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Learning building layouts with non-geometric visual information: The effects of visual impairment and age

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Abstract. Previous studies suggest that humans rely on geometric visual information (hallway structure) rather than non-geometric visual information (eg doors, signs, and lighting) for acquiring cognitive maps of novel indoor layouts. In this study we asked whether visual impairment and age affect reliance on non-geometric visual information for layout learning. We tested three groups of participants—younger (<50 years of age) normally sighted; older (50 – 70 years of age) normally sighted; and low-vision (people with heterogeneous forms of visual impairment ranging in age from 18 to 67 years). Participants learned target locations in building layouts using four presentation modes: a desktop virtual environment (VE) displaying only geometric cues (sparse VE); a VE displaying both geometric and non-geometric cues (photorealistic VE); a map; and a real building. Layout knowledge was assessed by map drawing and by asking participants to walk to specified targets in the real space. Results indicate that low-vision and older normally sighted participants relied on additional non-geometric information to accurately learn layouts. In conclusion, visual impairment and age may result in reduced perceptual and/or memory processing that makes it difficult to learn layouts without non-geometric visual information.

1 Introduction

A typical building contains abundant visual features for aiding navigation, from geometric cues about the structural layout of the floor plan to cues unrelated to the layout geometry such as the presence of objects (eg pictures, water fountains) and image characteristics (eg textures, color, and lighting). In this study we question how two important participant characteristics—visual impairment and age—influence the types of visual information needed for developing an accurate mental representation of a novel virtual environment. First, we ask whether rendering of purely geometric information is sufficient to enable navigation in virtual buildings by those with visual impairment, and whether the addition of non-geometric visual features helps or hinders. Second, because the prevalence of visual impairment is much higher in old age, we ask whether age influences the use of geometric and non-geometric visual information.

1.1 *Geometric and non-geometric cues*

In this study, geometric cues refer to the spatial configuration of hallways, specifically their length and intersection connectivity. In figure 1a, the geometric features are the hallways extending to the left, right, ahead, and behind. Non-geometric visual features are distinct from layout geometry, and in figure 1a include the bulletin board with postings, the trash cans in the corridor, and the lighting patterns on the walls and floor.

Previous work on both animals and human spatial cognition suggests that information about layout geometry is preferentially encoded when learning a space. After exploring a rectangular box, rats look for the target the same percentage of time at the correct corner as at the geometrically equivalent opposite corner, despite the presence of unique non-geometric cues (Cheng 1986). Furthermore, pre-verbal human children tend to use geometric information to locate the position of a toy in a rectangular room even when wall color, a non-geometric feature, provides more specific information (Hermer and Spelke 1996). These findings support the notion of a 'geometric module' in the brain dedicated to using information about the relative position of surfaces in an environment to compute orientation (Gallistel 1990).

Non-geometric cues are useful for learning environments when geometric cues are ambiguous. Monkeys and other species will rely more on non-geometric cues, such as cards with distinctive patterns, when the information they provide about target location conflicts with geometric cues (Gouteux and Thinus-Blanc 2001; Kelly et al 1998; Sovrano et al 2002; Vallortigara et al 1990; see review by Cheng and Newcombe 2005). However, these species are still able to use geometric information for localization when non-geometric information is not available.

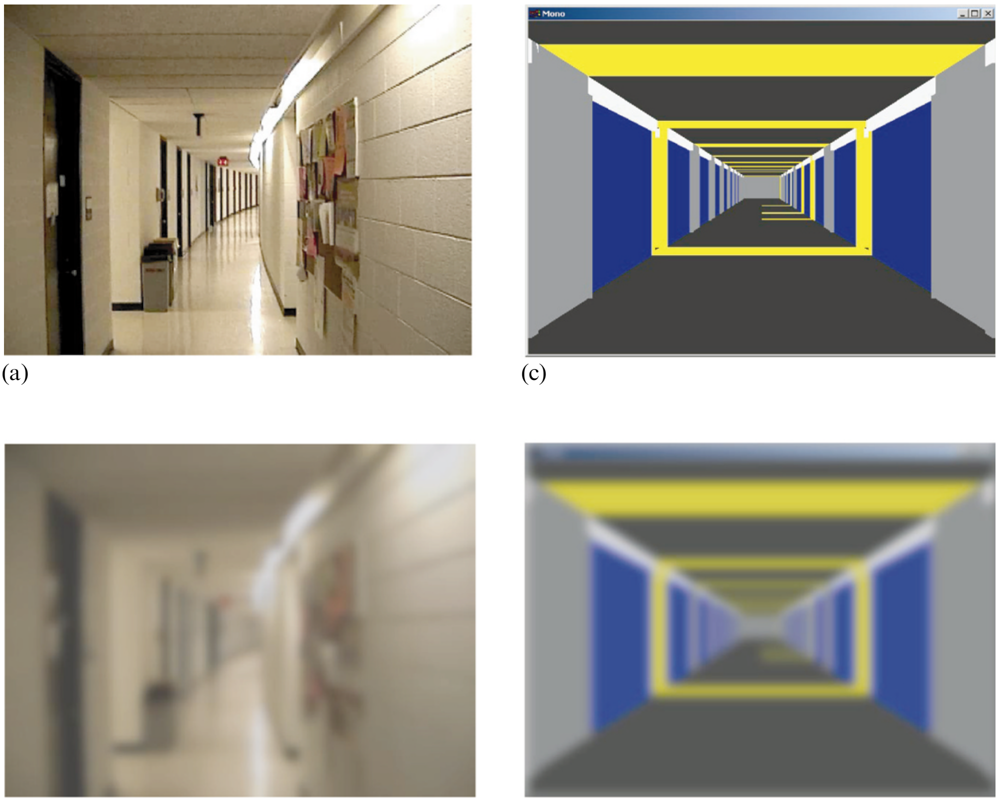
There is also evidence that humans are biased towards using geometric information when navigating through more complex spaces, such as the inside of a building. Non-geometric information, such as large objects placed at various intersections, improves navigation efficiency (measured by the route-distance traveled) (Lessels and Ruddle 2005; Ruddle et al 1997), and is useful for locating specific rooms and remembering where to make turns (Ruddle et al 1997). However, non-geometric information does not result in better knowledge of overall layout configuration (Ruddle et al 1997). Furthermore, participants demonstrate more accurate knowledge of geometric than of non-geometric information, even during the first few exposures to a novel indoor environment (Stankiewicz and Kalia 2007). These studies suggest that non-geometric cues provide some advantages when navigating through an environment, but they are not necessary for developing an accurate mental representation of layout information.

In the current studies we explored whether people with varying degrees of visual ability and age demonstrate similar use of non-geometric visual information when learning unfamiliar, large-scale layouts. Although previous studies suggest that younger, normally sighted individuals do not rely on non-geometric cues to develop an accurate mental representation of a layout, it is not known whether the same is true for older adults or people with visual impairments. We tested this by comparing learning of layouts in two types of virtual environment, one that displayed only geometric features (sparse VE) and another that displayed both geometric and non-geometric features (photorealistic VE). As in the studies by Lessels and Ruddle (2004, 2005), we did not select a single type of non-geometric feature to include in the VEs, because it was unclear which visual features humans choose to use in real spaces. Instead, the photorealistic VE allowed participants to use the range of non-geometric information available in real environments.

1.2 *Low-vision navigation*

The term 'low vision' refers to any chronic visual impairment that affects everyday functioning and is not correctable by glasses or contact lenses. There are two distinct problems associated with navigating with low vision: obstacle avoidance and wayfinding. Much attention has been given to the problem of how specific visual impairments make it difficult to detect and avoid obstructions along a path (Kuyk and Elliott 1999; Marron and Bailey 1982; Turano et al 2004; West et al 2002). The current study focuses on wayfinding behavior in people with low vision, including their ability to learn unfamiliar layouts and then to use this information to plan and execute paths between specific locations.

Low vision may influence wayfinding and the building of accurate mental spatial representations in two ways. First, it can be more challenging to visually extract layout geometry, making it more difficult to navigate between locations. If so, wayfinding should be improved by enhancing the salience of geometric visual features in a layout. VEs can accomplish this by, for example, depicting hallways and intersections in high-contrast colors. In figure 1, the intersecting hallways are more salient in the VE (figure 1d) than in the real environment (figure 1b) under conditions of blur and reduced contrast. Second, people with low vision may rely less on non-geometric information if reduced acuity, reduced field, or low contrast sensitivity make it difficult to resolve and identify these features. If such objects are hard to recognize, they might even act as distracting clutter which interferes with the extraction of cues to the geometrical layout. Thus, we might expect little or no improvement in wayfinding when non-geometric features are present in an environment. On the basis of these predictions, we hypothesized that low-vision participants would learn layouts better in the sparse VE, which displayed only high-contrast geometric information, compared to the photorealistic VE, which displayed additional non-geometric information.



(a) (c) (b) (d)

Figure 1. Example of a four-way hallway intersection as (a) viewed normally and (b) with simulated visual impairment produced with blurring and contrast reduction. The geometric and non-geometric features depicted in (a) become less distinct with its simulated visual impairment. In a virtual environment, geometric features can be displayed in high-contrast colors (c). Under reduced visual conditions, branching hallways are easier to detect in the virtual environment (d) than in the real environment. Although these images do not necessarily simulate the subjective experience of people with low vision, they give some idea of the reduction of visual information associated with reduced spatial resolution or reduced contrast sensitivity.

This study also addressed the practical question of whether low-vision individuals can use enhanced computer displays to learn a layout of a building prior to visiting the real space. Pre-journey learning, by means of maps on a digital touchpad augmented with auditory cues, has proven useful for blind individuals when navigating in the real environment (Holmes et al 1996). Here, we investigated whether the same is true for visual representations displayed on a computer, such as maps or first-person VEs.

1.3 *Aging and navigation*

The leading causes of vision impairment in the USA are age-related eye diseases, such as age-related macular degeneration, cataracts, diabetic retinopathy, and glaucoma (Eye Diseases Prevalence Research Group 2004). It is estimated that in the year 2000 there were approximately 3.3 million individuals older than 40 years with visual disabilities, with prevalence growing significantly with age (Eye Diseases Prevalence Research Group 2004). It is likely that age and visual impairment interact in their effects on spatial navigation. Consequently, our study also explores how age influences the use of geometric and non-geometric visual information when learning novel indoor layouts.

Several studies have shown that navigating in novel layouts becomes more difficult with age. A recent study by Sjölinder et al (2005) had younger (mean age 25.5 years) and older (mean age 66.9 years) individuals navigate through a virtual grocery store by simulating the real-world task of searching for items on a shopping list. The virtual rendering included visual details such as store shelves with different products and textured walls and floors. The older participants spent more time and were less efficient at finding the grocery items in the virtual store compared to the younger participants. They also developed less accurate survey knowledge of the store layout, and particularly overestimated distances between locations. Another study demonstrated that older (> 65.1 years) participants take more time and exhibit more errors when learning a route in a visually rich VE compared to younger participants (Moffat et al 2001). This is despite controlling for other factors such as computer experience and gender. Animal research on the use of place cells to encode spatial information also indicates that older rats have difficulty in developing spatial representations for new environments and associating target locations with visual cues (Rosenzweig et al 2003; Wilson et al 2004).

Age may also affect a person's ability to use geometric visual information during spatial learning. In a study by Moffat and Resnick (2002), younger (aged 25 – 45 years), middle-aged (aged 45 – 65 years), and older (aged 65 – 93 years) adults were trained to locate a hidden platform by virtually swimming in a Morris Water Maze. The circular pool, viewed from a first-person perspective on a desktop computer, was surrounded by walls with an irregular shape as well as distinct objects that served as non-geometric cues. When asked to draw a map of the environment, older participants were less accurate at depicting the outer wall, but were able to reproduce the non-geometric features of the environment. Furthermore, the older participants had difficulty locating the target with respect to the geometric cues provided by the shape of the walls compared to younger participants, but no differences between age groups were found when non-geometric cues were available. Older adults also exhibit more errors than younger adults when using a geometric representation of a route (a map consisting only of layout geometry) to navigate inside a building (Wilkniss et al 1997). These results suggest that older individuals may rely more on non-geometric than on geometric cues when learning locations within a space. Accordingly, in the current study we hypothesize that older adults will have a less accurate representation of layouts learned in the sparse VE, which only depicts layout geometry, than younger adults, but both age groups will perform similarly in the photorealistic VE.

1.4 *Current study*

To summarize, we asked whether non-geometric visual information usefully supplements (or, in the case of low vision, obscures) geometric information for learning novel indoor layouts. We tested the effects of two participant characteristics on the use of geometric and non-geometric information: (i) visual impairment; and (ii) age. Participants learned layouts in two types of environments displayed on a desktop computer: a sparse VE, depicting only information about layout geometry (hallway length and intersections); and a photorealistic VE, displaying a full range of visual features, such as posters on the walls, color, and lighting patterns, in addition to geometric information. For comparison, participants also learned layouts using two common methods—with a map and by exploring a real building.

We measured two aspects of learning: the rate of acquisition of layout information and the accuracy of the resulting mental representation. The rate of acquisition was measured by how much exploration was needed to learn the locations of several targets. Target localization and map drawing were used to measure the accuracy of the resulting mental representation and whether it contained the minimal information required to travel between locations (route-based knowledge), or additional information about the overall configuration of the layout (survey knowledge). In experiment 1 we tested young adults with normal vision; in experiment 2 we tested a heterogeneous group of low-vision individuals; and in experiment 3 we tested older people with normal vision.

2 Experiment 1

In this experiment we tested how well young, normally sighted individuals learned layouts in four presentation modes: two virtual environments (sparse and photorealistic) displayed from a first-person viewpoint; a map; and a real building. The sparse and photorealistic VEs were used to manipulate the non-geometric visual information available when learning layouts. The main goal of this experiment was to replicate previous findings that non-geometric visual information does not improve the accuracy of mental representations of space, but may aid other aspects of navigation for younger normally sighted individuals.

Two control conditions were included in this experiment. The map condition assessed learning when global information about the layout was available. The real-building condition provided an ecologically valid control for comparison, and also indicated whether non-visual cues are crucial for learning layouts. In this paper, non-visual cues refer to proprioceptive and vestibular information. Previous studies suggest that non-visual information allows for more accurate spatial updating as measured by judgments of the direction to objects (Chance et al 1998; Waller et al 2004) or to a starting location (Klatzky et al 1998). Also, non-visual information increases the efficiency of searching for targets in both a visually sparse and a photorealistic VE (Ruddle and Lessels 2006). By testing participants in these four conditions, we compared how acquisition and accuracy of layout knowledge is affected by the information available about the layout during learning.

2.1 *Method*

2.1.1 *Participants.* Sixteen undergraduate students (mean age 19 years, SD = 1 year; eight males, eight females) from an introductory psychology course participated in the experiment. Eleven of the sixteen participants were located and surveyed four years after the study on their videogame experience. Six of the eleven did not have experience with videogames at the time of the study; the other five spent 0.5 to 3 h per week playing videogames that involved navigating through VEs. Participation was voluntary and was rewarded with extra credit or monetary payment. All participants had normal or corrected-to-normal visual acuity and had little to no exposure to the building layouts tested in the experiment. Participants also provided informed consent.

2.1.2 *Materials.* The layouts we used for testing were obtained from several topologically distinct floors in the psychology building at the University of Minnesota. Computer representations of these layouts were created by mapping them onto a grid of nodes connected by line segments (see figure 2c as an example). Each node represented

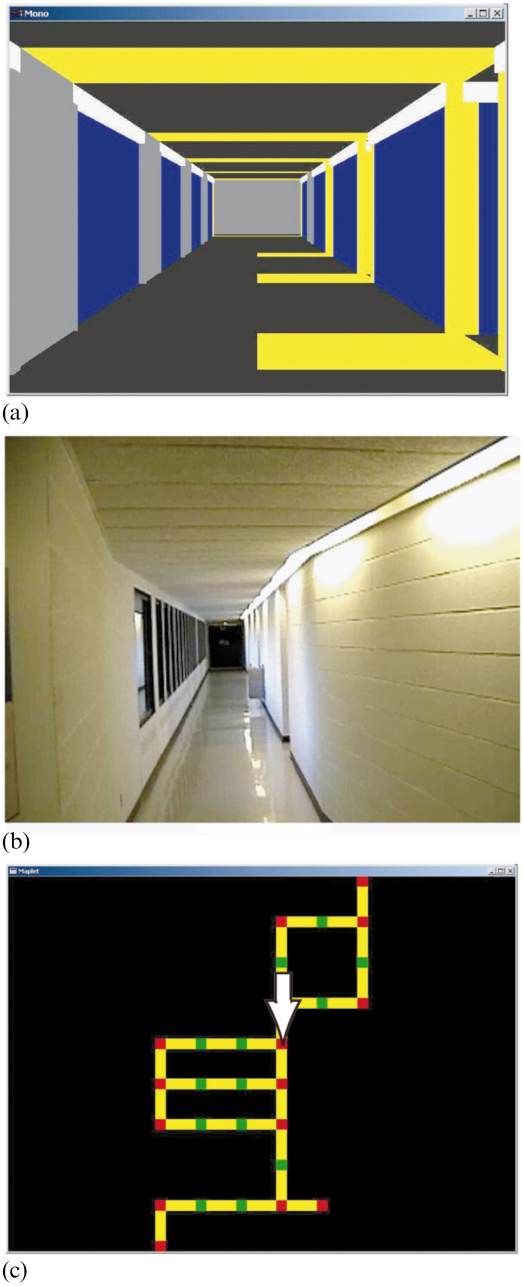


Figure 2. Examples of the same layout rendered in the (a) sparse VE, (b) photo-realistic VE, and (c) map presentation modes. The views in (a) and (b) are from the same location and orientation as indicated by the white arrow in (c) (the arrow is enlarged for this illustration). In (a), the yellow markings on the right side of the floor and wall indicate a hallway going to the right at the next three intersections.

a possible position in the computer-based VE and only discrete moves between nodes were allowed. Each line segment represented a hallway unit connecting one node to another, which corresponded to an approximate distance of 4.6 m (15 feet) in the real layout. Thus, for both VEs and the map displayed on the computer, participants moved from one node to another, or the equivalent of 4.6 m, every time they made a forward key-press.

Each layout contained four target locations represented acoustically but not visually. We have no reason to believe that memory for auditory targets is different from that for visual targets since previous work has shown that spatial representations acquired visually or verbally are functionally similar (see review by Loomis et al 2007).

When participants reached a target location, a computer voice stated the name of the target (eg "target cat"). The speech output was adjusted beforehand for all participants to ensure that it was highly intelligible. The targets were located either at dead ends or intersections and were chosen to be spread out across the floor. This required participants to explore most of the layout in order to find all target locations.

The same keystroke interface was used by the participants to move in all the three computer-simulated environments (sparse VE, photorealistic VE, and map conditions). Participants used key presses on the number keypad to either translate forward one hallway segment (key '8'), rotate 90° to the right ('4') or rotate 90° to the left ('6'). In the map condition, the keystrokes moved a cursor that provided a visual indicator of the particpant's current location (see below).

The map and sparse environments were viewed on PCs with 18-inch (45.7 cm) screens (ViewSonic E90f and MultiSync FE950+) and the photorealistic environments were viewed on a Macintosh PC with a 17-inch (43.2 cm) screen (Apple Studio Display). We used different computers, and therefore screens, because of the software requirements of the VE programs. The room lights remained on during testing because it was more comfortable for visually impaired (experiment 2) and older (experiment 3) participants and made the experiment less intimidating.

(a) Sparse VE. In the sparse condition, participants were presented with a virtual representation of the real floor viewed from a first-person perspective. These sparse virtual layouts were created on a rectangular grid and rendered only the hallways and intersections of the floor; they did not include non-geometric features.

To simplify the rendering, curved hallways were approximated as straight hallways. It is likely that modest curvature is a feature that humans do not typically preserve in their cognitive maps of a space. People typically encode environments as having a grid-like structure, with 90° intersections, even if the real environment deviates from a grid structure (Tversky 1981). It remains possible that even if hallway curvature is not represented geometrically, it could be encoded as a non-geometric image feature based on effects of shading, contour, or occlusion associated with the curvature.

Hallways were rendered with contrasting blue and yellow color patterns on the walls and ceiling; additional yellow markings on the walls and floor indicated the presence of intersecting hallways (figure 2a). Virtual movement from one node to the next was continuous and included optic-flow cues, thereby simulating real movement. Translations and rotations took about 1.3 s. These environments were generated with Virtual Reality Modeling Language (VRML), and were displayed with Virtual Reality Utility (VRUT; University of California, Santa Barbara).

(b) Photorealistic VE. The VEs in this condition were also rendered from a first-person perspective, but they included both the geometric and the non-geometric cues available in the real environment (figure 2b). The environments were created with movies of real space recorded by mounting a camera on a robot arm attached to a moving cart. The eye height of the camera was approximately 1.5 m (5 feet) off the ground. For rotations, the arm was turned at a controlled pace, taking approximately 1.7 s for a 90° rotation. For translations, the cart was pushed a distance of $\sim$4.6 m in 7.3 s. The movie was broken into clips to simulate every possible forward movement between nodes and every 90° rotation at intersections. Key-presses generated the corresponding movie of the translation or turn.

Translational and rotational speed in the photorealistic VE was slower than in the sparse VE because of the physical limitation of moving the cart. The difference in movement speeds in the two VEs did not affect participants' perception of distance, as measured by a distance-estimation task not reported in this paper.

(c) Map. Participants learned one layout using a map displayed on a computer screen (figure 2c). The map displayed nodes connected by yellow segments and each segment represented 4.6 m in the real layout. The nodes were green if they were located within a continuing hallway and red if they were at a dead end or an intersection. The display also included a white arrow indicating the participant's current position and heading. Participants explored the layout by moving the arrow with key-presses that indicated movement with respect to the arrow. For example, if the arrow was facing down on the screen, pressing '4' (the left turn key) would turn the arrow left with respect to its initial direction, meaning the arrow would point towards the right side of the screen. The reason for making movements with respect to the arrow—the participant's projected location—was to be consistent with exploration in the sparse and photorealistic VEs in which key-presses correspond to egocentric movements from a first-person perspective.

2.1.3 *Procedure.* Participants were tested in a within-subjects design by learning a different layout in all four conditions. They went through the procedure a total of five times, once for practice at the beginning of the experiment and then once for each of the four conditions. The order of the conditions as well as the layout–condition pairings were counterbalanced across participants with the restriction that only two of the four layouts could be learned in the photorealistic condition (because of the availability of materials). The layouts were quite different, with the intention that learning would not transfer.

First, participants practiced moving in each type of environment by key-presses and were told that each forward move was equivalent to moving 15 feet (4.6 m) in the real building. They then learned a practice layout and performed tests assessing layout knowledge, as described below.

Acquisition of layout knowledge. Each of the four experimental conditions started with an exploration period of a novel layout. Participants were explicitly told to explore until they definitively knew the locations of the targets and were familiar with the layout, but perfect knowledge of layout topology was not required. The exploration period ended when participants indicated they knew the target locations or they reached a maximum number of forward moves (determined by the size of the layout). Participants then performed a learning test that required them to navigate to each of the four target locations within a maximum number of forward moves (twice the number of moves needed to take the shortest path) in the same presentation mode as during exploration. The purpose of the learning test was to have participants achieve a common level of learning before they were assessed on their knowledge of the layouts. If participants did not pass this criterion level of learning, they resumed exploration. Participants were allowed to explore the layout for a maximum of four iterations to pass the learning test.

The rate of acquisition of layout knowledge was measured by recording the total number of forward moves used by the participant to explore the layout before passing the learning criterion. The acquisition score was calculated as the proportion of the number of moves used to the total number allowed in four possible exploration periods. For example, if the total number of moves allowed, summed over four exploration periods, was 200, and the participant used a total of 150 moves, the acquisition score would be $150/200 = 0.75$. A low score indicated that layout information was attained with little exploration, whereas a score of 1.0 indicated that participants used all the exploration time allowed by the experimenter.

Assessment of layout knowledge. Participants performed two tasks to test the accuracy of the knowledge acquired during the exploration session. Participants first made maps of the layouts, which assessed whether they had a survey understanding of the environment. The second task was to find routes between target locations in the real space; this assessed transfer of layout knowledge to the real building.

(i) Map drawing. Participants were given a 16×16 grid of dots and were asked to draw a map of the layout by connecting the dots with lines representing 15 foot (4.6 m) hallway segments. They also labeled the positions of the targets.

The accuracy of the map drawings was determined by a method adapted from Waller et al (2001). This method assessed only the accuracy of target placement on the maps relative to each other and thus did not consider how accurately the corridor network was depicted.

Error (E) was the sum of the distances, measured in hallway units, of the estimated locations of targets from their actual locations [equation (1) from Waller et al (2001)]. The vectors $\boldsymbol{\xi}$ and $\boldsymbol{\psi}$ were the coordinates of the actual locations of targets for each map and vectors $\boldsymbol{x}'$ and $\boldsymbol{y}'$ were the coordinates of the estimated locations of targets on the corresponding participant maps. The coordinates for actual and estimated target locations were centered relative to the average of these coordinates [equation (2) adapted from Waller et al (2001)]. The participant target placements were also rotated and scaled to produce a minimum error score for each map:

$$E = \sum_{i=1}^{n} \left[(\xi_i - x_i')^2 + (\psi_i - y_i')^2 \right]^{1/2} , \tag{1}$$

where

$$x' = x_i - \frac{1}{n} \sum_{j=1}^{n} x_j \, ; \quad y' = y_i - \frac{1}{n} \sum_{j=1}^{n} y_j \, . \tag{2}$$

(ii) Target localization. Participants were instructed to find the locations of targets in the real-building layout corresponding to the virtual layout they had explored. They navigated to targets in an order determined by the experimenter. If participants incorrectly localized a target, they were taken to the correct location to start the next trial. This method prevented errors made on a single trial from affecting performance on subsequent trials. Acoustic information about target locations was not available during this test. Participants received a score for target-localization accuracy for each of the four layouts learned. This score was calculated as the proportion of targets correctly located out of the total number of targets (four per layout).

Data analysis. Learning was assessed by measuring both the acquisition rate and the accuracy of spatial knowledge when participants explored layouts in the four presentation modes. Repeated-measures analyses of variance (ANOVAs) were conducted for acquisition rate and map error measures. Friedman tests (the non-parametric version of repeated-measures ANOVAs) were conducted for target-localization performance since the data for this measure were non-normal and could not be sufficiently corrected with transformations. Bonferroni-corrected pairwise tests determined which presentation modes accounted for significant differences in performance. Effect size, or how much the variance in the data was accounted for by presentation mode, was measured by partial eta squared (η_{p}^2).

2.2 *Results*

2.2.1 *Acquisition of layout knowledge.* There was a significant effect of presentation mode on the rate of acquisition of layout knowledge ($F_{3,45} = 28.785$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.66$). As shown in figure 3, acquisition was significantly faster (ie fewer moves were required to reach criterion learning) in the photorealistic VE than in the sparse VE ($p = 0.003$). The map and real-building conditions also required significantly less exploration compared to the sparse VE (map and real building: $p < 0.001$). Three participants included in this analysis did not pass the learning criterion in the sparse VE condition, but the accuracy of their layout knowledge was still assessed. These data are included in the following analyses because excluding them did not alter the pattern of results.

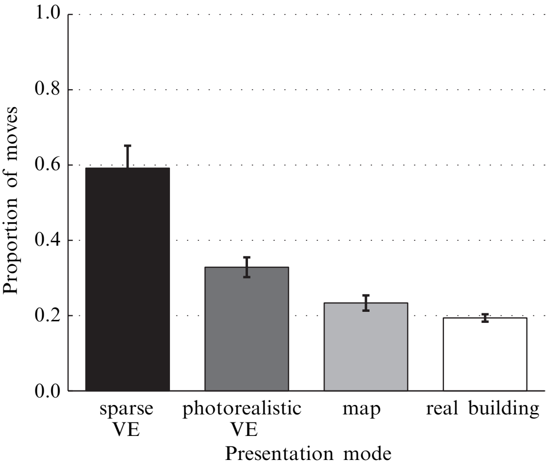


Figure 3. Exploration required for layout acquisition. Mean proportion of moves used by younger normally sighted participants to reach criterion learning in four presentation modes. Error bars indicate ±1 SE. The proportion of moves used is calculated as the number of moves they used divided by the total number of moves allowed to reach criterion learning. VE, virtual environment.

2.2.2 *Accuracy of layout knowledge.* No significant difference was found in target-localization performance between the four presentation modes ($\eta_p^2 = 0.09$) (figure 4). Although a significant difference was found in map drawing error ($F_{3,45} = 4.497$, $p = 0.008$, $\eta_p^2 = 0.23$), pairwise comparisons were not significant (figure 5). Individual scores on the target-localization and map drawing tasks averaged across conditions were significantly correlated ($p < 0.001$) with a correlation coefficient of -0.838. The overall trend for both tasks was that performance was least accurate in the sparse VE condition. Interestingly, a high proportion of targets was correctly located in the real space after learning in all presentation modes, indicating that the visual information provided in each condition, even in the sparse VE, was sufficient for learning to navigate between targets.

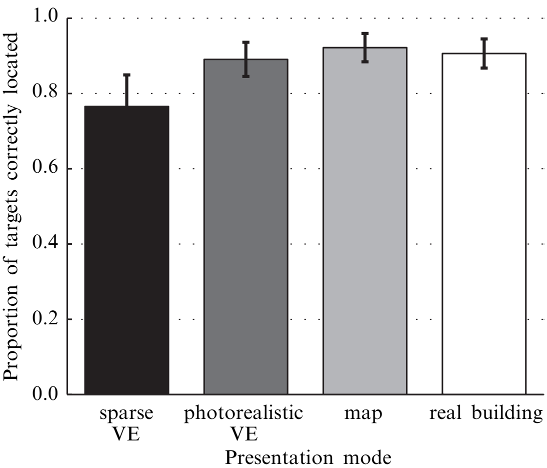


Figure 4. Target-localization accuracy. Mean proportion of targets correctly localized by younger normally sighted participants in four presentation modes. Error bars indicate ±1 SE. VE, virtual environment.

2.2.3 *The effect of videogame experience on performance.* Considering the age range of these participants, it is possible that videogame experience influenced performance in the VEs. Games such as first-person action and driving/racing games require navigating from a first-person perspective through VEs that are visually sparse, at least were so at the time of testing (ca 2004). Participants who played these types of games may have exhibited better performance in the sparse VE compared to people without videogame experience. Therefore, we conducted a post-experiment survey to evaluate the videogame experience of our participants 4 years after they were tested. We were

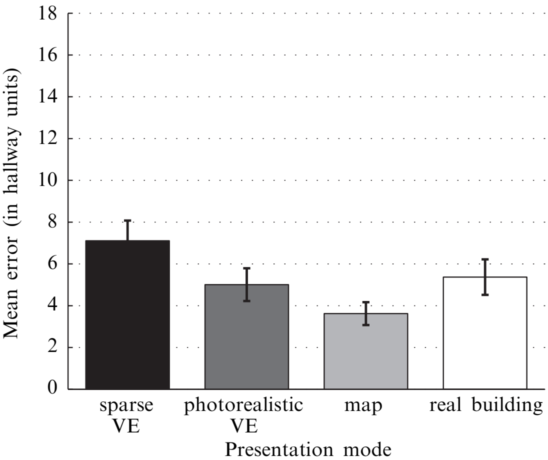


Figure 5. Map drawing error. Mean error (measured in number of 15 foot hallway units) in the map drawing task by younger normally sighted participants in four presentation modes. Error bars indicate ±1 SE. VE, virtual environment.

able to obtain data for only eleven of the sixteen participants. Six of these participants did not have experience with videogames at the time of the study; the other five spent at least 0.5 h per week playing videogames that involved navigating through VEs.

The target-localization performance and map drawing error of the videogame players and non-videogame players are shown in figures 6 and 7. Wilcoxon rank sum tests (the non-parametric version of the independent samplers t-test) did not reveal significant differences across conditions between participants with and without videogame experience in either the target-localization or the map drawing tasks. We acknowledge a trend that videogame players have higher target-localization accuracy in all conditions compared to non-videogame players, as shown in figure 6, but this difference was not significant. Because we were specifically interested in whether videogame experience accounted for similar performance in the sparse and photorealistic VEs, we conducted a Wilcoxon signed rank test (the non-parametric version of the matched-samples t-test) to compare performance in the VEs of the non-videogame players. We did not find significant differences in either target-localization accuracy or map drawing error, suggesting that videogame experience did not selectively improve performance in the sparse VE.

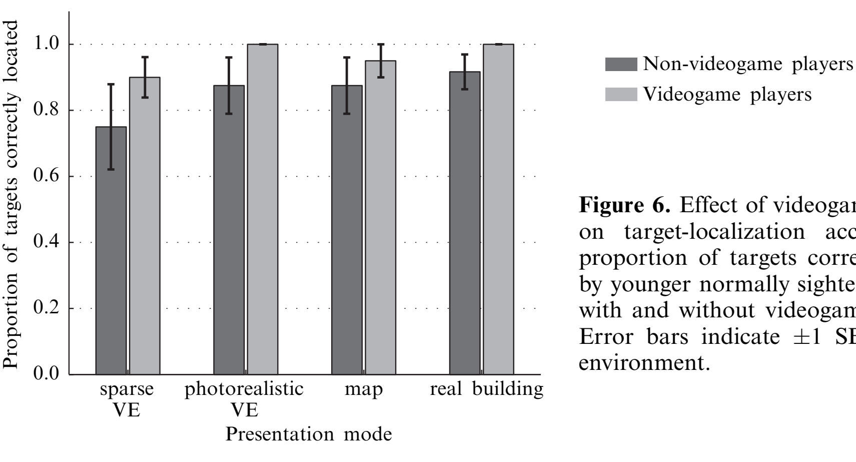


Figure 6. Effect of videogame experience on target-localization accuracy. Mean proportion of targets correctly localized by younger normally sighted participants with and without videogame experience. Error bars indicate ±1 SE. VE, virtual environment.

2.3 *Discussion*

For the normally sighted young adults we tested in this experiment, the type of visual information rendered in the first-person VEs significantly affected the acquisition rate but not the accuracy of layout knowledge. Non-geometric cues accelerated the acquisition of layout information; significantly less exploration was needed in the photorealistic

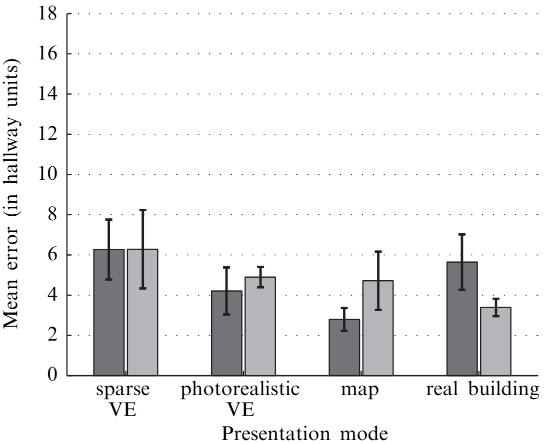


Figure 7. Effect of videogame experience on map drawing error. Mean error (measured in number of 15 foot hallway units) in the map drawing task by younger normally-sighted participants with and without videogame experience. Error bars indicate ±1 SE. VE, virtual environment.

VE compared to the sparse VE to learn the locations of targets in the layout. However, participants demonstrated similar layout knowledge after learning in either the sparse or photorealistic VE, which supports previous findings that non-geometric cues do not improve the accuracy of the acquired mental representation (Ruddle et al 1997; Thompson et al 2004). We interpret these results as showing that non-geometric information speeds up acquisition of layout knowledge for novel environments, but is not necessary for developing an accurate mental representation of the space.

Learning layouts in the map and real-building conditions did not significantly improve performance compared to learning in the photorealistic VE, indicating no advantage of having global layout information or non-visual cues. It is possible that the localization task was not challenging enough to distinguish performance between the photorealistic VE, map, and real-building conditions. Also, the types of VEs or tasks used to measure performance may influence these results. Previous studies in photorealistic VEs found that non-visual cues increase the efficiency of navigational search (Ruddle and Lessels 2006) and the ability to accurately point to targets in a layout (Waller et al 2004). Non-visual information also aids spatial updating when only sparse visual information is available (Chance et al 1998; Klatzky et al 1998). As in the current study, Ruddle and Peruch (2004) found that non-visual information did not improve target localization, measured as the distance travelled to targets, in mazes that included non-geometric cues. Our study is in agreement with this finding that non-visual information may not be useful for learning the locations of targets when non-geometric visual information is available.

Videogame experience did not account for comparable layout knowledge after learning in the sparse and photorealistic VEs. It is known that action videogames improve perceptual abilities such as the capacity, spatial distribution, and temporal characteristics of visual attention (Green and Bavelier 2003), but their influence on spatial navigation abilities needs further investigation. Studies that have examined the effect of prior computer experience and attitudes towards computers on VE learning have found mixed results (Waller 2000; Waller et al 2001); therefore, it is still unclear how computer experience might influence performance.

In experiment 1 we replicated previous findings that non-geometric information does not improve the accuracy of mental representations of building layouts for younger, normally sighted individuals. In experiment 2 we investigated whether the same is true for people with visual impairments.

3 Experiment 2

In experiment 2, we predicted that low-vision participants would acquire more accurate cognitive maps when learning in the sparse VE compared to the photorealistic VE because critical geometric information was rendered with high-contrast features, and extraneous non-geometric cues were removed. The presence of non-geometric features would hinder learning if they are hard to identify or are treated as visual clutter rather than as useful information. The idea of contrast enhancement to improve everyday activities for people with visual impairment is incorporated into closed-circuit TV (CCTV) magnifiers (Lund and Watson 1997) and has been explored in image-enhancement algorithms for face recognition (Peli et al 1994) and TV images (Peli 2005).

A practical goal of this experiment was to assess the potential utility of virtual visual displays as navigation aids for people with low vision. Blind individuals can use tactile maps (Holmes et al 1996) and verbal descriptions of layout geometry (Giudice 2004; Giudice et al 2007) to learn a layout before visiting it. Sparse VEs that display high-contrast renderings of geometrical information may also be useful low-vision aids if they improve wayfinding.

3.1 *Methods*

In experiment 2 we followed the same procedure as in experiment 1 except for the alterations discussed below.

3.1.1 *Participants.* Thirteen people with low vision (mean age = 41 years, SD = 18 years; six males, seven females) were recruited from the community. Participants had a wide range of visual characteristics as described in table 1. Visual acuity was measured with the Lighthouse Distance Visual Acuity chart. Contrast sensitivity was measured with the Pelli–Robson chart. Diagnosis and field status were obtained from reports supplied by the participant's ophthalmologist or optometrist. The participants were not familiar with the Psychology Building where the testing took place and received monetary compensation for their time.

We were non-selective in the nature of the visual conditions of the participants because our focus was on the general effect of low vision rather than on specific types of visual impairment. Enrollment was restricted to individuals with no known cognitive deficits or physical deficits that limited mobility, and to individuals with vision adequate enough to perceive the features in the VEs necessary for the navigation tasks. The experiments were time-consuming, requiring 5–6 h for each participant. Because of the length and demands of the testing paradigm, our sampling of low-vision participants was skewed towards younger individuals with long-standing forms of visual impairment.

3.1.2 *Materials.* The environments displayed on a computer were the same as in experiment 1 with one exception. In the map condition, the cursor was an enlarged, blinking, white-and-black triangle embedded in a gray square. The size of the triangle could be altered for each participant to ensure that its position and pointing direction could be seen.

3.1.3 *Procedure.* Participants were trained in each presentation mode displayed on the computer. The experimenter described in detail the features displayed on the computer screen (eg doors, windows, and lighting reflections in the photorealistic VE) and verified that participants could see and describe the geometry of nearby intersections as rendered on the screen. Next, participants practiced moving through the layout using key-presses, and followed a series of directions given by the experimenter (eg "Turn at the next intersection"). Participants had to successfully follow the experimenter's directions before continuing with testing.

Table 1. Description of the thirteen low-vision participants tested in experiment 2. Central field loss is scotoma within 5° of the fovea. Peripheral field loss is scotoma anywhere outside 5° from the fovea.

Participant	Age/ years	Gender	Diagnosis	LogMAR acuity	Log contrast sensitivity	Field loss
1	25	F	aniridia	0.78	1.65	none
2	20	M	retinitis pigmentosa	1.34	1.35	peripheral
3	29	F	albinism	0.9	1.5	peripheral
4	31	M	retinitis pigmentosa	0.58	0.9	peripheral
5	52	F	retinopathy of prematurity, nystagmus	0.96	1.05	peripheral
6	24	F	retinopathy of prematurity	1.18	0.9	none
7	38	M	Stargardts disease	1.04	1.05	central
8	53	F	optic atrophy, no vision in left eye	1.52	0.3	details not available
9	18	M	scotoma caused by brain tumour	1.02	1.2	details not available
10	67	M	macular degeneration in left eye, cataracts in both	0.88	0.9	central
11	51	M	macular degeneration (Doynes' macular dystrophy)	1.04	1.65	central
12	66	F	cone–rod dystrophy	0.70	1.20	central
13	62	F	retinitis pigmentosa	1.24	0.45	peripheral with spread to central

Low-vision participants used Lego™ to create a map of each layout. They were instructed to build hallways by connecting Lego™ pieces on a 15×15 grid of nodes. Each Lego™ piece represented one 15 foot (4.6 m) hallway segment in the real environment. Participants also pointed to the target locations on their Lego™ map.

3.2 *Results*

3.2.1 *Acquisition of layout knowledge.* The rate of acquisition was significantly affected by presentation mode ($F_{3,36} = 19.107$, $p < 0.001$, $\eta_p^2 = 0.61$); participants spent significantly more time exploring in the sparse VE than either with the map or in the real building ($p < 0.001$) (figure 8). However, there was not a significant difference in exploration time between the sparse and photorealistic VEs. Five of the eleven participants used as many or more moves to explore the photorealistic VEs compared to the sparse VEs. Therefore, acquisition of layout information was not necessarily easier with non-geometric information than with only geometric information, but varied by individual.

Six participants (participants 5, 7, 8, 10, 12, and 13 from table 1) did not pass the learning test in the sparse VE, and of them, two (participants 8 and 10) did not pass criterion in the photorealistic VE. Also, there was a significant order effect ($F_{3,36} = 4.847$, $p = 0.006$, $\eta_p^2 = 0.29$), but pairwise comparisons did not reveal significant differences between conditions.

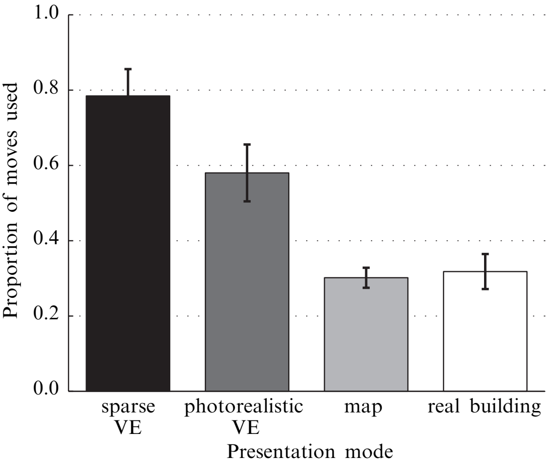


Figure 8. Exploration required for layout acquisition. Mean proportion of moves used by low-vision participants to reach criterion learning in four presentation modes. Error bars indicate ±1 SE. VE, virtual environment.

3.2.2 *Accuracy of layout knowledge.* Significant differences were found in both target-localization accuracy ($\chi^2_3 = 18.73$, $p < 0.001$, $\eta^2_\text{p} = 0.48$) and map drawing error ($F_{3,33} = 9.503$, $p < 0.001$, $\eta^2_\text{p} = 0.46$). These results are presented in figures 9 and 10. Performance in both tasks after learning in the photorealistic VE was better than in the sparse VE ($p < 0.01$), but similar to learning in the map and real-building conditions. These findings suggest that, contrary to our prediction, low-vision participants developed more accurate mental representations of layouts in the photorealistic VE than in the sparse VE. Furthermore, target localization was less accurate in the sparse VE condition than in the map ($p = 0.002$) and real-building ($p < 0.001$) conditions. Map drawing error was also greater after learning in the sparse VE compared to learning in the map condition ($p = 0.007$).

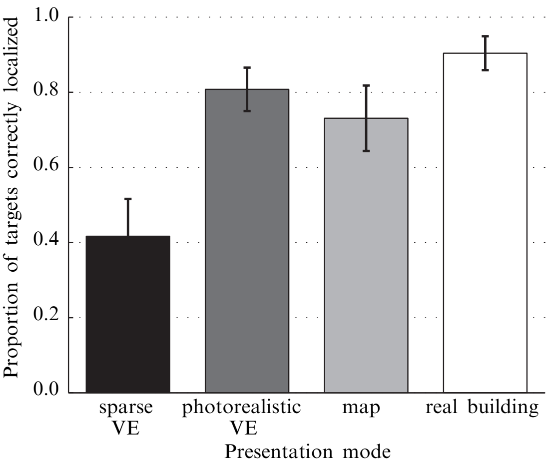


Figure 9. Target-localization accuracy. Mean proportion of targets correctly localized by low-vision participants in four presentation modes. Error bars indicate ±1 SE. VE, virtual environment.

3.2.3 *Relationship between performance and ocular factors.* Learning by participants in the VEs may be related to the nature of their visual impairment. Although we did not select participants with the goal of linking their performance to ocular factors, we did examine the relevant correlations to determine what relationships might exist. Also, because we recruited participants who had enough vision to see the VEs, there is likely a restriction in the range of acuity, contrast sensitivity, and field loss of those tested.

Acuity did not correlate with any of the performance measures for either the sparse or photorealistic VE. Strong correlations were found between the proportion of moves used during learning and log threshold contrast sensitivity in both the sparse VE

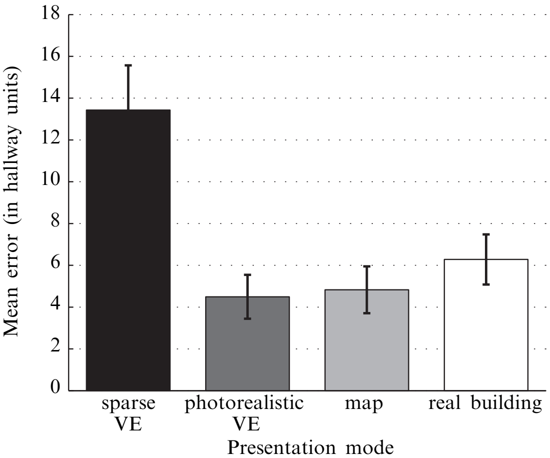


Figure 10. Map drawing error. Mean error (in hallway units) in the map drawing task by low-vision participants in four presentation modes. Error bars indicate ±1 SE. VE, virtual environment.

($r = -0.696$, $p = 0.008$) and the photorealistic VE ($r = -0.700$, $p = 0.008$). Previous research has also shown that contrast sensitivity has a greater impact on orientation and mobility than acuity (Marron and Bailey 1982). We did not have sufficient information on visual-field status to compute correlations, but previous studies indicate that visual-field loss is associated with increased errors in obstacle avoidance (Turano et al 2004). Field loss from eye disease (Rieser et al 1992) or artificial restriction (Mason 2002) also results in decreased wayfinding performance.

3.3 *Discussion*

Contrary to our prediction, low-vision participants demonstrated more accurate layout knowledge after learning with non-geometric information than with only high-contrast geometric information. Performance after learning in the photorealistic VE was equivalent to learning with a map or in a real building. Yet, acquisition of layout knowledge required similar amounts of exploration in both types of VEs.

Many participants did not pass the learning criterion with geometric information only. Given more exploration time, a difference might have emerged in the acquisition rate between the two VEs, and the difference in the accuracy of layout knowledge may have disappeared. Either scenario indicates that acquiring layout knowledge is more difficult with only geometric visual information.

Because performance in the photorealistic VE was comparable to learning with a map or in the real building, difficulty in acquiring layout knowledge in the sparse VE cannot be attributed to a lack of familiarity with first-person VEs or with the keystroke interface. Therefore, the results must be due to the visual information provided in these displays and how they are used to learn the layout.

In experiment 2 we also demonstrated that people with low vision can use visual displays to learn novel layouts; learning with a map or a photorealistic VE was comparable to learning by walking around in the real space. Both types of computer displays could potentially be used for pre-journey exploration and familiarization with buildings. High-contrast visual maps via a laptop or personal digital assistant (PDA) could be used on the fly during travel. Also, low-vision participants performed better with maps than in the photorealistic VE, a result found previously with normally sighted participants (Farrell et al 2003). This result, and the fact that it is easier and less costly to generate maps of buildings, suggest that maps are more practical as a visual navigation aid than VEs for the visually impaired.

The broad age distribution of the low-vision participants may be a contributing factor to the reduced performance in the sparse VE. Our low-vision group included seven participants younger than 50 and six older than 50. All but one of the participants who did not pass the learning test in the sparse VE were older than 50 years. This observation suggests that older participants may have had more difficulty acquiring layout knowledge in the sparse VE. The goal of experiment 3 was to test the effects of age on our navigation tasks, which helped in interpreting the low-vision results in experiment 2.

4 Experiment 3

Visual impairments are more common among the older population, largely because of the prevalence of age-related eye diseases. Non-visual age-related factors might contribute to the ability to use only geometric or additional non-geometric information when learning indoor layouts, as suggested previously by Moffat and Resnick (2002). Therefore, in experiment 3 we tested a group of older participants (ages 50 – 70 years) with normal vision to explore whether age affects the ability to learn layouts in the sparse and photorealistic VEs.

4.1 *Methods*

4.1.1 *Participants.* We tested four males and four females between the ages of 50 and 70 years (mean age = 60 years, SD = 5 years), all with normal or corrected-to-normal vision. All participants passed the Mini-Mental State Exam (scores ranged from 29 – 30 out of 30), designed to assess general cognitive functioning. Participants were also asked to rate their health status (1 = poor, 5 = very healthy, median participant rating = 4.5); level of activity (1 = not active, 5 = very active, median rating = 4); driving experience (1 = never drive, 4 = drive daily, median rating = 4); and computer experience (1 = never use computer, 4 = use computer daily, median rating = 3). Participants were not familiar with the psychology building where testing took place and were monetarily compensated for their time.

4.1.2 *Procedure.* The materials and procedure were identical to those used in experiment 1 except that participants were not tested in the map condition because the primary purpose was to assess how age affects performance in the sparse and photorealistic VE conditions.

4.2 *Results*

4.2.1 *Acquisition of layout knowledge.* Rates of acquisition varied significantly by presentation mode ($F_{2,14} = 27.973$, $p < 0.001$, $\eta_p^2 = 0.80$). Significantly more exploration was required in the sparse and photorealistic VEs than in the real building ($p < 0.01$) as shown in figure 11. However, there was no difference in exploration time between the two VEs. Furthermore, six participants were not able to pass the learning criterion in the sparse VE, and four of these participants also did not pass in the photorealistic VE.

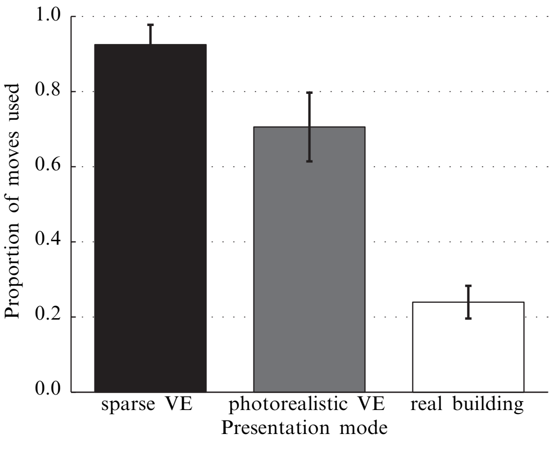


Figure 11. Exploration required for layout acquisition. Mean proportion of moves used by older normally sighted participants to reach criterion learning in three presentation modes. Error bars indicate ±1 SE. VE, virtual environment.

This indicates that some participants found it particularly difficult to learn layouts using desktop VEs.

4.2.2 *Accuracy of layout knowledge.* Performance on target localization varied significantly with presentation mode ($\chi^2_2 = 11.12$, $p = 0.004$, $\eta^2_p = 0.70$). As depicted in figure 12, performance was significantly worse after learning in the sparse VE than in either the photorealistic VE ($p = 0.012$) or in the real building ($p = 0.003$). Similar to the case of low-vision participants, non-geometric visual information was useful for encoding and representing the correct locations of targets in memory. Map drawing performance did not reveal significant differences between presentation modes ($F_{2,14} = 3.263$, $p = 0.069$, $\eta^2_p = 0.32$), although the trend was still that layout knowledge was least accurate in the sparse VE (figure 13). There were no significant correlations between individual ratings of computer ability and acquisition rate or accuracy of layout knowledge.

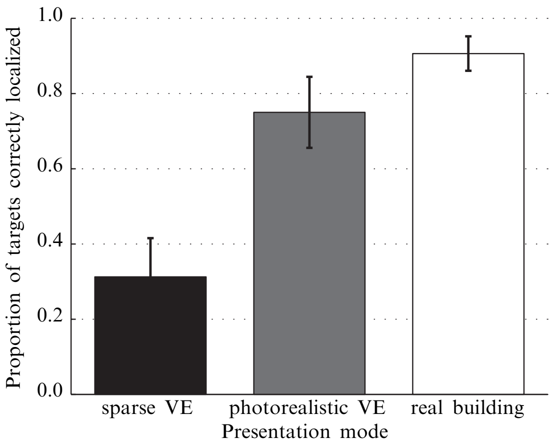


Figure 12. Target-localization accuracy. Mean proportion of targets correctly localized by older normally sighted participants in three presentation modes. Error bars indicate ±1 SE. VE, virtual environment.

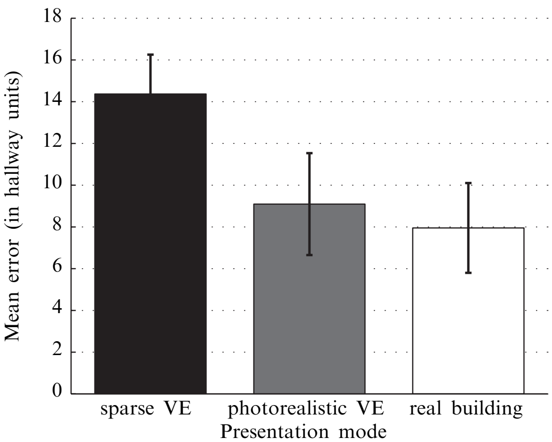


Figure 13. Map drawing error. Mean error (in hallway units) in the map drawing task by older normally sighted participants in three presentation modes. Error bars indicate ±1 SE. VE, virtual environment.

4.2.3 *Comparing the effects of visual impairment and age on performance.* The results of the older normally sighted adults showed a similar pattern to the low-vision group (experiment 2). The acquisition rates for both groups showed that the sparse VE required the most exploration to pass the learning criterion, but not significantly more than the photorealistic VE. Furthermore, both the low-vision and older groups demonstrated significant differences in overall layout knowledge between presentation modes. Target-localization accuracy was most affected by the visual information available during learning; both groups performed significantly worse after learning in the sparse VE compared to the photorealistic VE.

Figure 14 combines target-localization data from all three experiments in a plot of performance by visual ability and age. It indicates that individuals in the same age group had similar target-localization scores regardless of visual ability. We carried out Wilcoxon rank sum tests to evaluate the effects of visual condition and age, and a Friedman test to evaluate the effect of presentation mode. The results revealed a significant effect of age ($p = 0.011$) but not of visual condition. There was also a highly significant effect of presentation mode ($\chi^2_2 = 26.14$, $p < 0.001$) with significant differences between the sparse VE and the other conditions (Bonferroni-corrected pairwise comparisons: $p < 0.001$). Wilcoxon rank sum tests between the performance of younger and older individuals in the three presentation modes revealed a significant effect only in the sparse VE ($p = 0.002$) but not in the other conditions. Together, these results suggest that age, rather than the conjunction of age and vision loss, drives performance in the sparse and photorealistic VEs. Older people find it much more difficult to learn layouts solely on the basis of geometric information, and therefore seem to benefit more from the addition of non-geometric cues.

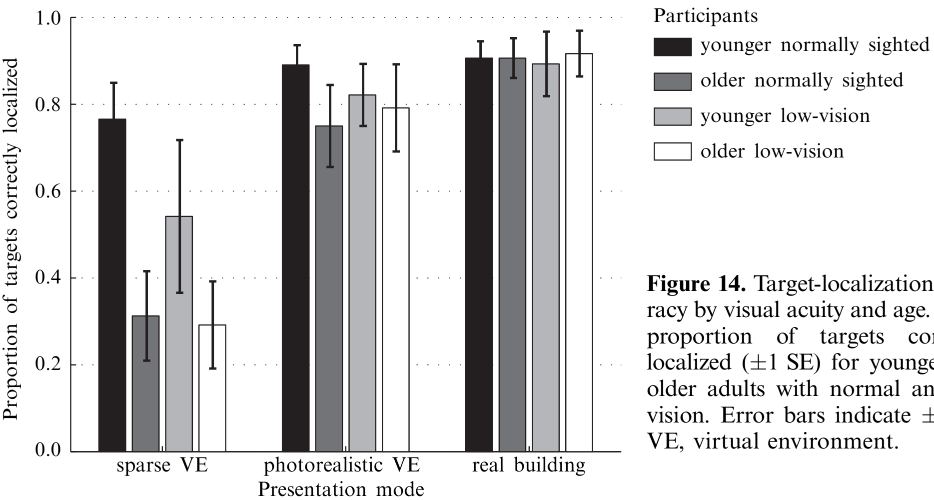


Figure 14. Target-localization accuracy by visual acuity and age. Mean proportion of targets correctly localized (±1 SE) for younger and older adults with normal and low vision. Error bars indicate ±1 SE. VE, virtual environment.

4.3 *Discussion*

These results indicate that age does influence the ability to learn layouts in VEs. Older participants had difficulty on tasks assessing layout knowledge, especially target localization, after learning in the sparse VE, which is consistent with previous studies (Moffat and Resnick 2002). This indicates that the decreased performance of low-vision participants in the geometric environment (experiment 2) could be at least partially due to the inclusion of older participants.

Aging is related to declines in declarative learning, which is influenced by working memory capability (Kirasic et al 1996). The demands of trying to disambiguate position with only geometric visual information may impose more cognitive load than can be handled by older people, resulting in a decreased ability to encode layout information. Previous research has demonstrated that even younger adults exhibit less than optimal navigation performance compared to an ideal observer because of limitations in remembering their path in geometric environments (Stankiewicz et al 2006). Older individuals may be even more affected by memory limitations while navigating and may rely more on non-geometric cues that require fewer cognitive resources when encoding locations in a mental representation of a layout. This coincides with the results of previous experiments that have suggested that older adults reproduce target locations more accurately with object landmark information than with only geometric information (Moffat and Resnick 2002).

Non-visual information, associated with walking in the real building, was advantageous for older normally sighted adults, allowing them to learn layouts more quickly. These cues seem to facilitate memory for spatial layout, perhaps by reducing the cognitive load required to integrate information over multiple views in the vision-only environments.

5 General discussion

In these experiments we investigated the types of visual information needed by younger and older normal and low-vision individuals when learning novel indoor layouts. By comparing performance in sparse and photorealistic VEs, we specifically tested whether geometric information by itself (sparse VEs) was sufficient for learning layouts from a first-person perspective or whether the rendering of additional non-geometric information (photorealistic VEs) was advantageous. We measured both the acquisition and the accuracy of layout knowledge after learning in the different presentation modes (sparse VE, photorealistic VE, map, and real building).

5.1 *Resolving ambiguous geometric visual information*

All groups of participants found it more difficult to learn layouts with only geometric information; the addition of non-geometric information improved acquisition and/or accuracy of layout knowledge. Geometric visual renderings can result in ambiguity about locations in a layout. For example, the rectangular environments described in section 1 had identical geometric structures at opposite corners that were easily confusable for rats (Cheng 1986) or children (Hermer and Spelke 1996). The same geometric ambiguities can exist in more complex environments. For example, suppose a layout, rendered only with geometric hallway structure, has two T-junctions. When you arrive at a T-junction, how do you know which one it is?

Consider two options for resolving the ambiguity. (i) Perceptual solution: the two T-junctions may differ in the distances to adjacent intersections and the branching patterns at the adjacent intersections. If you encoded geometric information to this level of detail during layout acquisition, you can use it to resolve the ambiguity. (ii) Path memory: you can resolve the ambiguity if you remember your previous location and the path taken to reach the current T-junction, assuming a unique path is required to reach each T-junction from the previous location. Both of these techniques provide means for spatial updating within purely geometric layouts, but require demanding perceptual encoding and/or memory processes.

It is plausible that impaired vision or natural aging could reduce the capacity to accomplish perceptually or cognitively demanding spatial updating. Individuals with visual impairments may not be able to detect perceptual differences in layout structure, and older adults may have reduced memory capacity. If so, a third kind of mechanism, the presence of additional redundant non-geometric cues, could be helpful. For instance, one of the two T-junctions might have a water fountain that could resolve the geometrical ambiguity if either of the two strategies previously outlined could not be used. Thus, non-geometric information may be especially useful for people with visual impairment or who are older.

5.2 *Conclusions*

The acquisition of layout knowledge was clearly influenced by the visual information available during exploration for all groups of participants. Non-geometric visual cues reduced the amount of exploration needed to learn a novel layout, especially for younger normally sighted individuals.

Non-geometric information improved the accuracy of layout knowledge for both the low-vision and the older normally sighted groups, but not for younger normally sighted individuals. Low-vision and older sighted people especially benefited when localizing targets in the real building after learning layouts with non-geometric information.

It is likely that age was a contributing factor in explaining the relatively poor performance of the low-vision participants when only geometric information was available during learning, as indicated by figure 14. One implication is that degradation in visual function does not necessarily lead to reduced performance. Also, considering that the low-vision population is older, this age effect is important in determining the types of visual displays that will be useful navigation aids for people with low vision.

We also compared learning in the first-person VEs to learning with maps and in a real building. Learning in the map condition resulted in similar performance to those in the photorealistic VE and the real building in all three experiments, suggesting no advantage to having global layout information when visually rich information from a first-person perspective is available. Non-visual information was only advantageous for older normally sighted adults.

Finally, we demonstrated that people with low vision can learn layouts as effectively using maps and photorealistic VEs displayed on a desktop computer as walking through a real building. Yet, older individuals may not learn as quickly in VEs as in real buildings.

In conclusion, this study showed that information about layout geometry is sufficient for learning complex indoor layouts, at least by younger individuals with normal vision. Additional non-geometric information aids learning by low-vision and older people. The reason for this reliance on non-geometric information may be due to the increased cognitive demands required to create and use cognitive maps with only geometric information. A positive practical outcome is that individuals with low vision can use virtual displays to learn layouts prior to going to a real building, which may have applications for developing indoor navigation aids.

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