	0.83	0.89
Severe Blur	0.78	0.83
Field Restriction	0.66	0.6
Preview	0.74	0.69
Aud. Only	0.64	0.59
No Visual/ Aud. Input	0.57	0.62

Table 4.3. Accuracy of distance estimates for the starting point and target.
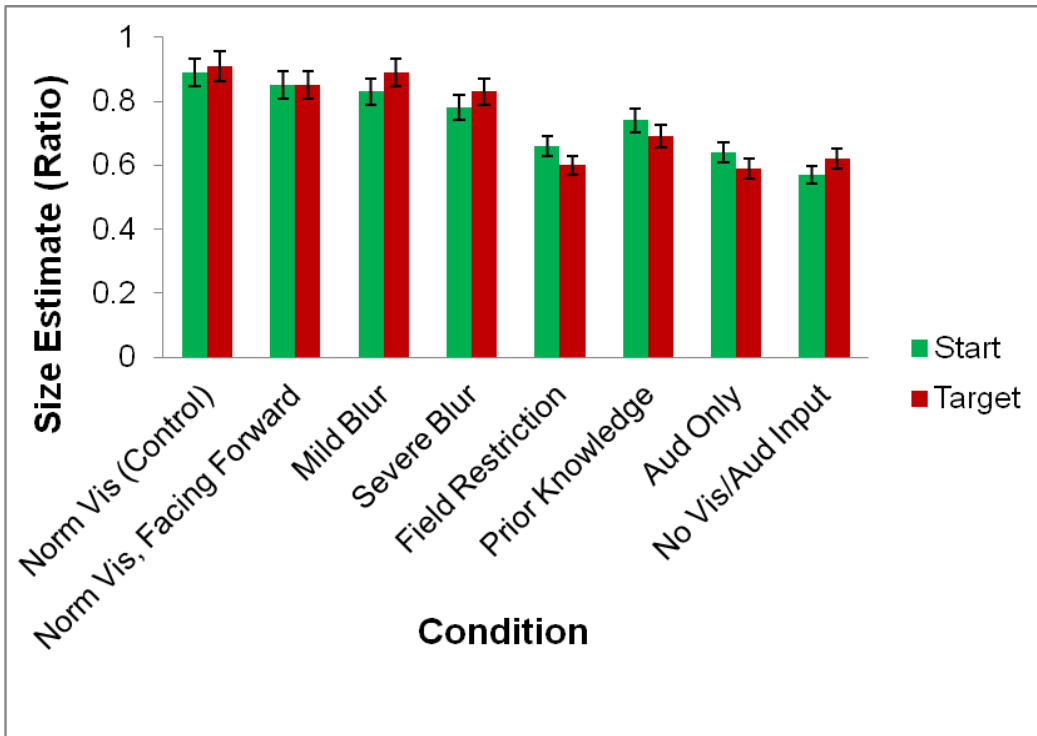
Figure 4.6. Accuracy of starting point and target distance estimates, according to condition, expressed as ratios of the estimated size divided by the real size.

Estimates of Direction to the Starting Point and Target

For the estimates of direction to the starting point (doorway), subjects' average absolute error was 18.0 degrees. For the target (bean bag), subjects' average absolute error was 21.1 degrees. These errors are not significantly different. For both the starting point and target, average absolute error did not significantly vary by sensory-deprivation condition. A possible explanation for this is included in the discussion section below.

Figure 4.7 shows that subjects biased their estimates toward zero (straight behind). The slopes for the Start and Target regression lines are both smaller than 1.0 (0.47 and 0.15,

respectively).
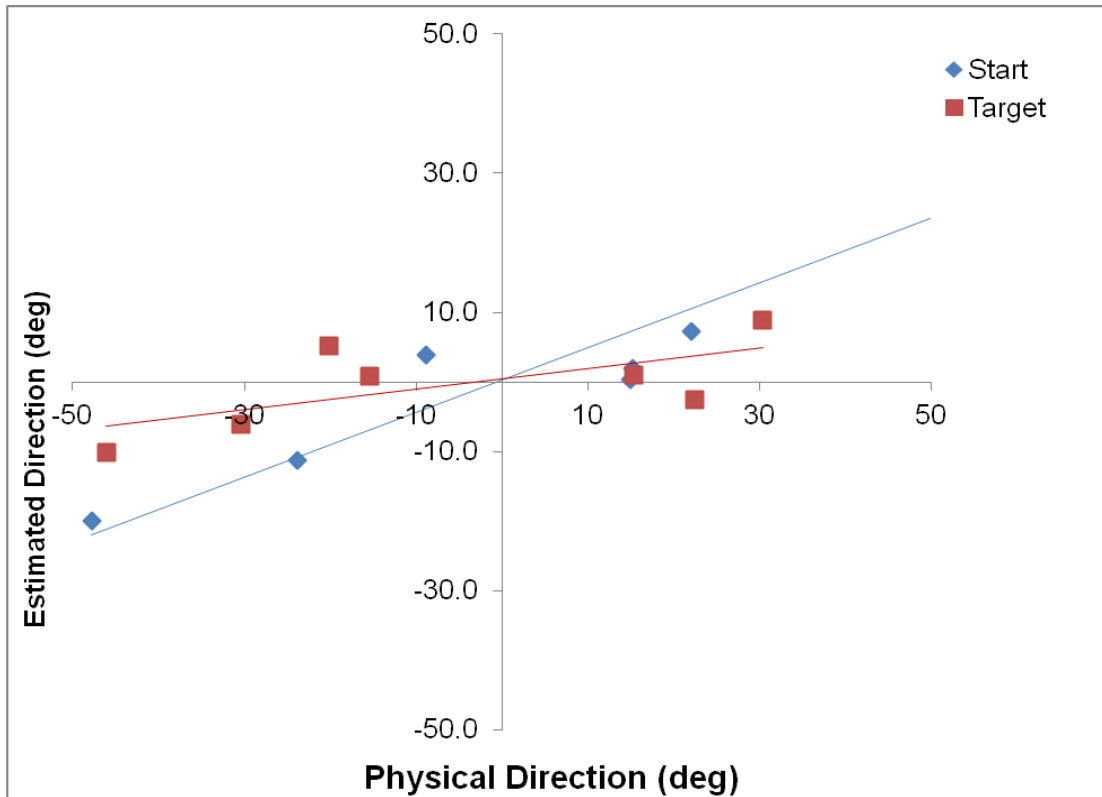
Figure 4.7. Mean angular estimates to starting point and target are plotted against the physical angular direction. Each point represents one of the seven spaces. Angles are given as deviations from straight back (0).

Discussion and Conclusions

The present study enquired how different forms of visual and auditory restriction affect spatial updating. We demonstrated that the accuracy of distance and dimension estimates, but not direction estimates, are affected by the vision status of the subject. One way of interpreting this result is in terms of the two types of spatial updating described by

Loomis et al. (1993): piloting and path integration. Piloting requires visual information about the context in a space, while path integration can be accomplished with body-centered cues (proprioceptive and vestibular input). Visual access to information about room size or other room features may have facilitated the distance component of spatial updating, which could be considered a form of piloting.

In the Preview condition, subjects performed worse than baseline (Normal Vision, Normal Vision- Facing Forward, Mild Blur, & Severe Blur combined) on estimated room dimensions and distance to the target (but not on estimated distance to the starting point). It is surprising that subjects performed so much less accurately in the Preview condition for these estimates because subjects viewed the room without visual restriction in all three conditions. However, in the Preview condition, subjects waited until after walking the route to make their estimates. Perhaps in this short time, their memory of the space deteriorated, negatively affecting performance.

Why did the preview seem to help distance to target estimates, but not distance to starting point estimates? People remember geometrical properties of a space, like the doorway, better than objects in the space, like the starting point (Wang & Spelke, 2000; see the Methods section, under Stimuli). An alternative explanation is also possible: at preview, the subject knows the location of the starting point in the context of the space and can use imagery (a cognitive map) to support updating. However, since placement of the target occurs during blind walking, the target location may not be as accurately located in the

cognitive map.

For the conditions tested in this study, auditory cues were not helpful in judging room dimensions or in spatial updating. But, there are two significant caveats. First, we selected rooms that were usually quiet, lacking distinctive auditory landmarks. Second, our subjects were all normally sighted. It is possible that visually impaired subjects who rely more on auditory cues in mobility might show benefits from auditory cues not useful for sighted subjects. In particular, highly directional and localized sound sources are likely quite effective in spatial updating (e.g., audio beacons used in street crossings).

Consistent with previous work, our subjects underestimated the extent of physical distances. According to Durgin and Li (2011) there are two potentially related, well-documented biases in space perception: distances along the ground are underestimated and slanted ground surfaces look steeper to humans than they are in actuality. The former bias is more relevant to the current work because none of our spaces have slanted floors. The magnitude of the perceived distance bias may depend on the subject response method. When observers estimate a distance on the ground plane by making a verbal response (e.g., "3 feet"), the bias obtains (Da Silva, 1985). However, when they estimate the distance with a physical action (by blind walking or blind pointing) the bias disappears (Loomis, Fujita, Da Silva, & Fukusima, 1992). Even so, Li, Phillips, and Durgin (2011) found distance underestimation with a nonverbal, self-positioning task, indicating that response method may not be the critical variable. The present study shows

that subjects using a verbal response method underestimate more when vision is restricted than with normal vision.

When making distance and dimension judgments, subjects with blurry vision and about 30-deg-diameter field size approached the accuracy of those with normal, unrestricted vision. This was true even for the Severe Blur condition, where acuity was only approximately 20/900. In contrast, subjects with normal vision looking through an extremely limited visual field of 8 deg performed much less accurately. In fact, their performance was not significantly different from non-visual (blindfolded) performance. These results suggest that low-vision individuals with a very limited visual field might have more difficulty with spatial updating than those with blurry vision.

In this study, the mean absolute angular error for the direction estimates was close to 20 degrees for both the target (bean bag) and the starting point (doorway). Kelly et al. (2008) found an absolute pointing error of 27.2 degrees for men and 45 degrees for women when subjects walked to a sequence of posts and then had to pick out a target. (For a more in-depth description of this study, please see the Introduction section.) Horn and Loomis (2004) found a fairly consistent mean absolute angular error of 14.8 degrees for targets located behind the subject. These authors asked subjects to update the location of a single target in an open field. Our task was more difficult because there were three segments in the route and subjects were updating both a target location and starting location at once. This may explain why we found a larger mean absolute angular error than they did.

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Although our study derives benefits from being in real indoor spaces, and involving real walking, as described in the Introduction, it also has some difficulties characteristic of real-world studies. Since the study was carried out in a real environment, it was difficult to control or discount all extraneous variables. For example, different spaces contained different potential landmarks such as types and quantities of furniture (see Fig. 4.3).

The earmuffs and white noise could not block out very loud environmental auditory noises, such as a door slam, without increasing the volume to a level that was uncomfortable for the subject. It is unlikely that these sounds affected our results because we saw no difference between the Auditory Only and No Input conditions, suggesting that too few acoustic cues were present to make auditory updating useful. Small light leaks around the edges of the goggles were also possible if the subject did not adjust them properly. However, light leaks of this type do not provide any visual information about the size of the space or objects in the space, so they should not affect our results.

Effects of response order may have resulted in the space size estimates influencing the starting point and target estimates because subjects always gave the former estimates prior to the latter. Subjects' estimates of distance/direction to the starting point and target were probably made within the reference frame of their previously-made space size estimate. Even so, this is unlikely to produce a systematic bias in our results.

Future examinations of spatial updating ability should recruit participants with impaired vision. We found no effect of auditory input with the normally sighted group in the current study, but low-vision and blind subjects may benefit from it. Visually impaired subjects tend to use auditory input as a substitute for unreliable or absent visual input. It would be particularly interesting to compare the performance of people with reduced acuity, but approximately normal visual field size (e.g., from cataracts), to that of people with approximately normal acuity and severely limited field size (e.g., from advanced glaucoma or retinitis pigmentosa). Based on the results of the present study, we hypothesize that the performance of the former group would look similar to performance with normal vision, while the performance of the latter would look similar to blind performance.

Future Directions

The three studies covered in this thesis have suggested future directions for research that we are now pursuing. The success of our low-vision version of the texture and locomotion experiment (Chapter 3) and the interesting results from the spatial updating study (Chapter 4) have encouraged us to take spatial updating research in two new directions.

First, we have begun running subjects with low vision on a version of the spatial updating experiment, in which performance with their existing vision is compared to blindfolded performance, with and without auditory information. In Chapter 4, we found that subjects were able to make more accurate distance estimates with blurry vision than with a restricted visual field. In fact, performance with the restricted field was not significantly different from blindfolded performance! We are interested to learn whether this pattern of results will hold in our low vision group. Although the auditory manipulation did not influence performance in subjects with normal vision, people with low vision might be more aware of auditory information and practiced at using it for navigation tasks, so auditory information may benefit their performance.

Second, we have run a group of subjects who were pushed in a wheelchair along the routes, instead of walking along them. Since proprioceptive information is important in spatial updating, we hypothesized that subjects pushed in a wheelchair would lose access

to some of the proprioceptive information available during walking, and this would negatively impact the accuracy of their estimates.

Open questions still remain. One of the most vital for the future of the Designing Visually Accessible Spaces project is how to go about converting these research findings (along with findings from other members of our research group) into an effective tool for architects and interior designers. Our investigations of the recognition of steps and ramps tackle an important category of frequently-encountered objects, but there are other frequently encountered categories of object that we did not consider. How well do our findings on the recognition of steps and ramps generalize (if at all) to the recognition of other common objects, such as doors or chairs? In the future, studying useful objects like doorways/cabinets, and hazards like overhangs, may yield valuable information for our design tool.

The spatial updating results also contain puzzles. Why did a visual preview of a space, before walking the route blindfolded, lead to performance accuracy that was between normal vision and blindfolded performance? Why did our subjects bias their direction estimates toward zero (straight behind them)?

Together, these studies provide insight into the visual accessibility of spaces for people with low vision, and suggest directions for future research.

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