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Research article

Gaze behavior during navigation with reduced acuity

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ABSTRACT

Navigating unfamiliar indoor spaces while visually searching for objects of interest is a challenge faced by people with visual impairment. We asked how restricting visual acuity of normally sighted subjects would affect visual search and navigation in a real world environment, and how their performance would compare to subjects with naturally occurring low vision.

Two experiments were conducted. In the first, 8 normally sighted subjects walked along an indoor path, looking for objects placed at unpredictable intervals to the left and right of the path, and identified single letters posted on the objects. A head-mounted eye tracker was used to assess their gaze direction in the environment. For half the trials, blur foils were used to restrict visual acuity to approximately logMAR 1.65. Gaze behavior, travel time, and letter recognition accuracy were compared between blurred and unrestricted conditions. In the second experiment, the same procedure was conducted, but performance was compared between acuity-restricted normally-sighted subjects and subjects with naturally occurring low vision (mean acuity 1.09 logMAR, range 0.48–1.85 logMAR).

In Experiment 1, neither Blur nor the Letter Recognition Task individually had a statistically significant effect on travel time. However, when combined, there was an interaction between the two that increased travel time by approximately 63%, relative to baseline trials. Blur modified gaze behavior such that subjects spent more time looking down toward the floor while walking, at the expense of time spent looking in other directions. During Letter Recognition Task trials with Blur, subjects spent extra time examining objects, though more objects were missed altogether. In Experiment 2, low-vision subjects spent more time looking toward the boundary between the floor and the wall, but gaze patterns were otherwise similar to acuity-restricted subjects with normal vision. Low-vision subjects were also more likely to miss objects compared to acuity-restricted subjects.

We conclude that under conditions of artificially restricted acuity, normally sighted subjects look downward toward the floor more frequently while navigating and take extra time to examine objects of interest, but are less likely to detect them. Low-vision subjects tend to direct their gaze toward the boundary between the wall and the floor, which may serve as a high contrast cue for navigation.

1. Introduction

Low vision, the impairment of visual function due to reduced acuity or restriction of the visual field, is associated with mobility problems, including increased travel times (Kuyk and Elliot, 1999; Patel et al., 2006; Turano et al., 2004) difficulty navigating unfamiliar environments (Hassan, Hicks, Lei & Turano, 2007), and increased collisions with obstacles (Kuyk, Elliott, Biehl, Fuhr, 1996; Patla, Sebastian, and Ishac, 2004). Gaze behavior, the control of the line of sight via rotation of the eyes in their orbits and the orientation of the head on the body (Freedman, 2008), has been shown to be affected by vision loss (Vargas-Martin and Peli, 2006, Geruschat, Hassan & Turano, 2003; Turano, Geruschat, Baker, Stahl & Shapiro, 2001).

Gaze behavior with low vision is of particular interest as an indicator of the visual cues that draw attention to important environmental features, such as signs, doorways, or tripping hazards, which aid in navigation, and why such environmental features are sometimes missed. A clear understanding of this behavior will inform environmental and architectural design and contribute to enhanced visual accessibility.

The present study was conducted to address two primary questions. First, how is gaze behavior affected by artificial acuity reduction? Second, how does the gaze behavior of low-vision subjects compare to the gaze behavior of normally sighted subjects with artificial acuity

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Table 1
Low-vision subject information.

Subject #	Gender	Age (Years)	Diagnosis	Acuity (logMAR)	Field Loss
1	F	42	Bilateral Retinopathy	1.30	Peripheral
2	M	28	Glaucoma	0.48	Peripheral
3	M	32	Retinopathy of Prematurity	1.0	Central
4	F	81	AMD	1.85	Central
5	F	58	Familial Exudative Vitreoretinopathy	1.48	Central
6	F	57	Diabetic Retinopathy	1.30	Peripheral
7	M	68	Glaucoma	0.78	Peripheral
8	F	74	AMD	0.54	Central

reduction? To investigate these issues, we performed two experiments, each focused on how visual impairment affects where subjects direct their gaze while navigating.

In Experiment 1, normally sighted subjects wore blur goggles to reduce acuity. We asked if artificially reduced acuity affected where people looked while they walked, what they looked at, and how long they looked. Previous work has found notable differences between how subjects explore a space with and without visual impairment. For instance, Legge et al, (2016) found that severe artificial acuity restrictions affected judgment of the dimensions of indoor spaces. After entering a rectangular room, subjects were asked to estimate the length of the walls. Unrestricted, subjects typically had fairly accurate judgements, estimating within 20% of the wall's true length. However, when their acuity was artificially restricted to approximately 20/900, subjects systematically overestimated the size of the room they had moved through, in some cases nearly doubling the magnitude of their errors. The present study further investigates the impact of artificial acuity restriction, assessing whether it affects gaze behavior as well as spatial perception.

Our second question, the focus of Experiment 2, addresses how closely the gaze behavior of low-vision subjects resembles the gaze behavior of normally sighted subjects with artificial acuity reduction. An informative research strategy has been to artificially reduce acuity or restrict the visual field of normally sighted subjects. This strategy allows for the standardization of visual conditions between subjects, and is sometimes logistically simpler than recruiting low-vision subjects. However, testing at one or two acuity or visual field levels can be problematic, as it does not capture the diversity of visual conditions or experiential factors found among people with natural low vision. Therefore, it is important to compare the effects of artificial restriction to the effects of natural low vision. After testing a group of eight low-vision subjects on the same letter recognition task as the artificially restricted normally-sighted group, we compared data from each group. In both experiments, a head mounted eye tracker was used to determine gaze direction during trials.

Previous work has assessed how low vision can affect mobility by counting the number of times subjects physically contacted objects in a high density, indoor obstacle course (Kuyk, Elliott, Biehl and Fuhr, 1996). For subjects with impaired visual acuity, obstacle avoidance was improved when objects had a high degree of contrast with their background. Another approach has been to utilize eye tracking to examine gaze behavior during navigation. Turano et al. (2001) found that low-vision subjects directed their gaze differently from normally sighted controls when walking through a novel environment. Using a head mounted video display in conjunction with an eye tracker, they showed that subjects with retinitis pigmentosa exhibit a scanning behavior not seen in controls. This scanning led to a sampling of a fixation area three times larger than controls, a possible compensation for visual field loss. In another eye tracking study, the effects of low vision on gaze behavior were examined while subjects watched video of a walk through an indoor space (Aspinall et al., 2014). Lower visual acuity was associated with a greater number of fixations, particularly in sections of the walk that subjects subjectively rated as difficult to navigate. Our procedure builds upon this prior research by using an ecologically relevant object search/letter recognition task, combined with visually-dependent outcome measures in a real world, physical space.

The current study was part of a larger program of research in our lab aimed at addressing one of the major problems faced by people with low vision – visual accessibility. For a space to be visually accessible, it must facilitate the use of vision for safe and efficient navigation, perception of its key features, and provide cues for the pedestrian's orientation within the space. In several studies, we have tested performance of normally sighted subjects with artificial acuity reduction and field restriction, and also subjects with low vision. These studies have focused on perception of local features within indoor spaces, such as steps and ramps (Legge, Yu, Kallie, Bochsler & Gage, 2010; Bochsler, Legge, Kallie & Gage, 2012; Bochsler, Legge, Gage & Kallie, 2013) and the perception of large-scale features such as room size and cues to one's location and orientation within the space (Legge et al., 2016a,b). Here, we examine how restricted acuity affects where subjects distribute their gaze among small and large scale features while navigating and completing a letter recognition task.

2. Methods

2.1. Participants

Eight normally sighted subjects participated in Experiment 1, mean age of 23 (range = 16–49 years), and all corrected to 20/20 acuity or better. Eight low-vision subjects participated in Experiment 2, their mean visual acuity was logMAR = 1.09 (in their better eye), with a mean age of 55 years (individual data in Table 1). Participants' visual acuities were measured using a Lighthouse Distance Visual Acuity chart. One participant required their service dog to complete the study's tasks; however, the service dog did not impede the participant's navigation mobility while navigating the course. All subjects gave written informed consent after the nature of the study was described. The research procedures were approved by the University of Minnesota Internal Review Board, and adhered to the tenets of the Declaration of Helsinki.

2.2. Eye tracker setup

Before each experiment, subjects were outfitted with the Tobii Glasses 1 (this model is no longer commercially available), a mobile head-mounted eye tracker, shown in Fig. 2 (Tobii Technology, Inc., Falls Church, VA., https://www.tobii.com/). The device is a pair of glasses, which is attached with a wire to a small control module. Viewing through the glasses is binocular, while the eye tracking is monocular in the right eye. The device includes a forward facing scene camera on the right arm of the glasses, used to record video for the duration of the experiment. The scene camera records at a resolution of 0.1 degrees of visual angle/pixel, at 30 frames per second. The glasses weigh 75 g, and were secured on the head with an adjustable strap, while the control module was either clipped onto the subjects' belt, or held in the left hand. The eye tracker was calibrated with a 9-point

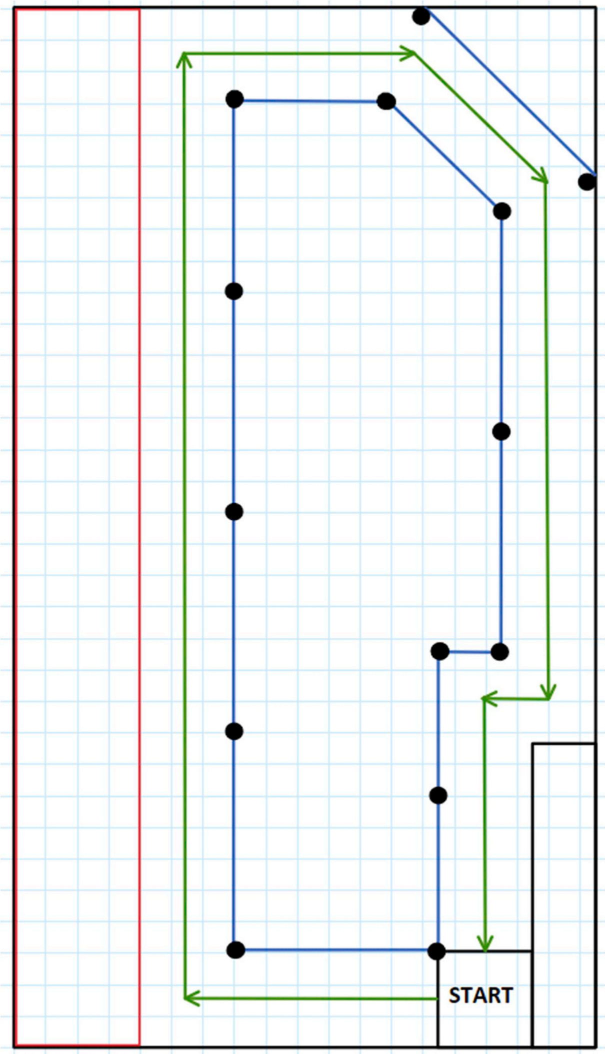


Fig. 1. A blueprint of the experimental space used for both experiments. The box labeled "START" is where subjects began each trial, while the green arrows indicate the path they walked around the room. The blue lines represent the chain boundary, which subjects held onto as they walked. The black circles indicate the locations of stanchions, which were used to hold up the chain. The red box on the left side represents a raised platform that objects were placed on, and which constituted the left side of the path for that section of the course. Each square on the background grid is scaled to one square foot.

fixation method, according to manufacturer specifications. After calibration was complete, the glasses began recording video. Subjects were then asked to fixate on a target placed 3 m directly in front of them, at their eye height, for 30 s. This was done to establish a reference point within the video frame for a natural forward facing head position, which was dubbed the primary gaze location, and will be discussed further in the Video Analysis section.

2.3. Experimental procedure

2.3.1. Walking course

Subjects completed eight trials, each composed of walking along a path, which made one lap around the perimeter of a room. Subjects were instructed to walk at whatever pace felt most comfortable to them, and to hold onto a guide chain with their right hand while they walked. The chain served to guide them safely along the path. The path was 23.5 m (77 ft) in length, and included four 90° turns, as well as two 45° turns. All turns were to the right, except for the final turn, which was to the left. The testing room is illustrated in Fig. 1, a blueprint of the trial course. The total time it took subjects to walk around the course was recorded for each trial and was used as one of our dependent variables.

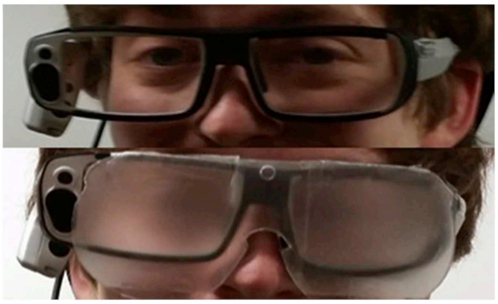


Fig. 2. The Tobii glasses, a head mounted eye tracker, with the forward facing video camera visible on the right arm. The monocular eye tracker is partially visible behind the forward facing camera. The bottom panel shows the glasses with acuity restricting blur foils attached.

2.3.2. Trial conditions

In Experiment 1, with normally sighted subjects, there were eight trial conditions, defined by the presence or absence of three factors: Artificial Acuity Reduction, an Object Search and Letter Recognition Task, and Artificial Puddles to avoid. Trials in the absence of the three factors were called Baseline trials. These trials were conducted to determine course completion time and gaze behavior during free walking. The order of conditions was counterbalanced across the eight subjects.

Artificial Acuity Restriction, which will henceforth be referred to as "Blur," was accomplished by attaching Bangerter Occlusion Foils (Odell, Leske, Hatt, Adams & Holmes, 2008) to the front of the glasses, which occluded subject vision (also used in our lab's previous work to artificially restrict acuity, Legge et al., 2010). This setup is shown in Fig. 2. The blur foils restricted normally sighted subjects to an effective acuity of 1.65 logMAR (Snellen 20/900), based on acuity measurements through the foils with the Lighthouse Distance Visual Acuity Chart.

In the Object Search and Letter Recognition Task, henceforth referred to ask the "Letter Recognition Task," subjects visually located eight objects that were placed adjacent to the path, and identified the letters posted on them. Objects were made from white polystyrene, were either cylinders or rectangular prisms, and were either 60 or 120 cm in height. Letters were black, 15 cm tall, printed on cardstock paper, and attached to the objects with a pin. Objects were set up on both the left and right side of the path, at distances between 0.6 and 1.5 m from the guide chain, in four distinct configurations (one for each of the four Letter Recognition Task trials). Objects on the right side of the path were always placed on the floor, while those on the left side of the path were placed on a raised platform, such that target letters were one foot higher than for objects on the right side. The layout for each trial was unique, requiring subjects to search the room as they walked. Subject responses were classified as "correct" if they correctly reported the letter on the object, "incorrect" if they reported the wrong letter, or "miss" if did not report the letter or object at all. During trials without the Letter Recognition Task, the objects were removed from the course. Subjects were told they did not need to search for any objects.

Ground clutter, henceforth referred to as "Artificial Puddles," were placed on the walking path. Subjects were instructed to avoid stepping on them, as if they were real pools of water. Puddles were made of black paper and were all small enough to avoid with a single step. The choice of high contrast black paper was made to ensure that subjects would see the puddles, maximizing their effect on gaze behavior. Like objects, Puddles were placed in different locations for each layout, requiring subjects to notice their location as they walked. The walking path, Puddles, and objects are pictured in Fig. 3.

Low-vision subjects were tested in Experiment 2. There were four

Fig. 3. A picture of the course layout showing the objects set up for the Letter Recognition Task with Artificial Puddles. In the Letter Recognition Task condition, objects had one letter pinned on them, and could be placed either on the left or on the right side of the path. During trials without the Letter Recognition Task, objects were lined up against the wall on the left side of this photo, with no letters attached to them.

trial conditions, defined by the presence or absence of the Letter Recognition Task and Artificial Puddles. Each subject was tested twice in each condition for a total of eight trials, matching the number of trials for the normally sighted subjects in Experiment 1. Trial instructions were the same as in Experiment 1.

2.3.3. Subject instructions

Before each trial began, subjects were read a set of instructions concerning the trial. Different instructions were given depending on whether subjects completed the Letter Recognition Task or not, and whether the Artificial Puddles were present on the course or not.

During Baseline trials (no Letter Recognition Task, no Puddles), subjects were instructed to walk through the course at their normal, comfortable walking speed, holding onto the guidance chain with their right hand for the duration of the trial. They were told there were no obstacles or targets to find, they simply had to walk around the course once.

During Letter Recognition Task trials, subjects were instructed to look for objects as they walked, while holding on to the chain boundary, and to read out loud the letter posted on each object. They were reminded that objects were placed on both the left and right sides of the path. They were asked to try to identify letters accurately, but not to spend too much time on a letter if they could not identify it quickly. Alternatively, if they were unsure about what letter was posted (or if they found an object but could not find the letter), they could guess, or they could report that they saw something, but could not tell which letter it was. When subjects reported they were unsure, their response was recorded as incorrect. They were once again reminded to walk at their most comfortable pace for one lap around the room, and to hold on to the chain at all times. They were also instructed to not lean over the chain or crouch down to get a better look at the objects.

Before trials with Artificial Puddles, subjects were told that there would be several Puddles on the path as they walk. They were told to do their best to avoid stepping in them, as they would with real aquatic puddles.

2.4. Video Analysis

2.4.1. Establishing the primary gaze location

Before trials began in each experiment, subjects were instructed to fixate on a target directly in front of them for 30 s. This was recorded using the forward facing camera on the eye tracking headset, and the average pixel location (in x and y coordinates on the screen) where this target appeared within the video was marked as the "Primary Gaze Location (PGL)." The PGL was a static point in the video frame that indicated where a subject's gaze would be directed if their eyes were fixating straight ahead, at optical infinity.

2.4.2. Video coding

The PGL was used to analyze the forward facing video to assess where subjects were looking as they completed trials. This was done because fixation data could not be gathered for several low-vision subjects, due to calibration difficulty and problems imaging the right eye. Environmental cues, such as the guidance chain and the floor-wall boundary, were used to divide the space into directional categories, both horizontally and vertically, illustrated in Fig. 4. Horizontally, these categories included "left of the path," "on the path," and "right of the path." Vertically, the categories were "Floor," "Floor-wall boundary," and "above the floor wall boundary." Researchers manually coded the recorded video offline (interrater agreement for all frames: horizontal axis = 83%, vertical axis = 77%), using Tobii Studio software (Tobii Technology, Sweden), marking each video frame with both a horizontal and vertical gaze category label. If the PGL came within 5° of vertical angle from the floor wall boundary, gaze was classified into that category. A fourth category, "object inspection," was also included in the analysis of Letter Recognition Task trials, used when the PGL was on or near (within 5°) of an object. The duration spent looking toward each gaze category was calculated using the total number of frames spent looking in each category. Thus, gaze behavior was quantified by the total time spent looking in each direction category, or at target objects.

The PGL was also compared between the beginning and end of the experiment for each subject, to check for slipping or moving of the glasses on the face. While there were minor differences for some subjects, none of these differences exceeded 5°.

2.5. Statistical analyses

In both experiments, there were two types of performance measures – total travel duration (in seconds), and the distribution of gaze durations (in seconds) across the directional categories. The effects of the experimental conditions (Blur, Letter Recognition Task, etc.) were

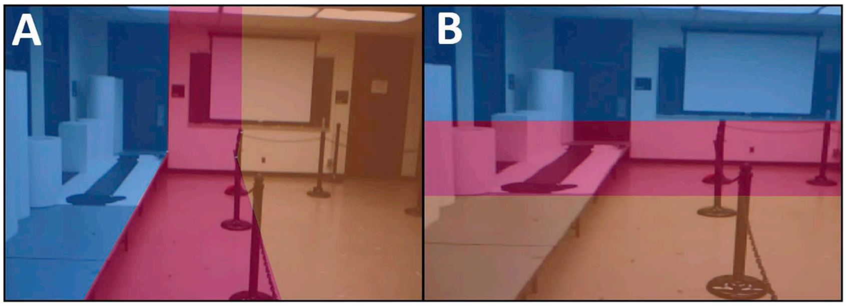


Fig. 4. Directional gaze categories. Panel A illustrates the categories along the horizontal axis (blue = left, pink = path inspection, orange = right), while panel B illustrates categories along the vertical axis (blue = above floor-wall boundary, pink = floor-wall boundary, orange = floor).

treated as difference scores with respect to baseline times. Effect sizes of the conditions were checked using a linear mixed-effects (LME) model fit to the data using the nlme package of R (Bates et al., 2015). For Experiment 1 analysis, "Blur", "Task", and "Puddles" were included as fixed effects, within-subject factors. Analysis of Experiment 2 used the same fixed effects, but here Blur was replaced with a "Group" (low vision vs normal vision with blur) between-subjects factor. A random effect, "Subject," was also included to account for variance due to individual differences in both analyses. For the Experiment 1, a repeated measures 3-way ANOVA was conducted on the fitted coefficients to determine identify significant interaction effects and simple main effects, at a significance threshold of p = .05. For Experiment 2, a mixed design 3-way ANOVA was used for the same purpose. Simple main effects were investigated using paired samples t-tests, comparing relevant trial conditions' times to baseline times for each group. These tests were also utilized to assess the effects of independent variables when ANOVA results showed no interaction effects. Significance of those tests was determined after applying the Bonferroni correction for Type I error. 95% Confidence intervals for travel time and gaze direction time variables were calculated using the normal Bootstrap method within the lme4 package by sampling data with replacement (N = 10,000) for each participant trial.

3. Results

3.1. *Experiment 1: effect of artificial acuity reduction*

Normally sighted subjects were tested with blur foils which artificially reduced their acuity. Three independent variables were manipulated: 1) whether or not subjects navigated with artificially reduced acuity (Blur), 2) whether or not subjects completed the Letter Recognition Task while navigating, 3) whether or not ground clutter (Puddles) were placed on the ground while subjects walked. There were two dependent measures: 1) the time to walk around the course (Travel Time), and 2) time spent looking in various directional categories (Gaze Direction).

3.1.1. *Travel Time*

Fig. 5 shows the mean travel times for all eight possible conditions. Mean baseline travel time, without Blur, Letter Recognition Task, or Puddles, was 23.9 s (C.I. = ± 6.2 s).

ANOVA testing showed a statistically significant two-way interaction between Blur and Task *F*(1,49) = 25.439, $p < .001$. Blur increased mean travel time by 5.3 s (CI = ± 5.6), and showed a statistically significant simple main effect, *F*(1, 49) = 85.153, p < .001. However, after Bonferroni correction to a significance threshold of p = .025, pairwise comparison with the baseline showed no significant difference for Blur trials (without the Letter Recognition Task or Puddles), t(7) = −2.548, *p* = .0382. Similarly, Letter Recognition Task increased mean time by 3.2 s (CI = ± 5.6), and showed a statistically significant simple main effect, *F*(1, 49) = 55.05, $p < .001$, but was not statistically significant upon pairwise comparison with the baseline, t(7) = −2.282, *p* = .0565. There was also a statistically significant simple main effect for trials with both Blur and Task, *F*(1, 49) = 25.439, p < .001, which increased travel time by 15.1 s on average (CI = ± 8). This effect was significantly different from baseline, t(7) = −4.907, *p* = .002, indicating that the combination of Blur and Letter Recognition Task was enough to increase travel times, while neither did so independently.

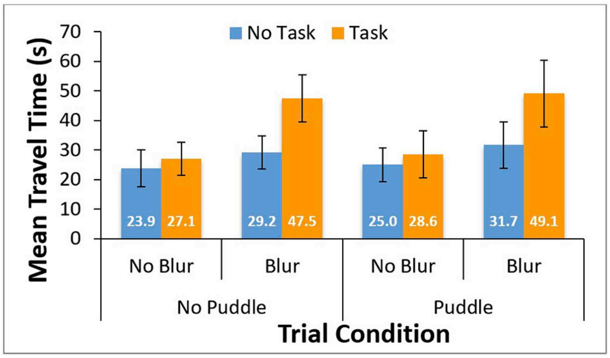


Fig. 5. Effect of Trial Condition on Travel Time. Mean travel durations for normally sighted subjects under different trial conditions. Error bars represent 95% confidence intervals. Trial conditions are grouped by those that did not include Artificial Puddles (50% of all trials) on the left, and those that Included the Artificial Puddles on the Right. The orange bars refer to those of trials which included the Letter Recognition Task (50% of all trials). Travel time for each condition is specified at the base of each bar.

3.1.2. *Gaze Direction*

The results of the gaze direction analysis are displayed in Table 2, including LME fixed effect coefficients and 95% confidence intervals. Table 2 includes only the effects of the dependent variables, not interactions, as there were no significant interaction effects. Therefore, the effects of the independent variables were assessed via multiple comparisons via pairwise t-tests. Effects that were found to be significantly different from the baseline after Bonferroni correction are marked with an asterisk in the table.

The key finding for this experiment is that Blur modified the distribution of gaze times during Letter Recognition Task trials. Specifically, Blur increased the time spent looking toward objects during Letter Recognition Trials. In Task trials without Blur, subjects spent on average 3.3 s (CI = ± 3.9) looking at objects. However, with Blur, this time was significantly increased, t(7) = −5.065, p = .001, to 16.1 s (CI = ± 4.8).

Unsurprisingly, pairwise comparisons of trials with the Letter Recognition Task showed that it affected times spent looking left, right, and at the path straight, refer to Table 2 for effect sizes. After Bonferroni correction, the effect of the Letter Recognition Task on gaze times in all three directional categories was found to be statistically significant upon pairwise comparison with baseline times. Looking left was significantly affected at t(7) = −6.352, p < .001, looking right at t(7) = −4.569, p = .002, and looking ahead toward the path at t(7) = 5.741, p = .001.

3.2. *Experiment 2: Comparing performance of low-vision subjects and normally sighted subjects with artificial acuity reduction*

In Experiment 2, the low-vision subjects were tested in four conditions – with and without Puddles, and with and without the Letter Recognition Task. Their results were compared with the corresponding data from the normally sighted subjects with Blur in Experiment 1. Once again, the dependent variables were Travel Time and Gaze Direction.

3.2.1. *Travel Time*

Fig. 6 shows mean travel times for the Blurred normal and low-vision groups in the four conditions. Mean baseline travel time, without the Letter Recognition Task or Puddles, was 29.2 s (CI = ± 16.4) for low-vision subjects and 23.9 s (CI = ± 6.4). There were no significant interaction effects, indicating there was no significant difference between the low vision and Blurred normal group with respect to trial time. The Letter Recognition Task added 18.3 s (CI = ± 11.1) to travel time, averaged across both groups. Pairwise comparison with the baseline showed this effect was significantly different from baseline, at t(7) = −3.842, p = .006.

3.2.2. *Gaze Direction*

The results of gaze analysis for the Blurred normal and low-vision groups are presented in Table 3, which is formatted in the same fashion

Table 2
Effects of Trial Conditions on Gaze Direction Durations for Normally Sighted Subjects Estimated from the LME Model. Rows represent trial conditions, while columns represent gaze direction categories (color coded in reference to Fig. 4). Here, "above floor-wall boundary is replaced with "Wall." Cells in the "Baseline Time" row display the amount of time in seconds spent looking in each direction while subjects walked the course on baseline trials (those with no Blur, no Letter Recognition Task, and no Puddles; subjects simply walked around the course). Cells in subsequent rows contain LME fixed effect coefficients (representing the effect of each condition on gaze time on each category) in seconds, as compared to the baseline. Values in parentheses below the coefficient are 95% confidence intervals around that value. Cells marked with an asterisk indicate category-condition combinations with statistically significant simple main effects, which were found to be significantly different from the baseline upon Bonferroni corrected pairwise comparisons.

		Horizontal Categories			Vertical Categories		
		Left	Path	Right	Wall	Boundary	Floor
	Baseline Time (s)	.1 (±0.7)	21.5 (±4.8)	2.3 (±2.8)	12.6 (±3.9)	4.8 (±2.3)	6 (±6.5)
LME Coefficient	Blur	+0.3 (±1)	+3.3 (±4.6)	+2 (±3.6)	-4.5 (±4.8)	+3.2 (±3.3)	+6.7 (±6.1)
	Task	+2.4* (±1)	-8.2* (±4.7)	+6.2* (±3.7)	-3.4 (±4.8)	+3.4 (±3.2)	+0.6 (±6.1)
	Puddle	+0.2 (±1)	+2.0 (±4.6)	-0.7 (±3.7)	-9.3* (±4.8)	+3 (±3.3)	+7.6* (±6.1)

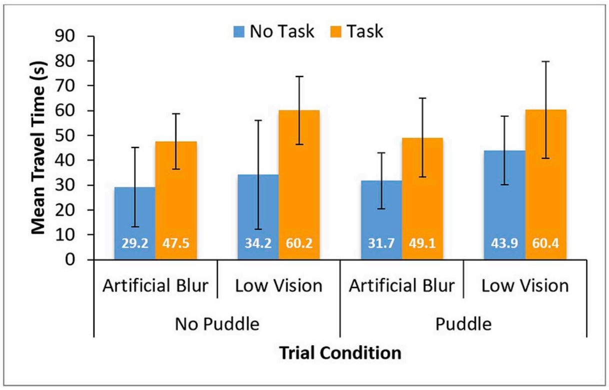


Fig. 6. Mean travel times for normally sighted subjects with Artificial Blur (the controls for this experiment) and low vision subjects under different trial conditions. Error bars represent 95% confidence intervals. Trial conditions are grouped by those that did not include Artificial Puddles (50% of all trials) on the left, and those that Included the Artificial Puddles on the Right. The orange bars refer to those of trials which included the Letter Recognition Task (50% of all trials). Travel time for each condition is specified at the base of each bar.

as Table 2. Here, trial effects are compared against a baseline defined by the Blurred normal group in the absence of the Letter Recognition Task or Puddles. Although the two groups did not differ in Travel Time, the gaze analysis revealed noticeable differences in the distribution of gaze directions. For example, on trials with no Letter Recognition Task and no Puddles, low-vision subjects spent 7.2 s (CI = ± 4.3) additional seconds on average looking toward the floor-wall boundary. This was found to be a significant increase over baseline time by pairwise comparison, t(12) = −3.856, p = .002 (Reference Fig. 4, the pink section of panel B).

Another key finding was how low-vision subjects adjusted their gaze patterns for Puddle and Letter Recognition Task trials, as compared to the Blurred normal group. For example, during the Puddle condition, the Blurred normal group adjusted their gaze to look downward toward the floor significantly longer, t(7) = −3.875, p = .006, 11.2 s longer on average (CI = ± 7.5). While the low-vision subjects also looked downward longer during Puddle trials, t(7) = −4.427, p = .003, they adjusted less, for an average of 4.9 s (CI = ± 4.6). Low-vision subjects also spent significantly less time, 16.9 s (CI = ± 9.5) looking ahead toward the path during Letter Recognition Task trials, t(7) = 4.218, p = .004. In contrast, after Bonferroni correction, Blurred normals did not spend significantly less time looking toward the path during Letter Recognition Task trials, t(7) = 2.644, p = .033 (threshold = 0.025). There was also no significant difference in the amount of time the groups spent looking at objects.

3.3. Letter recognition accuracy

Letter recognition accuracy for the unrestricted normals, Blurred normals, and low-vision subjects is reported in Table 4.

In the Letter Recognition Task there were 8 objects, each with a posted letter to be recognized. The table shows the percentage of objects entirely missed, the percentage of letters correctly recognized, and the percentage of letters incorrectly recognized (this includes incorrect guesses and responses in which subjects recognized the presence of a letter, but could not identify it). Data are combined across Puddle and no Puddle trials. The top row shows baseline values for normally sighted subjects without Blur from Experiment 1. The second and third rows compare performance for the Blurred normal and low-vision trials.

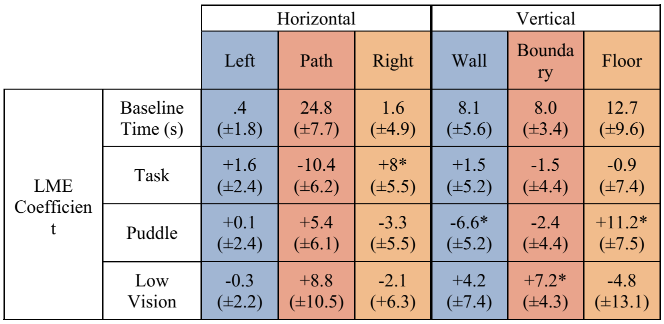
4. Discussion

To briefly review the major results of Experiments 1 and 2:

- Experiment 1, with normally sighted subjects:
  - o Blur and the Letter Recognition Task interacted to increase Travel Time.
  - o Blur increased time spent looking directly at objects during the Letter Recognition Task.
  - o The Letter Recognition Task increased time spent looking to the left and right of the path, at the expense of looking straight ahead at the path itself.
- Experiment 2, comparing Blurred normal and low-vision subjects:
  - o The Letter Recognition Task increased Travel Time for both low-

Table 3

Effects of Trial Conditions on Gaze Direction Durations for Both Acuity Restricted Normally Sighted and Low-Vision Subjects. Using the same format as Table 1, mean time differences (in seconds) spent looking in each gaze direction category, are displayed here. The baseline for these comparisons is the normally sighted group with acuity restriction, without task or Puddles. Confidence intervals are again at 95%. Significant effects after Bonferroni correction are once again marked with an asterisk.



		Horizontal			Vertical		
		Left	Path	Right	Wall	Boundary	Floor
LME Coefficient	Baseline Time (s)	.4 (±1.8)	24.8 (±7.7)	1.6 (±4.9)	8.1 (±5.6)	8.0 (±3.4)	12.7 (±9.6)
	Task	+1.6 (±2.4)	-10.4 (±6.2)	+8* (±5.5)	+1.5 (±5.2)	-1.5 (±4.4)	-0.9 (±7.4)
	Puddle	+0.1 (±2.4)	+5.4 (±6.1)	-3.3 (±5.5)	-6.6* (±5.2)	-2.4 (±4.4)	+11.2* (±7.5)
	Low Vision	-0.3 (±2.2)	+8.8 (±10.5)	-2.1 (+6.3)	+4.2 (±7.4)	+7.2* (±4.3)	-4.8 (±13.1)

		Horizontal			Vertical		
		Left	Path	Right	Wall	Boundary	Floor
LME Coefficient	Baseline Time (s)	.4 (± 1.8)	24.8 (± 7.7)	1.6 (± 4.9)	8.1 (± 5.6)	8.0 (± 3.4)	12.7 (± 9.6)
	Task	+1.6 (± 2.4)	−10.4 (± 6.2)	+8* (± 5.5)	+1.5 (± 5.2)	−1.5 (± 4.4)	−0.9 (± 7.4)
	Puddle	+0.1 (± 2.4)	+5.4 (± 6.1)	−3.3 (± 5.5)	−6.6* (± 5.2)	−2.4 (± 4.4)	+11.2* (± 7.5)
	Low Vision	−0.3 (± 2.2)	+8.8 (± 10.5)	−2.1 (+6.3)	+4.2 (± 7.4)	+7.2* (± 4.3)	−4.8 (± 13.1)

Table 4

Letter recognition accuracy. Percent of total responses to letter stimuli posted on objects during Letter Recognition Task trials. Responses were classified as Correct when subjects reported the letter on the object, Incorrect if they reported any other letter, and Miss if they did not see the letter.

	Correct	Incorrect	Miss
Normal	96%	1%	3%
Blurred-Normal	68%	11%	21%
Low Vision	64%	5%	31%

vision and Blurred normal groups.

- Vision status (low vision or artificial acuity restriction) did not affect Travel Time.
- Low-vision subjects spent more time than Blurred normals looking at the boundary between the floor and the wall.
- Blurred normally sighted subjects were affected more strongly by the presence of puddles, spending more than twice as much time looking downward when they were present.

These experiments were conducted with two primary questions in mind. First, how does reduced acuity affect mobility and a Letter Recognition Task in a novel environment? Second, how do the results obtained from artificially restricting acuity compare to results obtained from subjects with natural low vision?

Experiment 1 aimed to answer the first question, examining how Artificial Acuity Restriction (i.e. “Blur”) and a Letter Recognition Task affected trial performance. Blur alone did not significantly increase travel time, suggesting that low acuity itself did not substantially hinder mobility. Similarly, the Letter Recognition Task did not add sufficient travel time to reach statistical significance, demonstrating that simple visual search alone did not necessitate a slower gait. However, while neither the Blur nor the Letter Recognition Task had a significant effect on Travel Time, the gaze analysis suggests that Blur affected how subjects controlled their gaze during the Letter Recognition Task.

While the effects of the Blur and Letter Recognition Task alone were not significant, the combination of the two had a substantial impact on performance. First looking at travel time, the Blur-Task interaction increased travel times by far more than the sum of their individual effects. Looking to the gaze analysis, most of this extra time was spent looking at objects. We propose that subjects were using that time to read the letters, as the Blur substantially reduced the amount of information available in each fixation. Specifically, the level of fine detail resolution needed for rapid letter discrimination was lost, causing the letters to appear ambiguous. Resolving this ambiguity required either longer fixations on the letters and/or more fixations, both of which added to the travel times. Indeed, while with unrestricted normal vision, subjects could typically read the letters on the move, with Blur they frequently needed to stop walking altogether and examine a letter for several seconds before reporting letter identity.

However, taking extra time to read letters did not solve all the problems imposed by the Blur. In addition to the extra travel time, Blur also caused subjects to completely miss targets far more frequently, and the gaze direction data offers an explanation why. Importantly, gaze time looking to the left or right was not affected by the addition of Blur to the Letter Recognition Task trials. Instead, the excess time was spent looking toward objects. This suggests that while subjects were taking extra time to examine individual objects, they were not devoting the necessary time to searching the room for other objects. The effect of this gaze pattern is clear from the letter response accuracy data; letters were missed nearly twice as frequently as they were incorrectly read. It seems that with Blurred acuity, normally sighted subjects were able to read letters correctly most of the time, if they took the time to examine them. This effect suggests that the saliency of targets themselves, rather than just the legibility of text on them, was likely a major contributor to letter recognition accuracy. After all, subjects could not correctly read letters they could not find.

How did the performance of the acuity-restricted, normally sighted subjects compare with the low-vision subject group in Experiment 2? Travel times were similar for the two groups, but we observed some differences in their gaze behavior. For example, the low-vision group spent more time looking toward the floor-wall boundary in conditions without the Letter Recognition Task or Puddles. We propose that in some situations, the floor-wall boundary can serve as a functionally significant spatial layout cue for these low-vision subjects. If the boundary between the floor and wall is a high contrast cue, the angle between the viewer's line of sight and the boundary can provide information about both the dimensions of a room, and the viewer's location within it. This was true in the room in which testing was conducted for these experiments, and our viewing data suggests that this was indeed a point of interest for low-vision subjects. This idea was proposed in a study conducted by Legge et al., in 2016, after finding that low-vision subjects performed as well as normally sighted subjects when estimating room size. This strategy may be a key difference between the artificially restricted subjects and the low-vision subjects. While using the floor wall boundary as a spatial cue is useful, it is not an immediately obvious tactic for someone navigating with restricted acuity for the first time. Learning to take advantage of such a subtle element of the environment is a tactic that would come with time and experience navigating with impaired vision, and this difference is reflected in the gaze behavior of the two groups.

This use of the floor wall boundary may be analogous to behavior observed in previous research on gaze control during navigation. Foulsham, Walker, and Kingstone (2011) found that while walking outdoors, normally sighted subjects directed their field of view such that the center of their gaze fell slightly below the horizon. The authors suggest that this could have been an important orientation strategy, utilizing the horizon as a stable reference point while navigating a large, outdoor space. We propose that indoors, the floor wall boundary assumes the role of the horizon while navigating, serving as a stable reference point, visible from anywhere in the room. This cue may be especially important for low-vision subjects, who do not benefit as much from other sources of orientation information.

Our data bear some similarities to the results from Turano et al. (2001). They showed that persons with visual field loss due to advanced retinitis pigmentosa directed their gaze differently from normally sighted controls while navigating. While walking through a novel environment, their subjects with field loss fixated on different targets than those with normal vision. In particular, boundaries between walls and the floor, ceiling, and other walls were fixated more frequently. Our finding, that subjects with low vision spent more time looking toward the floor-wall boundary, mirrors that result. Also worth noting is that we did not find any systematic differences in total trial duration or gaze behavior between those subjects with central field loss and those with peripheral field loss. We acknowledge that our sample size for the two categories of field loss was small at four subjects for each type.

The letter recognition accuracy data may have also been affected by field loss differences between the groups. Referring to Table 4, missing targets was a more common cause of error in the low-vision group than in the Blurred group, at 31% and 21% of total responses, respectively. What could have caused this difference in miss rate? We propose that with a smaller field of view, any given fixation is less likely to land on or near a target. Therefore, finding all the targets would require far more visual scanning and/or searching, which may be troublesome while also maintaining balance while walking. Thus, it may have been necessary for these subjects to make a trade-off between spending extra time to search for objects and efficiently moving through the course, resulting in a lower detection rate. One might expect to see a substantial difference in miss rate between those subjects with central field loss, and those with peripheral field loss, as those with peripheral loss would seemingly be less likely to catch a target in their field of view with a single given glance. This was not the case for our subject group, wherein those with peripheral loss missed 33% of targets, and those with central field loss missed 29% of targets. Given the course nature of our field loss classification and small sample size, this difference does not seem conclusive either way. That being said, exploring how these different forms of field loss affect target detection could be a worthwhile direction for future study.

Extrapolating this finding to a real-world situation, it seems that the visibility of a sign itself, and its location in a room, should be considered as important as the legibility of the text on it. After all, even a highly legible sign will offer no help if it is not seen in the first place. This issue was raised by Arditi (2017), who noted that there are no strict requirements for directional (e.g. “Bathroom →“) sign placement in the 2010 Americans with Disabilities Act's Standards for Accessible Design protocol. Arditi proposes that developing a consistent, approachable location for these signs will be valuable for aiding indoor navigation for people with low vision. For instance, signs could be placed at consistent distance above floor-wall boundaries, where people with low vision naturally direct their gaze while navigating, to provide a more reliable location to search when attempting to locate signage.

We acknowledge two issues regarding our subject groups: age differences between the low-vision and normally sighted group, and the generalizability of the low-vision group to the visually impaired population at large. Our normally sighted group was much younger than our low-vision group, and it is possible that our results may have been different with age-matched groups. For instance, older subjects may generally walk more slowly than younger subjects. But since we found that the mean travel times for our low-vision group was similar to the travel time of the normally sighted group with blur, it is plausible that reduced acuity was more important than age in determining travel time.

Regarding generalizability, it is important to note the heterogeneity of eye conditions and life experiences within the low-vision population. While our eight subjects certainly provide insight into how real visual impairment affects gaze and navigation behavior, we emphasize that these conclusions should not be uncritically applied to all people living with visual impairment.

5. Conclusion

In summary, we addressed two primary issues with this study. In Experiment 1, we found that the combination of a Letter Recognition Task and restricted acuity slows walking speed far more than either effect alone, and that subjects were using this extra time to read the letters. However, while subjects compensated for acuity restriction by focusing on letters they found, they frequently missed target objects altogether, suggesting that finding targets is as problematic as discerning text or other features on the targets. In Experiment 2, we found that travel time and overall accuracy data were similar between the subjects with low vision and normally sighted subjects with artificial acuity reduction. However, gaze behavior showed interesting differences between the two groups, as artificially restricted subjects did not look toward the floor wall boundary for as long, possibly due to underdeveloped cue utilization strategies.

Declarations of interest

None.

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