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**FACULTY OF GRADUATE AND  
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**Spatial Vision Meets Spatial Cognition:  
Examining the Effect of Visual Blur on Human Navigation Performance**

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**Spatial Vision Meets Spatial Cognition:  
Examining the Effect of Visual Blur on Human Navigation Performance**

Megan E. Therrien

Thesis submitted to the  
Faculty of Graduate and Postdoctoral Studies  
In partial fulfillment of the requirements  
For the MA degree in Experimental Psychology

School of Psychology  
Faculty of Social Sciences  
University of Ottawa

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Statement of Candidate Contribution

The candidate, Megan Elizabeth Therrien, was the primary contributor to all of the following work that forms her MA thesis. In terms of the entire research process, she was the primary contributor to the conception of the thesis questions and the methods used to analyze these questions, the data collection and analyses, and the writing of the thesis itself. Dr. Charles Collin offered a supportive role in all of the above aspects, including sharing knowledge, advice, direction, and editing.

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## Abstract

Navigation is a task that involves processing two-dimensional light patterns on the retinas to obtain knowledge about how to move through a three-dimensional environment.

Therefore, modifying the basic characteristics of the two-dimensional information provided to navigators should have important and informative effects on how they form their representations of the environment. Despite this, few basic research studies have examined the effects of systematically modifying the available levels of spatial visual detail on mobility performance. In this study we tested the effects of a range of visual blur levels—approximately equivalent to various degrees of low-pass spatial frequency filtering—on participants' route learning performance using desktop virtual renderings of the Hebb-Williams mazes. Our findings show that the function of blur and time to finish the mazes follows a sigmoidal pattern, with the inflection point around +2 diopters of blur. This suggests that visually guided route learning is fairly robust to blur, with the threshold level being just above the limit for legal blindness. These findings have implications for models of route learning, as well as for practical situations in which humans must navigate under conditions of blur.

## Introduction

Navigation is a fundamental ability of animals that has been explored from a vast range of perspectives, so much so that the mouse in the maze has become an icon of psychology. Despite this wealth of research, there has been very little exploration of the basic spatial visual aspects of navigation. Although a great deal of applied and clinical work has investigated perceptual effects on this class of tasks, no studies have parametrically examined the effect of basic manipulations of spatial details as they apply specifically to route learning. This is unfortunate, because route learning is an important aspect of navigation, and it is fundamentally a task that involves transforming two-dimensional spatial variations in luminance on the retinas into information about the observer's three-dimensional environment. Changes in the basic characteristics of the two-dimensional spatial inputs to the navigation system will no doubt have an impact on the formation of the representations of three-dimensional space, and exploring such effects will almost certainly inform models of spatial cognition in important ways.

At the outset, we wish to define and constrain our use of the term *navigation*. In its broadest sense, this term refers to an extensive array of tasks whose performance is affected by a wide range of variables. For example, navigation in real-world settings is affected by the nature and density of landmarks, as well as the availability of proprioceptive and vestibular cues. In the current work, we are interested in examining a narrower concept involving the use of visual information alone to learn a route from point A to point B in an environment, without the aid of explicit landmarks or proprioceptive cues. We therefore refer to our study as examining *visually guided route learning*

performance. This term is used to differentiate the construct we are examining from the larger concept of navigation in general.

In the present study we provide an experimental examination of the effects of manipulating spatial frequency (SF) on visually guided route learning in humans. Specifically, we examine the effects of applying defocus, via spherical lenses of various strengths, on maze completion times in a desktop-style virtual environment. Our goal is to assess to what degree participants can tolerate spatial degradation of their view of an environment while completing a route learning task. In doing so, we are motivated in part by findings regarding the effects of spatial filtering of stimuli on other visually guided tasks. We are also motivated by a number of practical issues, such as navigation by the visually impaired and by individuals experiencing artificially-imposed blur, such as pilots wearing Night Vision Goggles. In the most general sense, we are interested in characterizing the importance of fundamental features of visual information to spatial learning.

#### *Visual Function and Mobility*

While there has been little previous basic research examining the effects of visual blur on mobility, there have been a few studies examining similar issues. For instance, Vivekananda-Schmidt and colleagues (2004) examined the effects of diffusive blur on mobility performance in a real-world environment. They found that contrast sensitivity reductions caused by diffusive blur led to a significant impairment in performance. Participants were slower to walk through a room, and exhibited different visual examination strategies, when their contrast sensitivity was reduced by roughly a factor of two. This shows that reductions in available spatial visual information will have a

significant effect on visually guided mobility. However, because Vivekananda-Schmidt et al. described the route to their participants ahead of time, this study cannot tell us about the effects of blur on route learning. Another limitation to their study was their use of only two levels of contrast sensitivity reduction, which is not enough to allow for information regarding the shape of the function linking spatial information and mobility.

One study that did vary visual function levels parametrically was that by Pelli (1986), who measured mobility performance of normally sighted participants after introducing varying levels of reduced visual acuity, contrast sensitivity, and visual field. Pelli found that it took a substantial reduction in each of these visual functions to produce an effect on performance. However, the routes used in this study were very basic, requiring participants to simply maneuver around a fairly open environment. Therefore, like the Vivekananda-Schmidt study, Pelli's cannot inform us about the effect of blur on route learning.

Other relevant studies have examined more basic components of mobility than those examined in the present study. For instance, Heasley and colleagues (2004, 2005) examined the effect of wearing diffusion-causing lenses--designed to simulate cataracts--on the ability of visually normal older adults to take a step up to a higher level. They found that blur impaired task performance, and suggested that this was likely due, at least in part, to difficulty in seeing the step's edge. Vale and colleagues (2008) examined a similar stepping task, but imposed blur using spherical lenses. They found that as little as +2 diopters of blur introduced to the dominant eye could significantly impair performance. These studies suggest that blur might impair edge detection in a navigation

environment and that this might in turn be an important determinant of visually guided route learning performance.

In addition to this basic research examining the effects of blur on mobility, there has been a great deal of relevant work examining clinical and applied aspects of navigation performance in the visually impaired (see, e.g., Black et al., 1997; Haymes, Guest, Heyes, & Johnston, 1994; Kuyk, Elliott, & Fuhr, 1998a, 1998b; Marron & Bailey, 1982; Patel et al., 2006; Wood & Troutbeck, 1994). Collectively, these studies have shown that a number of visual factors affect mobility performance in these populations, with the greatest effects coming from impairments of contrast sensitivity and visual field deficits. In the present study, we were interested in measuring the effects of parametrically reduced visual acuity (spherical defocus) on route learning performance. Although the literature on visual impairment has generally found this factor to be less important for predicting mobility performance than other factors (see, e.g., Marron & Bailey, 1982; Owsley, Stalvey, Wells, Sloane, & McGwin, 2001; Patel et al., 2006), there are some studies that have found it to have significant effects (see, e.g., Brown, Brabyn, Welch, Haegerstrom-Portnoy, & Colenbrander, 1986; Geruschat, Turano, & Stahl, 1998; Haymes, Guest, Heyes, & Johnston, 1996). One possibility as to why such varied results have been found is that examining the effect of visual acuity deficits in visually impaired populations is complicated by the fact that such impairments are typically co-morbid with other visual deficits such as central scotomas (Hassan, Lovie-Kitchin, & Woods, 2002). This makes it difficult to determine the degree to which visual acuity *per se* is an important determinant of mobility performance. In the current study we aimed to measure

the effects on route learning of parametrically altering visual acuity in isolation. This has not, to our knowledge, been done previously.

Those without visual impairment also sometimes face the necessity of navigating under conditions of visual blur. One example of such a situation concerns those using Night Vision Goggles (NVGs). Although these systems enhance luminance, they do not provide true daytime vision. The view through NVGs is impaired by visual field limitations, dynamic scintillating luminance noise, and—most germane to the current study—a significant degree of blur (Gauthier et al., 2008; Macuda et al., 2005). The effect of this blur on navigation performance has been a concern, as NVG systems are routinely worn by soldiers and pilots who must navigate using them and there is evidence that their use is implicated in many accidents or near-accidents (Braithwaite, Douglass, Durnford, & Lucas, 1998; Vyrnwy-Jones, 1988). Although there have been a number of studies examining the effects of NVGs on navigation and spatial awareness, none have examined the effects of the blur that they produce in isolation. Assessing the function of blur and navigation performance may therefore help guide the design of NVGs and similar systems in the future, possibly enhancing their safety.

#### *Spatial Vision and Visually Guided Cognitive Tasks*

Although there has been relatively little research to date specifically examining the effects of SF manipulations on mobility, there has been a great deal of recent work in spatial vision that has made important inroads into understanding how certain other higher-order visually guided cognitive tasks are performed, particularly visual recognition tasks. For instance, there is a large body of work on how SF manipulations affect face recognition (for a review, see Ruiz-Soler & Beltran, 2006) and object

identification (Biederman & Kalocsai, 1997; Collin, 2006; Collin, Liu, Troje, McMullen, & Chaudhuri, 2004; Collin & McMullen, 2005; Yue, Tjan, & Biederman, 2006). This has allowed the creation of powerful models of these processes that have a high degree of biological plausibility (Serre, Wolf, Bileschi, Riesenhuber & Poggio, 2007; see also Yue et al., 2006). The current study is motivated in part by the likelihood that similar sorts of explorations examining the impact of spatial vision on spatial cognition will yield equally positive insights.

Two general findings have emerged from previous work on the interaction of spatial vision and higher-order cognitive tasks. One is that certain ranges of spatial information are most useful for a given specific task. For instance, in face recognition, a critical band of SFs has been established that seems to contain the information most useful for identification (Bachmann, 1991; Costen, Parker, & Craw, 1994, 1996; Gold, Bennett, & Sekular, 1999; Nasanen, 1999; Parker & Costen, 1999); Object recognition, on the other hand, seems to be possible using a wide range of SFs (Biederman & Kalocsai, 1997; Collin, 2006; Collin et al., 2004). The second general finding in this area is that there is a degree of cognitive penetrability into spatial vision, such that humans are able to attend particular frequency ranges when task demands make this beneficial (Ozgen, Payne, Sowden, & Schyns, 2006; Schyns, 1998). This means that there is a degree of flexibility in the use of spatial visual information, and that human observers are able to extract the most useful available information in the stimulus presented to them.

While it may be that similar sorts of findings to the above will hold for mobility, there are obvious and important differences between this task and visual recognition tasks that need to be considered. For instance, the stimuli in typical visual recognition tasks are

static relative to the observer. By comparison, in typical navigation tasks the environment is in motion relative to the observer most of the time. This provides an important source of information that interacts in a vital way with spatial vision to provide the overall structure of the environment. A rich, moving, three-dimensional environment may provide sufficient higher-order visual cues that altering low-level information may have relatively little impact. This argues for a robustness of mobility performance to visual blur, relative to performance with static images.

Another relevant difference between visual recognition—particularly face recognition tasks—and mobility, is that the former often involves relatively homogeneous stimuli compared to way-finding tasks, which may take place in natural or artificial environments containing an almost infinite assortment of visual objects. Based on this, one might reason that a single critical band of SFs for navigation is unlikely. However, there are some commonalities that can be relied upon in comparing mobility and visual recognition tasks. For instance, although face recognition tasks typically involve homogenous stimuli, object recognition tasks often use stimuli that range widely in their degree of heterogeneity, similar to mobility. Given that a wide range of SFs are useful for object recognition tasks even when discriminations are between exemplars within the same subordinate category (Biederman & Kalocsai, 1997; Collin et al., 2004), this again argues that a simple critical SF range for mobility is unlikely and that a wide range of frequencies may be useful for this task.

### *Navigational Paradigms*

A wide variety of experimental methodologies have been used to study navigation. Traditionally, navigation paradigms have generally fallen into two categories:

in-lab tasks, such as studying routes on a map, and real-world navigation where participants actually navigate through the environment (for examples of both see, e.g., Thorndyke & Hayes-Roth, 1982). While each of these techniques has contributed useful insights into navigation, both have important limitations. It has been suggested that the use of maps or scale models in lab tests is not testing the construct of interest, spatial cognition, but may instead be a test of some altogether different construct such as map reading ability. The use of real-world navigation environments solves this problem, since it clearly employs an ecologically valid task, however it is limited by the difficulty in controlling many aspects of the environment through which the task is taking place, making it difficult to manipulate it satisfactorily (see Sandstrom, Kaufman & Huettel, 1998, for further discussion of these issues).

More recent work frequently makes use of virtual environments to explore navigation abilities, with the aim to combine the benefits of both in-lab and real-world navigation tasks. These virtual environments allow for greater generalizeability to actual navigation as spatial cognition can be examined in easily controlled environments through which the participants can navigate either physically or through simulation. The present study used a paradigm involving a desktop style of virtual environment. This consisted of a number of mazes through which participants navigated from a first-person perspective. Although the use of a desktop system has some limitations because it lacks the vestibular and proprioceptive information available in some immersive environments (Ruddle & Lessels, 2006), it still allows for good control and precise measurement of navigation behaviour. Previous work has explored visual determinants of mobility in a virtual environment (Fortenbaugh, Hicks, Hao, & Turano, 2007). In their study,

Fortenbaugh et al. specifically examined the effect of visual field loss on mobility performance. However, due to constraints in technology that included limited refresh rates, their virtual system involved a number of delays, leading to rough flow of movement through the environment (Fortenbaugh et al., 2007, pp. 559-560). For the current study we chose to use dioptric lenses to blur vision, rather than manipulate the computer-presented environment itself, in order to provide a real-time examination of this factor on mobility.

### *Outline and Hypotheses*

The present study examines the effect of visual blur, introduced using spherical defocus, on navigation performance in a desktop-style virtual environment. It is difficult to make precise quantitative predictions as to our findings due to the limited previous research on this specific topic. As previously mentioned, those studies which have used a similar spherical defocus to ours have focused mainly on participants' movements while taking a step, and not on mobility as a whole, as ours does. While it is almost certain that navigation performance will drop monotonically as visual blur increases, it is not clear a priori what the shape of the function will be. It is possible, for instance, that a gradual linear decline in performance will be observed as blur is increased. However, should we find a steep threshold-like function instead, it is likely that the position of this threshold on the SF spectrum will be quite low. We posit this for a number of reasons. Firstly, if mobility is similar to object identification in its visual requirements, as we have argued above, then one would expect a broad range of SFs to be adequate for performance of the task. Also, navigation takes place in a relatively rich, three-dimensional environment with flow field information and other higher order cues available, so degradations of low-level

spatial information may have to be extreme before they affect performance. Finally, some studies have suggested that raw visual information is not of primary importance in mobility tasks (Ruddle & Lessels, 2006), again suggesting that only a minimal degree of two-dimensional spatial information will be necessary. For all these reasons we predict that any detriment to visually guided route learning will occur at the low end of the SF spectrum.

### Experiment 1

In Experiment 1 we used spherical lenses of various positive dioptric strengths to alter the levels of visual detail available to participants as they navigated through a series of mazes presented from a first-person point of view. Each maze was navigated 5 times, allowing participants to progressively learn its layout. The lenses had effects roughly equivalent to applying low-pass spatial filters to the two-dimensional pictorial information available to the participants. The purpose of this experiment was to assess the function of SF cut-off on route learning.

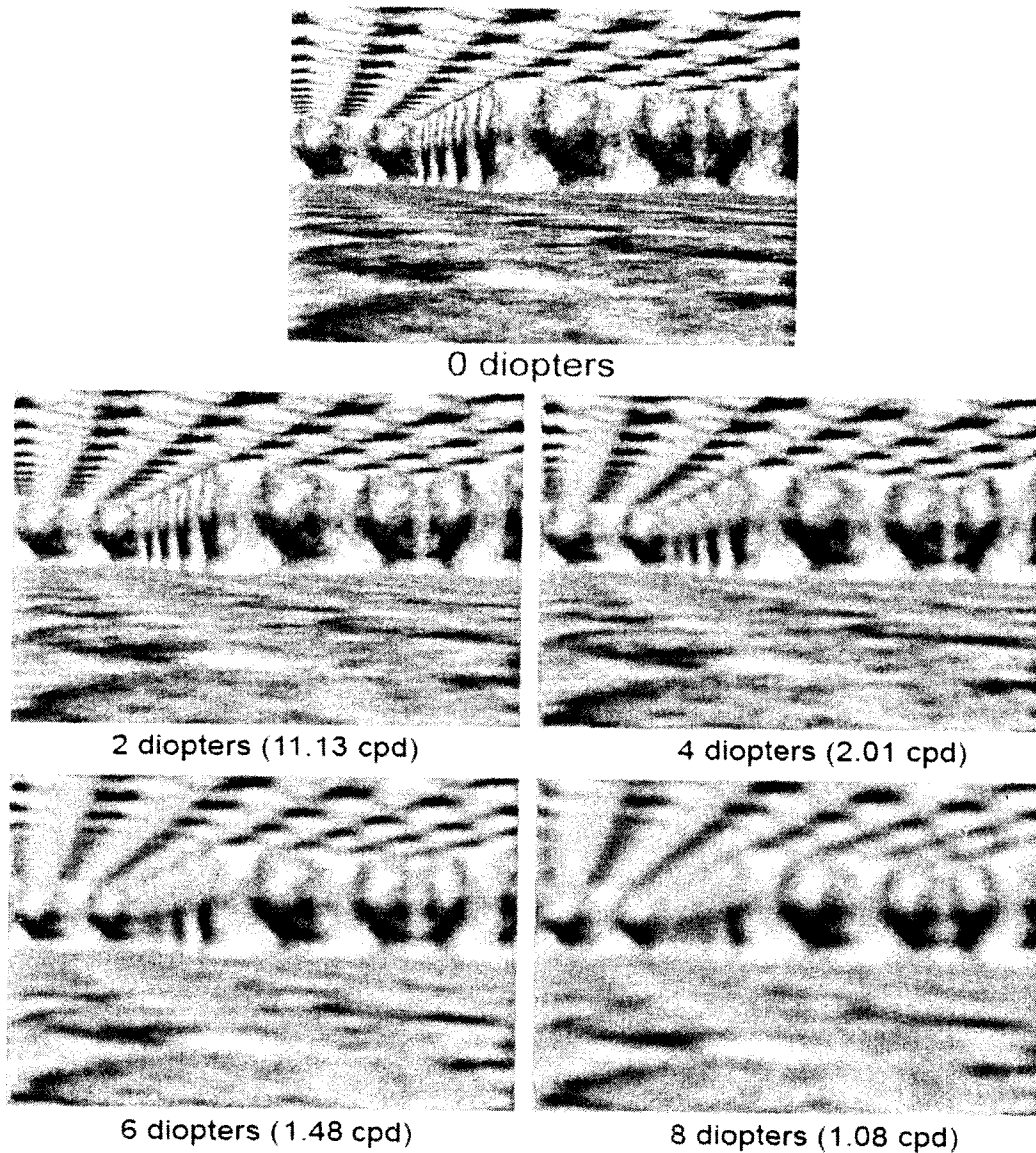
#### *Method*

*Participants.* Forty-eight undergraduate students from the University of Ottawa participated for either a small honorarium or course credit. Thirteen were unable to complete the experiment due to experiencing dizziness and/or nausea during the study. This low rate of completion is likely due to the visual blurring adding an additional challenge to the task for those prone to motion sickness. The mean age of the remaining 35 participants (17 females) was  $20.8 \pm 3.6$  years. All participants had normal or corrected-to-normal spatial vision as determined by contrast sensitivity testing with The Vision Contrast Test System (Vistech Consultants, Inc.).

*Stimuli & Materials.* Participants were asked to run through a set of virtual mazes originally developed by MacInnis and colleagues (MacInnes, 2004; MacInnes, Banyasad, & Upal, 2001; Shore, Stanford, MacInnes, Klein, & Brown, 2001). These mazes consist of three-dimensional renderings of the traditional Hebb-Williams mazes (Hebb & Williams, 1946; Rabinovitch & Rosvold, 1951) presented on a computer screen in a fashion similar to first-person style video games. The mazes were generated using OpenGL graphics library routines in C++. In order to provide proper timing, the Windows event handler is suspended while the program is running. Also, continuous keyboard monitoring is implemented to allow rapid response by the program to key presses by the participants.

An example of the participants' view of one of these mazes can be seen in the top panel of Figure 1. The maze walls, ceiling and floor were rendered with fractal noise patterns. That is, the bitmaps applied to the three-dimensional structure of the maze consisted of an array of grey pixels selected at random from a Gaussian distribution of the 256 gray levels available in the 8-bit color gamut. This bitmap was then put through a SF filter with a gain profile of  $1/f^{1.1}$  where  $f$  is the SF of the image components in a Fourier analysis. This filtering has the effect of making the amplitude spectrum of the bitmap equivalent to that of an average natural image (see, e.g., Field & Brady, 1997; Tolhurst, Tadmor, & Chao, 1992), but without any higher-order structure. In this particular sense, the bitmap is effectively an average of many natural images. In addition to providing a naturalistic amplitude spectrum to the participants' views of mazes, using a fractal noise pattern also had the effect of making the maze walls have a similar level of structure at a wide range of virtual viewing distances. This pattern was repeated along all

maze surfaces in order to provide an environment devoid of any landmarks that could aid participants in navigation, as our intent was to measure visually guided mobility in a simple, landmark-free environment in order to examine only the effects of low spatial frequency levels on route learning.



*Figure 1.* Examples of a scene from the virtual maze as presented to participants in Experiment 1. The upper panel shows an unfiltered version of the scene. The lower four panels show filtered versions of the same scene, filtered to the levels experienced after accommodation, passed through a Butterworth low-pass filter (exponent 5) in order to provide an approximation of the view of the maze experienced by participants wearing lenses of +2, +4, +6 and +8 D of blur, equivalent to +0.36, +2.01, +2.75, and +3.76 D of experienced blur, respectively. The 50% cut-offs applied are shown below each image.

The average brightness of the maze images was  $66.6 \text{ cd/m}^2$ . Average brightness was determined by taking 30 arbitrary screen snap shots of the mazes, averaging the gray levels therein, and measuring the luminance of that average gray level on the same monitor using an LS-110 photometer.

Participants moved through the maze using the standard keyboard arrow keys. Assuming an average viewing height of 168 cm ( $\approx 5'6''$ ) the rendering of the entire maze area was 20 meters on a side at scale. Movement speed was approximately 12 km/h at scale, with a turn rate of  $50^\circ/\text{second}$  and a visual field of  $55^\circ$ .

As can be seen in Figure 2, each maze's structure was based on a 6x6 grid with 1x1 square alcoves at diagonally-opposite corners. As with the original Hebb-Williams mazes, one of these alcoves always served as the start and the other as the goal. From the original set of 12 Hebb-Williams mazes, 10 were selected as the most difficult based on the efficiency data of Shore et al. (2001). From this subset of 10 mazes, 10 new ones were created by flipping the layout of the mazes right-to-left along a diagonal line extending from the start alcove to the goal alcove. This yielded a set of 20 mazes, as seen in Figure 2.



From the 20 mazes, 5 groups of 4 mazes were created, such that each set had an equal overall mean of difficulty ranking based on Shore et al.'s (2001) efficiency data. These groups of 4 mazes were presented in one of two fixed orders, with one order being the reverse of the other, for a total of 10 possible sets of 4 mazes. This had the effect of completely counter-balancing the order positions of the mazes across participants.

An optometrist's set of trial frames and trial lenses were used to blur participants' vision while navigating the mazes. The lens strengths used were: 0, +2, +4, +6, and +8 diopters (D). These were overlaid in the trial frame on top of lenses that matched each participant's regular prescription, if any.

To better characterize the blur levels produced by these lenses, we calculated the modulation transfer function (MTF) of an average age-appropriate eye having +2, +4, +6 or +8 D of defocus blur using the formulas given in Appendix 1 of Akutsu, Bedell, and Patel (2000; see also Charman & Jennings, 1976 and Smith, 1982). To do this, we first tested the acuity of a group of 17 age-matched participants ( $21.5 \pm 4.6$  years) when wearing the lenses. We then used these acuity levels to determine the actual mean defocus experienced by the participants, taking accommodation into account. For the lenses of +2, +4, +6, and +8 D of blur, the mean experienced blur was +0.36, +2.01, +2.75, and +3.76 D, respectively. We next calculated the SF at which the MTF of the experienced defocus level drops to .5 to get an approximation of the 50% cut-off value of a low-pass filter that would yield the same degree of blur. This yielded equivalent cutoffs of 11.13, 2.01, 1.48, and 1.08 cycles per degree (cpd) for +2 (+0.36 D), +4 (+2.01 D), +6

(+2.75 D) and +8 (+3.76 D) diopter lenses, respectively<sup>1</sup>. Images filtered at these cut-off frequencies are shown in Figure 1 to provide an approximation of what the participants saw during testing. These images were SF filtered using a Butterworth lowpass filter of order 5 in MATLAB at the cutoffs specified above.

The images in Figure 1 subjectively match with participants' reports and our own informal observations of the degree of blur experienced when viewing the mazes through the various strengths of blurring lenses. However, the SF cut-offs given above can only be taken as approximations of the effects of the lenses for a number of reasons. For one, calculation of the MTF requires pupil size as a factor and this varies widely among individuals. The values given above are based on an average pupil diameter of 3.86 mm, calculated using Stanley and Davies' (1995) formula for pupil size as a function of luminance and stimulus size. This value was calculated based on a stimulus diameter of 20.4°, derived from the fact that our screen area was 15.8° x 20.8° = 327.2 square degrees (screen dimensions were 32.3 by 24.0 cm at 85 cm). This is equivalent in area to a circular stimulus of radius 10.2° (Stanley & Davies, 1995). The other factor required for calculating average pupil size is the average luminance of the screen, which was 66.6 cd/m<sup>2</sup>. This was measured as described above in the stimulus section. Although pupil size

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<sup>1</sup> As Akutsu et al. (2000) note, the optical MTF for dioptrically blurred targets has a series of negative and positive lobes above the first zero crossing. That is, it does not simply drop smoothly from 1 to 0 as does a Butterworth or half-gaussian filter, but instead has a series of rises and falls relative to 0 following the first zero-crossing. Here we simply ignored these additional lobes and calculated the frequency at which the function has a value of .5, which always occurs uniquely before the first zero crossing. If the information beyond the zero crossing is useful then SF filtering to the levels above will not yield the same performance as the associated level of dioptric blur (performance with the lobes included should be better). However, Akutsu et al. (2000) note that applying spatial filters that mimic the effects of these lobes beyond the zero-crossing yields no advantage in acuity testing when compared to leaving them off (what they call their 'truncated filter' condition).

no doubt varied among participants, previous research indicates that this calculated average is very likely to be close to the group average in our sample (Stanley & Davies, 1995) and therefore the SF cut-off estimates above should not be far off based on this factor.

The Vision Contrast Test System by Vistech Consultants, Inc. was used to assess participants' spatial vision prior to testing. Maze stimuli were presented on an IBM ThinkCentre M50-COE with an AccuSync900 monitor. A chin rest was used to maintain a fixed viewing distance of 85 cm from the computer monitor.

A questionnaire was given to all participants prior to testing to gauge their previous relevant video game experience (see Appendix A). The questionnaire measures the number of hours participants have spent playing computer and video games during their lifetime. It also asks about hours spent playing first-person style video games, of particular relevance here. Total lifetime hours spent playing video games and total lifetime hours spent playing first-person style games were calculated for each participant from their answers to these questionnaires. The latter value was used as a covariate in the analyses.

*Procedure.* Participants were randomly assigned to two of four blur level conditions—+2, +4, +6, or +8 D—and all participants underwent the 0 D baseline condition. Participants ran through these three blur conditions in random order. For each blur condition one of the 10 sets of four mazes (see description of maze stimuli, above) was chosen at random. Each of the four mazes was run through 5 times in succession.

Prior to running in the experiment, each participant was first given the computer and video game questionnaire. Participants were then fitted with the trial frames and

lenses were added to match their prescription glasses, if any. Those wearing contact lenses were asked to leave them in. To ensure that the inserted prescription was correct and that all participants had normal spatial vision, participants underwent contrast sensitivity testing while wearing the trial frames. This was done using the Vision Contrast Test System (Vistech Consultants, Inc.)<sup>2</sup>. Results indicated normal contrast sensitivity in all participants.

To begin the experiment, a participant was first placed with their chin positioned in the chinrest at a viewing distance of 85 cm. They were then shown a practice maze through which they navigated using keyboard keys until they felt comfortable with the arrow key controls. Next, the appropriate lens strength (0, +2, +4, +6, or +8 D) for the first blur condition was placed into the trial frames.

At this point, participants were given instructions. They were told that for each lens type they would be required to navigate through 4 mazes, each repeated 5 times in order for them to learn the routes in each maze and that they would participate in 3 lens conditions for a total of 60 maze runs. They were also told that their sole objective was to navigate through the mazes as quickly as possible.

Participants were given a break between each new maze and encouraged to remove the trial frames while taking the break to give their eyes a rest. Once the first set

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<sup>2</sup> In order to do this, a participant was first questioned on their prescription strength or their best approximation. While wearing the appropriate prescription lenses or blank lenses for those claiming to have 20/20 vision, the participant's contrast sensitivity was then tested using the Vision Contrast Test System (Vistech Consultants, Inc.). Contrast sensitivity has been proven to be very highly related to acuity and so if the participant was shown to be in the normal contrast sensitivity range, they then proceeded on to the testing which included the lenses with their prescription. If a participant failed to show a normal range, they were retested using a different prescription until they demonstrated contrast sensitivity levels in the normal range and then proceeded with the testing.

of 4 mazes (5 runs each) had been completed, the lenses were exchanged with a new set by the experimenter and the participant navigated through a new set of 4 mazes. This occurred three times total so that each participant navigated through one set of mazes with the baseline 0 D lenses and two of the blurring lens levels (+2, +4, +6, or +8 D) determined randomly for each participant such that every possible combination of two lens types was used multiple times. This resulted in total run numbers of 35 for the baseline 0 D conditions, 18 for the +2 and +4 D conditions and 17 for the +6 and +8 D conditions. For each run, the computer program automatically recorded the participant's path through the maze, number of errors—based on Hebb and Williams' (1946) error coding scheme—and time to completion.

After completing all 60 maze runs (3 sets of 4 mazes, run 5 times each), participants were debriefed as to the purpose of the experiment and given compensation.

### *Results and Discussion*

Note that for the rest of the results and discussion (including figures), the diopter strengths indicated will be those that take accommodation into account, such that lenses of +2, +4, +6, and +8 D will be described as +0.36, +2.01, +2.75, and +3.76 D, respectively.

Completion time was recorded for all trials of all mazes. These data were subjected to a single-pass outlier-rejection procedure using a standard deviation cutoff based on the sample size in each lens condition (Van Selst & Jolicoeur, 1994). Any lens condition for a participant that had 2 or more maze runs missing out of 5 (more than 40% missing data) due to the standard deviation cutoff, was eliminated. This eliminated one lens condition from each of 5 people, including one each of +2.01, +2.75, and +3.76 D

and two of 0 D. All empty cells generated by the outlier rejection were replaced with the mean for their particular lens type and maze run (Tabachnick & Fidell, 2001). This replaced a total of 9 cells out of 525.

Results from our questionnaire regarding video game experience showed that participants had a median of 624 hours of lifetime experience playing first-person style videogames. The distribution was somewhat positively skewed, with an interquartile range of 0 to 1794 lifetime hours. Thus, there was a wide range of video game experience levels.

Maze completion times were analyzed using a  $5 \times 5$  mixed analysis of covariance (ANCOVA) with maze run (1st to 5th) as a within-subjects factor, lens type (0, +0.36, +2.01, +2.75, and +3.76 D) as a between-subjects factor, and first-person player video game experience as a covariate. Despite the fact that our participants showed a wide range of experience levels with first-person style video games, the covariate in the model did not substantively change the results and therefore will not be discussed any further. Mean completion times and standard errors can be seen in Figure 3. Participants show a fairly standard learning curve shape for all lens strength levels, although there is clearly high variability in the data for the stronger lenses.

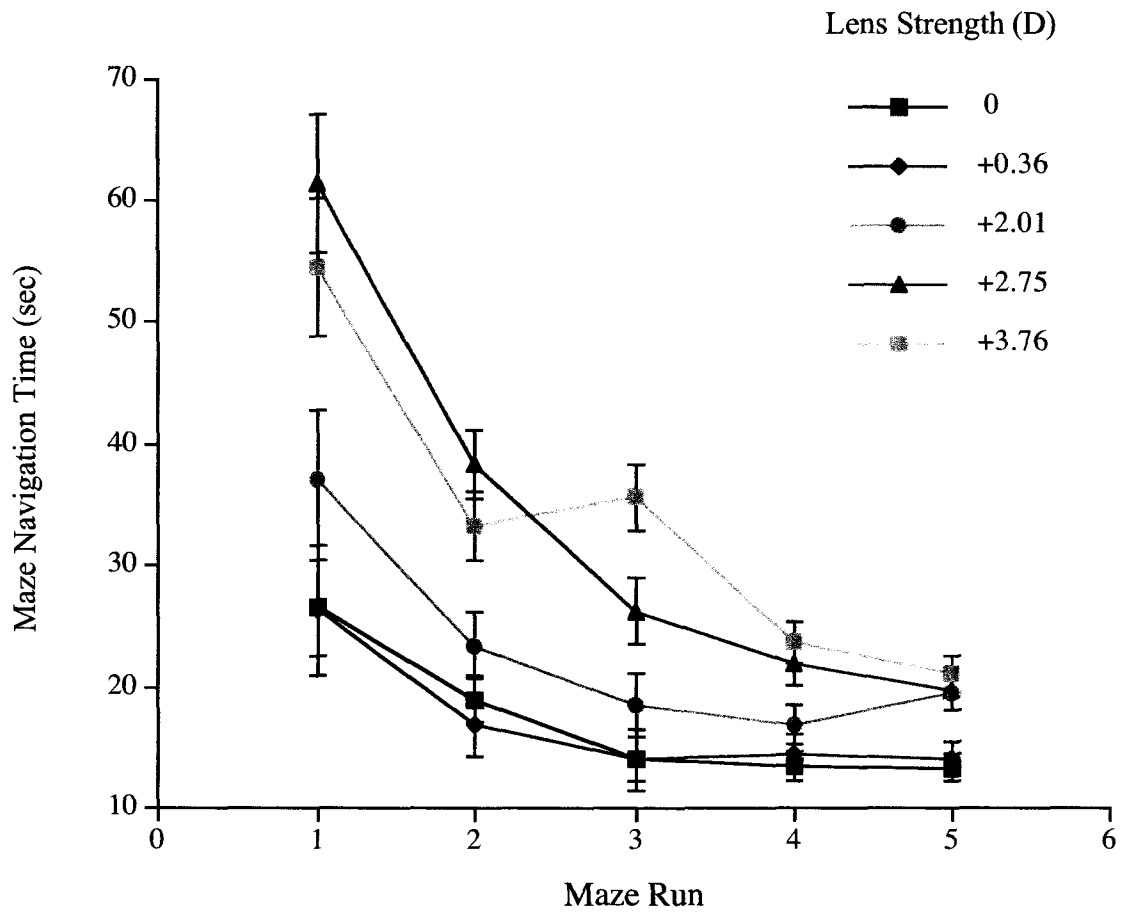


Figure 3. Results from Experiment 1: Mean maze completion times for each run (run1, run2, run3, run4, run5) under each lens condition (0, +0.36, +2.01, +2.75, +3.76 D).

Standard errors of the mean are shown by the error bars.

The ANCOVA revealed a main effect of maze run,  $F(1.944, 182.702) = 60.086$ ,  $p < .001$ , with later runs being navigated faster than earlier ones, as well as a main effect of lens type,  $F(4, 94) = 19.607$ ,  $p < .001$ , with stronger lenses resulting in slower navigation times than weaker ones. Furthermore, a significant interaction between maze run and lens type was found,  $F(7.775, 182.702) = 4.386$ ,  $p < .001$ .

Simple main effects of lens type within each level of maze run revealed significant findings for all runs: run1:  $F(4, 94) = 9.465$ ,  $p < .001$ ; run2:  $F(4, 94) = 12.717$ ,  $p < .001$ ; run3:  $F(4, 94) = 13.586$ ,  $p < .001$ ; run4:  $F(4, 94) = 8.732$ ,  $p < .001$ ; and run5:  $F(4, 94) = 7.399$ ,  $p < .001$ . That is, lens strength continued to be a factor even after participants had thoroughly learned the maze.

To further analyze these simple main effects of lens strength, post-hoc one-way ANOVAs and t-tests were performed on all of the lens strengths for each level of maze run, using Fisher's least significant difference ( $\alpha = .05$ ) to account for the familywise error rate. For the mean differences and significance levels of all post hoc tests, see Table 1.

Table 1

Mean differences (in seconds) between lens types (0, +0.36, +2.01, +2.75, and +3.76 diopters) under each level of maze run (run1, run2, run3, run4, and run5).

Variables	Lens Type (diopters)				
	0 D <sup>a</sup>	+0.36 D <sup>b</sup>	+2.01 D <sup>b</sup>	+2.75 D <sup>c</sup>	+3.76 D <sup>c</sup>
Run 1					
0 D	--	--	--	--	--
+0.36 D	-0.2	--	--	--	--
+2.01 D	10.6	10.8	--	--	--
+2.75 D	34.8 <sup>t</sup>	35.0 <sup>t</sup>	24.2**	--	--
+3.76 D	27.8 <sup>t</sup>	28.1**	17.3*	-7.0	--
Run 2					
0 D	--	--	--	--	--
+0.36 D	-2.1	--	--	--	--
+2.01 D	4.4	6.5	--	--	--
+2.75 D	19.3 <sup>t</sup>	21.4 <sup>t</sup>	14.9 <sup>t</sup>	--	--
+3.76 D	14.3 <sup>t</sup>	16.4 <sup>t</sup>	9.8*	-5.0	--
Run 3					
0 D	--	--	--	--	--
+0.36 D	-0.0	--	--	--	--
+2.01 D	4.6	4.5	--	--	--
+2.75 D	12.2 <sup>t</sup>	12.2**	7.7*	--	--
+3.76 D	21.6 <sup>t</sup>	21.6 <sup>t</sup>	17.1 <sup>t</sup>	9.4*	--
Run 4					
0 D	--	--	--	--	--
+0.36 D	1.0	--	--	--	--
+2.01 D	3.4	2.4	--	--	--
+2.75 D	8.4 <sup>t</sup>	7.2**	5.1*	--	--
+3.76 D	10.27161 <sup>t</sup>	9.3 <sup>t</sup>	6.9**	1.8	--
Run 5					
0 D	--	--	--	--	--
+0.36 D	0.6	--	--	--	--
+2.01 D	6.2**	5.6**	--	--	--
+2.75 D	6.3**	5.7**	0.1	--	--
+3.76 D	7.7 <sup>t</sup>	7.1**	1.5	1.4	--

Note. <sup>a</sup>n = 35. <sup>b</sup>n = 18. <sup>c</sup>n = 17

\*p < .05. \*\*p < .01. <sup>t</sup>p < .001

These tests revealed that for run1, the navigation times under the 0, +0.36, and +2.01 D lenses were not significantly different from each other, nor were the navigation times under the +2.75 and +3.76 D lenses from each other; However these two groups of levels differed significantly from each other with the latter group having slower navigation times than the former. Generally, this same pattern of results occurred in the other runs, suggesting that a significant performance decrement occurs between the +2.01 and +2.75 D lenses, but that performance above and below this range is little affected by variations in visual blur<sup>3</sup>.

Figure 3 shows that, as expected, completion times generally get faster for each subsequent run for all of the lens conditions, although there is clearly a high level of variability in the data for the stronger lenses. ANCOVA and post-hoc analyses also showed that completion times tend to get faster with each run<sup>4</sup>.

The data analyses discussed above suggest a performance decrement between +2.01 and +2.75 D of blur. To further examine this issue, completion time data were collapsed across maze run in order to visualize the effect of lens strength overall. As can

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<sup>3</sup> Minor exceptions to this overall pattern include the following: 1) In run3 navigation times under 0, +0.36, and +2.01 D lenses were not significantly different from each other and they all were significantly different from the navigation times for +2.75 and +3.76 D lenses; However, the +2.75 and +3.76 D lenses were also found to be significantly different from each other, which was not the case for other runs. 2) On run5, the two groups of diopters shift somewhat, with navigation times for the +2.01 D lens being equivalent to the +2.75 and +3.76 D lenses, making two new groups (0 and +0.36 D; +2.01, +2.75, and +3.76 D) which differ significantly from each other, with the latter having slower navigation times than the previous.

<sup>4</sup> There are two exceptions to this pattern of completion times getting faster with each run. One occurs in the +3.76 D lens condition, where completion time is longer, though not significantly so, in run3 than run2. This is likely a product of the extreme variability found in this task due to the difficulty associated with it (for instance, +3.76 D of defocus is below the limit of legal blindness, +2.5 D (Bailey, 1998). The other exception is for the +2.01 D lens where completion times are longer for run5 than run4. This difference is small in magnitude, at 2.76 seconds, but is nonetheless statistically significant ( $p = .029$ ).

be seen with the black line in Figure 4, this results in sigmoidal functions for all lens strengths, a typical difficulty-by-performance relationship. In an attempt to characterize the inflection point of these functions, we fit them with a cumulative logx-normal distribution and calculated the point at which they reached the 50% point between run1 and run5 completion times. This showed a mean inflection point of around +2.09 D (approximately equivalent to a low-pass cutoff of 1.94 cpd). This is compatible with the ANCOVA analyses discussed above, suggesting a performance decrement somewhere between +2.01 and +2.75 D.

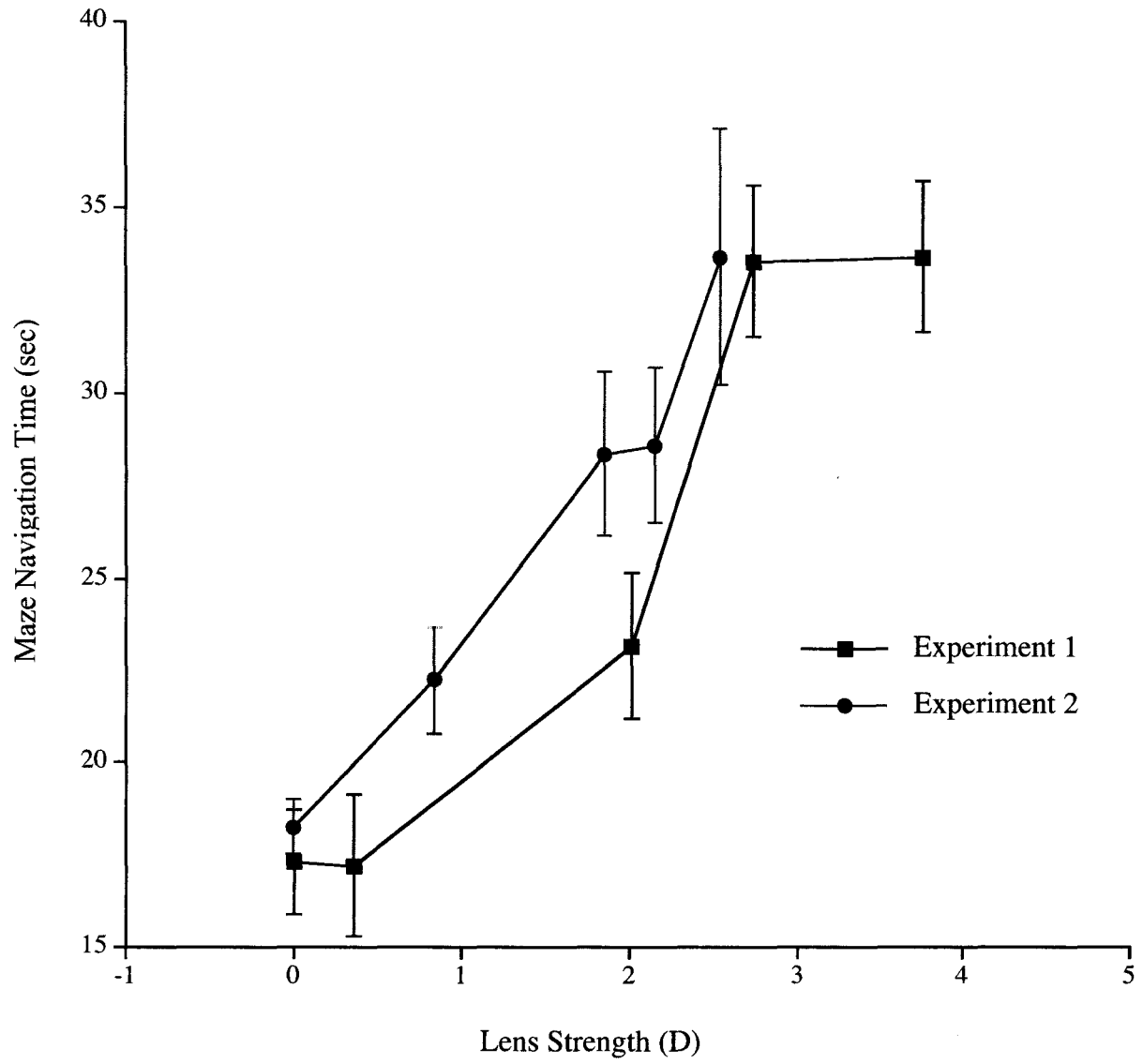


Figure 4. Mean maze navigation times (collapsed across runs) for each lens type for Experiment 1 and for Experiment 2.

## Experiment 2

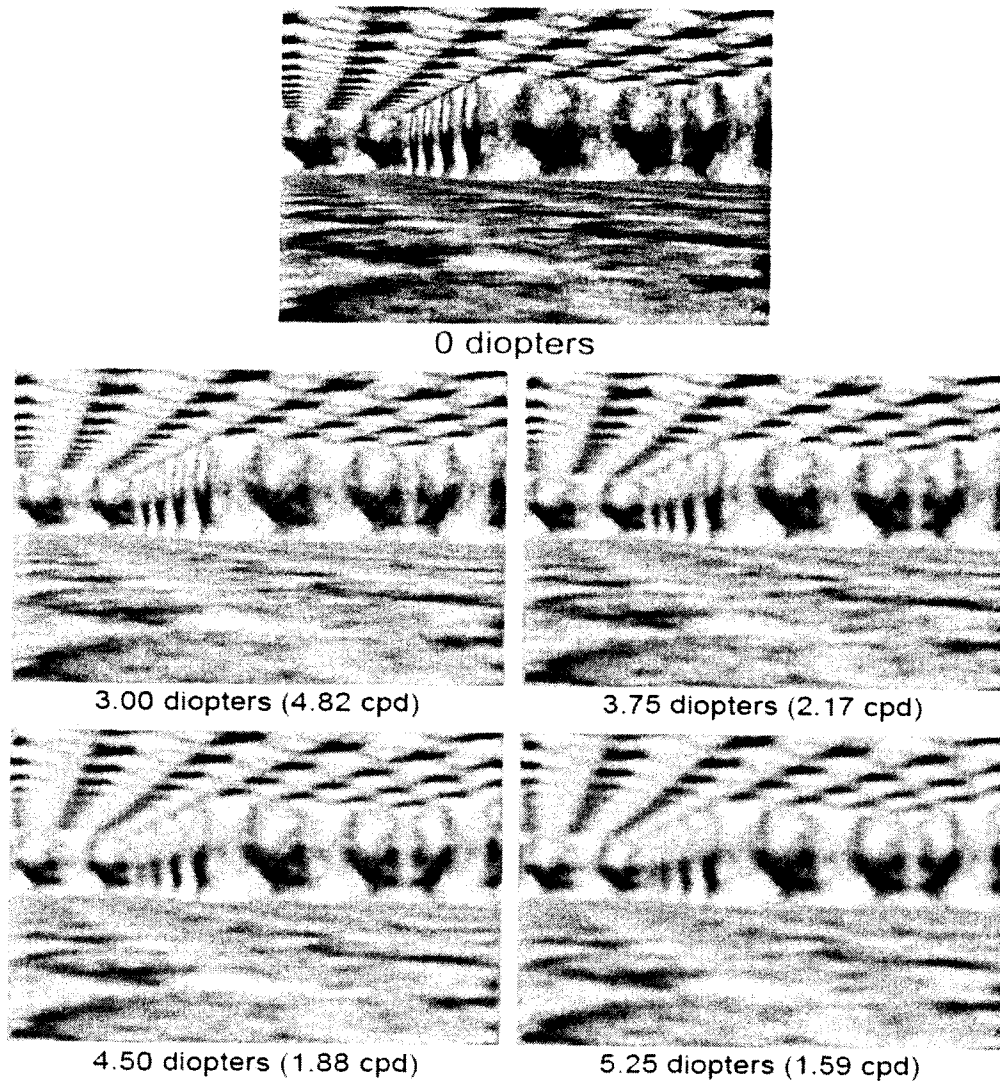
In order to better understand the function of maze completion times and lens strength around the +2.09 D level we extended Experiment 1 by examining finer gradations of lens strength—and therefore finer gradations of low-pass SF filtering—around that point. Several methodological improvements were also implemented. First, each participant received all 5 lens conditions so that Experiment 2 was a completely within subjects experiment. In addition to this, the maze pairings that were created were better equated for difficulty, as will be discussed in the *Stimuli and Materials* section.

*Method*

*Participants.* Forty-eight participants from the University of Ottawa volunteered for this experiment. Of these, 7 were unable to complete it due to experiencing headaches and/or nausea during the study. One additional participant was eliminated due to his misunderstanding of the instructions and subsequent removal of the trial frames during test trials. The remaining 40 participants (21 female) had a mean age of 22.7,  $\pm$  5.0 years. None of the participants had taken part in Experiment 1 and all were naïve as to the purpose of the study. All participants had normal or corrected-to-normal vision and received either a small honorarium or course credit for a psychology course as compensation for their participation.

*Stimuli and Materials.* The stimuli and materials were the same as for Experiment 1 except that the four lens strengths used were +3.0, +3.75, +4.5, and +5.25 D. In order to take accommodation into account, we tested the same age-matched control group as in Experiment 1 on their relative acuities while wearing each of the lenses. This yielded actual experienced blur levels of +0.84, +1.86, +2.15, and +2.55 D for the +3.0,

+3.75, +4.5, and +5.25 D lenses, respectively. We then characterized the effects of these lenses in terms of an approximate low-pass SF cut-off for the actual dioptric blur experienced, resulting in equivalent cutoffs of 4.82, 2.17, 1.88, and 1.59 cycles per degree (cpd) for +3.0 (+.84 D), +3.75 (+1.86 D), +4.5 (+2.15 D) and +5.25 (+2.55 D) diopter lenses, respectively. As with Experiment 1, we will discuss diopter strengths in terms of the levels experienced after taking accommodation into account, such that +3, +3.75, +4.5, and +5.25 D of blur will be described as +0.84, +1.86, +2.16, and +2.55 D of blur, respectively. Once again a 0 D baseline condition was included. Figure 5 provides images filtered at all of these levels.



*Figure 5.* Examples of a scene from the virtual maze as presented to participants in Experiment 2. The upper panel shows an unfiltered version of the scene. The lower four panels show filtered versions of the same scene, filtered to the levels experienced after accommodation, passed through a Butterworth low-pass filter (exponent 5) in order to provide an approximation of the view of the maze experienced by participants wearing lenses of +3, +3.75, +4.5 and +5.25 diopters of blur, equivalent to 0.84, 1.86, 2.15, and 2.55 dp of experienced blur, respectively. The 50% cut-offs applied are shown below each image.

An additional difference from Experiment 1 was that maze sets in Experiment 2 were created using a slightly different procedure. First, maze difficulty was determined by taking the average efficiency score across all 5 trials of each maze, rather than just the slowest and fastest runs, as was done for Experiment 1<sup>5</sup>. Mazes were then paired with equivalent overall efficiency ratings for each pair. This created a total of 5 pairs for the 10 mazes and another 5 pairs were created which were simply the reverse order of the original 5. Each pair contained 1 original maze and 1 reversal maze so that all mazes were presented an equal number of times.

*Procedure.* The procedure for Experiment 2 was the same as Experiment 1 except that each participant received all 5 lens conditions and only navigated through 2 mazes per lens (repeated five times each). Thus the design was completely within-subjects.

### *Results and Discussion*

As with Experiment 1, completion times for each maze under each run and lens condition were recorded. Data was subjected to a single-pass outlier rejection procedure with a cut-off based on the sample size (Van Selst & Jolicoeur, 1994). Next, each participant's data was examined to determine if any had greater than 20% missing data (6 or more cells missing out of 25). One such participant was found and that individual's data was removed from the analysis, leaving 39 participants (20 female). Finally, all remaining empty cells were replaced with the mean of their lens type and maze run

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<sup>5</sup> Due to an error in the efficiency calculation, the two most difficult mazes were switched such that the second most difficult maze was paired with the easiest maze and the most difficult maze was paired with the second easiest maze. However, this should not have caused any difference to the results for two reasons. First, it was two mazes adjacent to each other in the difficulty rankings that were switched so the difficulty rating between them was fairly small. Second, since all maze pairs were randomly assigned to lens conditions, the mistaken pairs were found equally in all 5 lens conditions, so that no lens condition would receive them any more than any other lens condition.

(Tabachnick & Fidell, 2001). In all, these procedures replaced a total of 32 cells out of 975.

Results from our questionnaire regarding video game experience showed that participants had a median of 312 hours of lifetime experience playing first-person style videogames. Again, the distribution was somewhat positively skewed and quite broad, with an interquartile range of 0 to 1560 lifetime hours.

A 5 X 5 repeated ANCOVA was used to analyse this data with maze run (1st to 5th) and lens strength (0, +0.84, +1.86, +2.16, and +2.55 D) as within-subjects factors, and first-person player video game experience as a covariate. As with Experiment 1, inclusion of the covariate had no effect on the results and therefore will not be discussed any further. As can be seen in Figure 6, the results from Experiment 2 follow the same pattern as those from Experiment 1.

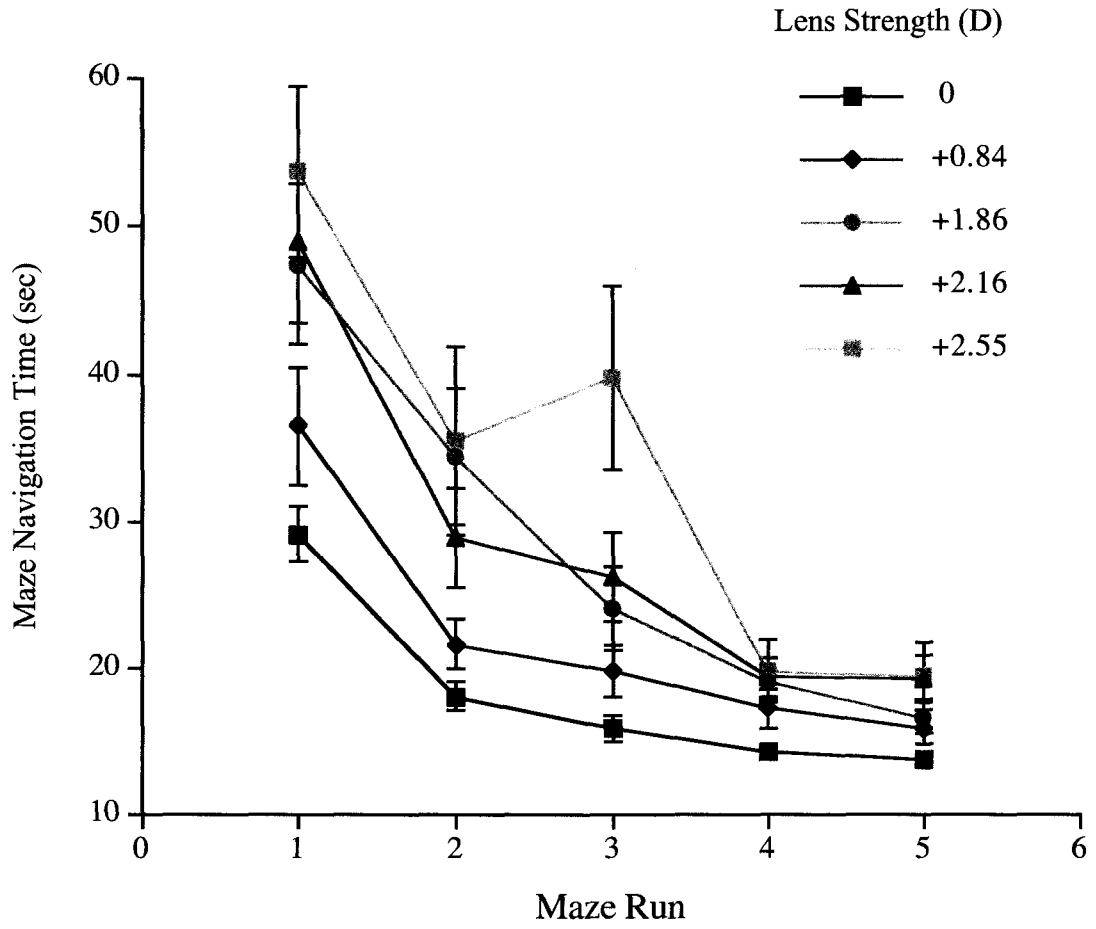


Figure 6. Results from Experiment 2: Mean maze completion times for each run (run1, run2, run3, run4, run5) under each lens condition (0.0, +0.84, +1.86, +2.16, +2.55 D). Standard errors of the mean are shown by the error bars.

The ANCOVA revealed a main effect of maze run,  $F(2.525, 294.184) = 48.008, p < .001$ , with later runs being navigated faster than earlier runs, as well as a main effect of lens type,  $F(2.914, 294.184) = 11.513, p < .001$ , with weaker lenses resulting in faster navigation times than stronger lenses. More importantly, a significant interaction was found between maze run and lens type,  $F(7.951, 294.184) = 2.938, p = .004$ .

In order to examine the effect of lens strength within each level of maze run, simple main effects analyses were performed. These revealed significant effects of lens for all runs: run1:  $F(4, 34) = 7.150, p < .001$ , run2:  $F(4, 34) = 6.055, p = .001$ , run3:  $F(4, 34) = 6.993, p < .001$ , run4:  $F(4, 34) = 5.816, p = .001$ , and run5:  $F(4, 34) = 5.385, p = .002$ . Post-hoc analyses using Fisher's least significant difference ( $\alpha = .05$ ) to account for the familywise error rate showed an overall pattern of results that replicates Experiment 1. That is, completion times get faster across maze runs and slower across lens strengths in almost all cases. See Table 2 for the mean difference and significance levels of all post-hoc tests.

Table 2

Mean differences (in seconds) between lens types (0, +0.84, +1.86, +2.16, and +2.55 diopters) under each level of maze run (run1, run2, run3, run4, and run5).

Variables	Lens Type (diopters)				
	0.0 D	+0.84 D	+1.86 D	+2.16 D	+2.55 D
Run 1					
0.0 D	--	--	--	--	--
+0.84 D	7.4	--	--	--	--
+1.86 D	18.3**	11.0	--	--	--
+2.16 D	19.8**	12.4	1.5	--	--
+2.55 D	24.6 <sup>†</sup>	17.2*	6.3	4.8	--
Run 2					
0.0 D	--	--	--	--	--
+0.84 D	3.5*	--	--	--	--
+1.86 D	16.2**	12.7*	--	--	--
+2.16 D	10.8**	7.2*	-5.5	--	--
+2.55 D	17.3*	13.8*	1.1	6.5	--
Run 3					
0.0 D	--	--	--	--	--
+0.84 D	3.9*	--	--	--	--
+1.86 D	8.3**	4.4	--	--	--
+2.16 D	10.4**	6.5	2.1	--	--
+2.55 D	23.9 <sup>†</sup>	20.0**	15.6*	13.5*	--
Run 4					
0.0 D	--	--	--	--	--
+0.84 D	3.0*	--	--	--	--
+1.86 D	4.8**	1.8	--	--	--
+2.16 D	5.2**	2.2	0.3	--	--
+2.55 D	5.6*	2.6	0.8	0.5	--
Run 5					
0.0 D	--	--	--	--	--
+0.84 D	2.1	--	--	--	--
+1.86 D	2.8*	0.7	--	--	--
+2.16 D	5.5**	3.4	2.7	--	--
+2.55 D	5.6*	3.5	2.8	0.1	--

Note.  $n = 39$ .

\* $p < .05$ . \*\* $p < .01$ . <sup>†</sup> $p < .001$

Generally, performance levels with the +1.86, +2.16 and +2.55 D lenses were statistically indistinguishable from each other throughout the runs, while the completion times for the 0.0 D lens were significantly faster than this group of lenses. The +0.84 D lens fluctuated between having navigation times statistically the same as the 0.0 D lens, the stronger set of lenses, or both.

The data analyses discussed above suggest a performance decrement between +0.84 and +1.86 D, in roughly the same range as Experiment 1 (+2.09 D). As with Experiment 1, we collapsed the completion time data across maze runs in order to quantitatively examine the effect of lens strength overall. As expected, this results in sigmoidal functions for all lens strengths (see the red line of Figure 4). We fit these data with a cumulative logx-normal distribution and calculated the inflection point at which completion times reached the 50% level between run1 and run5 completion times. This showed a mean inflection point of around +1.91 D, approximately equivalent to a low-pass cutoff of 2.12 cpd.

In sum, the results of Experiment 2 match those of Experiment 1 quite well, although there seems to be an overall improvement in performance in the second experiment. Taken together, the two experiments suggest that the effect of blur on visually guided mobility is non-linear, with a significant decrement occurring at around +2 D of optical blur, or a low-pass SF cut-off of about 2 cpd.

### General Discussion

In order to understand any visually guided task, it is important to understand the visual inputs the task requires. Relatively few basic studies have examined the effect of optical blur on visually guided mobility performance. Of those that have, most have

examined diffusion blurring--which lowers contrast sensitivity--as opposed to spherical defocus--which mainly has an effect on visual acuity. No study that we are aware of has examined the effects of parametrically modifying spherical defocus on route learning. The purpose of the current study was to provide an examination of the effect of spatial degradation of the visual environment on mobility performance and spatial learning. Spatial degradation was achieved by systematically varying the levels of SFs available to participants via spherical defocus. Of particular importance was exploring the shape of the function produced by these manipulations. As indicated previously, we expected the function to drop monotonically, and to exhibit a rapid drop-off at a threshold point located in the low end of the SF spectrum.

Both experiments reported in the present study agree with our expectations, pointing towards a low SF threshold below which mobility performance drops off rapidly. This pattern is similar to what has been found with other higher order cognitive tasks with regards to the effects of SF filtering (e.g., Collin, 2006; Ruiz-Soler & Beltran, 2006). Both of our experiments suggest that under the conditions tested here, an inflection point around 2 cpd exists in the function of maze completion time and low-pass SF cut-off. In Experiment 1, a threshold of +2.09 D (approximately equivalent to a 1.94 cpd low-pass SF filter cut-off) was found, while a threshold of +1.91 D (approximately equivalent to a 2.12 cpd low-pass SF filter cut-off) was found for Experiment 2. The slight difference between the values obtained in Experiments 1 and 2 can likely be explained by differences in methodology, which may have caused better overall performance in Experiment 2 relative to Experiment 1. In particular, Experiment 1 exposed the participants to more powerful lenses than Experiment 2, which may have led

to greater fatiguing during Experiment 1 and, therefore, slightly worse performance overall than Experiment 2.

In both experiments, the inflection point was just slightly above the limits for legal blindness, which is conventionally held to be at +2.5 D of defocus (Bailey, 1998), indicating that visually guided route learning in an environment devoid of explicit landmarks and distracters can be accomplished with fairly impoverished spatial information. This is in line with our prediction that any detriments to navigation would occur at a fairly low SF cut-off. As previously outlined, there are a number of reasons to expect robustness to spatial filtering in the mobility task we have examined. First, navigation involves movement through an environment filled with objects. Even in the simple environments we have used in the current experiments, walls, corridors and openings act like sharp-edged objects that mark locations where navigation decisions must take place. Given that object recognition has been shown to be fairly resistant to SF changes (Biederman & Kalocsai, 1997; Collin, 2006; Collin et al., 2004), it is unsurprising that route learning would show similar performance levels under a broad range of SFs. This is not to say that visual discrimination of objects in the environment is entirely unaffected by spatial visual manipulations. For instance, a number of studies examining step climbing in older populations found that participants increased the amount of toe clearance from the step under impaired vision, indicating potential difficulties in detecting the edge of the step (Heasley, Buckley, Scally, Twigg, & Elliott, 2004, 2005; Vale, Scally, Buckley, & Elliott, 2008). However, given our results, there is still clearly a robustness associated with spatial filtering to sharp-edged objects, such as the openings found in our environments.

A second reason why route learning performance might be resistant to SF filtering is the richness of the environment. In contrast to stimuli typically used in experiments on the effects of spatial information manipulations on recognition tasks, typical mobility tasks occur in an environment involving higher-order motion cues. This includes cues such as optical flow, which occurs when a scene flows across an observer's field of view, providing the observer with information about their movement through the scene (Gibson, 1947). Other motion cues include expansion and contraction of the scene when one moves through it, including the focus of expansion, a distant point in the moving observer's field of vision where the scene does not appear to be moving (Gibson, 1947). Clearly these higher order motion cues likely play an important role in visually guided mobility. It therefore follows that changes to low level visual processes, such as spatial vision, might not have as much influence as the higher order information and would need to be quite extreme to cause an effect. However, given that these higher order motion cues were not of primary interest in the current studies, we did not specifically manipulate them and, therefore, can only speculate as to their relative importance to mobility.

Interestingly, the cutoff level found in the current experiments of 2 cpd is around the same level as the SF cutoff level which is detected and carried by the magnocellular visual pathway (see, e.g., Tolhurst, 1975). Two parallel streams exist in the brain for processing visual information: the dorsal visual stream, which is important for both spatial processing as well as directing action, and the ventral visual stream, which is important for object identifier information such as shape and colour (Milner & Goodale, 1995). The dorsal visual stream, which receives signals from the magnocellular pathway,

is most sensitive to the detection of low SFs, particularly for stimuli that have high temporal frequencies (such as the moving environments in our studies). For stimuli containing only higher SFs, their detection switches over to the ventral stream. A number of studies, both human behavioural studies and animal lesion studies, have pointed to this cross-over point, the cpd where SF detection switches from dorsal to ventral processing, as occurring around 1.5 cpd (for a review, see Skottun, 2000). It therefore follows that when the SFs available in a transient stimulus contain SFs up to and including 1.5 cpd, the dorsal stream receives the information needed to allow for proper mobility. However, when the SFs available in that same stimulus are filtered to contain less than 1.5 cpd, critical information for dorsal stream processing is lost, affecting mobility. This is very near what we observed in the current experiments, with mobility being affected when the environment was filtered to contain less than 2 cpd.

In terms of models of the navigation process, our results suggest that, under the parameters that we have examined here, there is a lower limit to the range of basic spatial information that is useful for this task, although it is low in the spectrum compared to that for recognition tasks. This suggests that early inputs from areas like V1 may be effectively filtered prior to being processed by later modules responsible for dealing with representations of environments. It has been suggested that this is the case with other processes, such as face recognition (Nasanen, 1999) and that such filtering may reflect a “divide and conquer” strategy in the brain that serves to reduce the processing burden inherent in higher-order tasks. However, as Schyns and colleagues have pointed out (Ozgen et al., 2006; Schyns, 1998), there is a high degree of cognitive penetrability to SFs, in the sense that attention can be directed to different levels of spatial scale. Because

of this, we cannot conclude that the limit we have found here represents the edge of a preferred or 'optimal' range for navigation; Rather, this represents a potential absolute lower limit of useful information for the task. It may be that the optimal band for navigation (if any) has a lower cutoff higher in the spectrum, and that the  $\approx 2$  cpd limit found here applies only to cases where a broader spectrum of information is unavailable. Further research will be needed to determine if this is the case.

One of the novel contributions our study makes to the literature investigating the effect of visual blur on mobility is in our ability to measure learning effects. By requiring our participants to navigate through each maze five times sequentially, we were able to measure how performance improved under the various blur conditions. In both experiments, mobility performance showed significant improvement from one run to the next in almost all cases. This was true under all lens by run conditions, with only minor exceptions<sup>3,4</sup>. Interestingly, by run 4, participants in all lens conditions appear to have reached a plateau in their time to complete the mazes. However, the level at which performance peaked differed according to lens strength. The lenses producing greater levels of blur (around 1.86 D and stronger), resulted in slower navigation times than those producing less blur, even on the final two runs. These effects can be seen in Figures 3 and 5. This indicates that although performance improved and peaked under all blur conditions, the maximum level of performance on our task was still affected by blur after the mazes had apparently been learned quite thoroughly. These results have important implications for navigation models, indicating that while spatial learning is still able to occur under fairly extreme levels of spherical defocus, deficits in visual detail still negatively influence mobility performance.

Regarding implications for mobility and spatial learning under conditions of blur in the real world, our results show that way-finding ability exhibits a surprising degree of robustness to blur. There were no significant differences in navigation time between 0 D and about +2 D of blur in most conditions, and the inflection point of the function of blur and performance was not reached until approximately 2 cpd. This implies that it should be possible in principle to undergo similar mobility tasks using residual vision nearing the levels of legal blindness limits. Of course, there are multitudinous other factors to consider in mobility training for the visually impaired. Still, we believe that further research could provide useful general guidelines for rehabilitation efforts regarding residual vision and navigation potential.

As mentioned in the introduction, some previous studies of visually impaired individuals have suggested that acuity is not a primary determinant of their navigational performance. Our results suggest a reason why this might be so. Specifically, we show that mobility is quite robust to acuity losses, so that impairment of this faculty might not affect navigation ability as strongly as others, such as contrast sensitivity and visual field losses. An advantage of the current study over previous ones, which primarily examined individuals with a range of visual impairments (e.g., Patel et al., 2006), is that we examined visual acuity in isolation and parametrically. This permitted us to give a quantitative estimate as to the point where acuity losses *per se* produce impairment.

In terms of vision-enhancement systems such as Night Vision Goggles (NVGs), our results suggest that any impairment they induce in navigation ability is primarily due to factors other than the blur they produce. This is because NVGs reduce acuity to between 20/30 and 20/60 (Macuda et al., 2005), which is far less blur than the point at

which we see significant impairments to route learning performance (around 20/110 to 20/130). Thus, it seems likely that it is the visual field limitations or scintillating motion noise that NVGs produce (Gauthier et al., 2008; Macuda et al., 2005), or some combination of these and other factors, that contributes to spatial positioning difficulties while wearing them. Research examining how NVGs affect spatial knowledge have typically examined their effects in a global fashion. That is, participants wear NVGs and experience all of the visual limitations they impose (e.g., Gauthier et al., 2008; Macuda et al., 2005). Our research suggests that examining the various forms of visual component limitations in isolation would provide useful feedback on how to design better systems and how to compensate for the limitations imposed by current systems.

In examining our results, it should be evident that the threshold values measured here are unlikely to hold precisely for all navigation tasks. The current studies examined visually guided route learning performance under very precise and simple stimulus and task conditions. Alterations in either of these areas would likely change the overall threshold level. For instance, the inclusion of explicit visual landmarks could very well alter the results, as could employing a more immersive virtual environment. Similar variations relative to basic thresholds are seen in research on SF effects in visual recognition tasks (Collin, 2006; Collin & McMullen, 2005; Ruiz-Soler & Beltran, 2006). However, such variations are modest and tend to center around a central basic threshold. We anticipate similar findings with mobility tasks. We are currently running and planning a series of further studies to examine the effects of such manipulations on the function of visually guided route learning performance and SF cut-off.

Although using a virtual environment has a number of advantages (Fortenbaugh et al., 2007), it also presents several limitations that must be considered in interpreting our findings. For instance, the type of virtual environment employed here does not allow for stereoscopic depth to be experienced. Additionally, proprioceptive and vestibular information are not available to participants. Finally, the blur induced by the lenses in our task is imposed relative to the flat two-dimensional presentation of the three-dimensional maze environment, and does not faithfully reflect the way that more distant objects would be affected by defocus in a real-world setting. We are currently planning studies to examine similar questions in real-world human scale Hebb-Williams navigation environments. These future studies will complement the present one by allowing us to overcome the limitations imposed by the virtual environment.

One goal of the present study was to quantify the low-pass SF threshold at which visually guided route learning becomes impaired. To do this, we filtered spatial frequencies by applying spherical defocus via lenses of varying dioptric strengths. While this has approximately the same effect as applying more traditional digital image processing techniques (e.g., applying a Butterworth filter to the fourier transform), it does create some differences. For instance, as Akutsu et al. (2000) note, the modulation transfer function of a spherically defocused imaging system has a number of lobes below the first zero crossing. Some of these are negative, producing phase reversals. In approximating the SF cut-off produced by our lenses, we ignored these lobes and simply calculated the 50% gain point of the function. While this means that our SF cut-offs are only approximations, it should be noted that Akutsu et al. found no difference in functional visual measures when they excluded these additional lobes. We therefore

believe that our calculated threshold of approximately 2 cpd is a reasonably accurate measure of the point at which visually guided route learning becomes impaired. Future studies, in which the images of the mazes will be digitally filtered in real-time, are planned to confirm this.

### Conclusion

In conclusion, we have provided some of the first systematic examinations of SF limitations on visually guided mobility performance, specifically that of learning new environments. Our findings indicate that the function of low-pass SF cut-off and navigation performance is non-linear, following a sigmoidal pattern characteristic of a behavioural threshold. This threshold is quite low on the spectrum, around 2 cpd, indicating that navigation ability is fairly robust to blur. Our results also demonstrate that while mobility performance is improved with increased exposure to the environment (aka. learning) under all levels of blur, absolute performance is ultimately affected. That is, stronger levels of blur produce slower absolute times to complete a mobility task once learning has occurred. These findings have important implications for models of way-finding, specifically route learning, as well as real-world situations in which individuals must navigate under conditions of visual blur.

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## Appendix

## Computer/Video Game Usage Questionnaire

The intent of this questionnaire is to determine your experience and exposure to computer and video games throughout your lifetime. It is important that you answer each question as truthfully as you can and to the best of your knowledge as this information will be used as part of the study. Please note that all information provided is completely confidential and only accessible by the researchers.

Name: \_\_\_\_\_

Gender: \_\_\_\_\_

Age: \_\_\_\_\_

Handedness: \_\_\_\_\_

Please answer each question to the best of your knowledge, using educational guessing as necessary. Circle only one response for each question.

Question 1.

Between the ages of **7 and 12**, how many hours per week **on average** did you play computer and/or video games?

\_\_\_\_\_ hours

Question 2.

Of the hours responded in **Question 1**, how many of these hours **on average** were spent playing first-person shooter games (ex. Wolfenstein, Doom, Halo, Quake, etc.)?

\_\_\_\_\_ hours

Question 3.

Between the ages of **13 and 18**, how many hours per week **on average** did you play computer and/or video games?

\_\_\_\_\_ hours

Question 4.

Of the hours responded in **Question 3**, how many of these hours **on average** were spent playing first-person shooter games (ex. Wolfenstein, Doom, Halo, Quake, etc.)?

\_\_\_\_\_ hours

Question 5.

Since (and including) the age of **19**, how many hours per week **on average** did you play computer and/or video games?

\_\_\_\_\_ hours

Question 6.

Of the hours responded in **Question 5**, how many of these hours **on average** were spent playing first-person shooter games (ex. Wolfenstein, Doom, Halo, Quake, etc.)?

\_\_\_\_\_ hours

Question 7.

If you have any general comments, please describe them here:

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Thank you for taking the time to fill in this questionnaire.