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Darkness visible

Accurate distance estimation with a night vision device

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IMPORTANT INFORMATIVE STATEMENTS

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Abstract

The unguided visual estimation of depth and distance with night vision devices is often inaccurate. Observers estimate distances more accurately when given metric feedback on their reports of distance. Observers were asked to estimate distances between LED point-lights as seen through night vision goggles. The point-lights varied in azimuth and in elevation to the observer. Two weeks later, observers told distance accurately in the same scene without further feedback. Higher illumination (half-moon conditions rather than starlight) when feedback was administered made for better accuracy and better retention of training. The geometric consistency of observers' estimates improved with practice alone, unlike the accuracy of their distance estimates. This effect of training was found with a desktop computer display of the same scene, and lasted at least a month.

Significance to defence and security

1. Feedback training improves distance estimation with night vision devices.
2. This effect of training lasts for two weeks if training takes place under half-moon illumination.
3. The effect of training does not last two weeks if training takes place in starlight conditions.
4. Feedback training on a simulated scene improves distance estimation for a month.
5. The consistency of distance judgments improves whether initial feedback is given or not.

Résumé

L'estimation visuelle de la profondeur et de la distance est souvent erronée lorsqu'on utilise un appareil de vision nocturne sans assistance. L'observateur arrive souvent à estimer les distances avec plus de précision lorsqu'on lui offre la validation métrique des distances rapportées. On a demandé à des observateurs d'estimer la distance entre des sources ponctuelles de lumière DEL vues à travers des lunettes de vision nocturne. L'azimut et l'altitude des sources lumineuses étaient variables du point de vue de l'observateur. Deux semaines plus tard, les observateurs ont bien estimé la distance des sources observées dans la même scène, sans autre validation. Lorsque la validation était offerte aux observateurs sous une scène mieux éclairé (en présence d'une demi-lune plutôt que sous une scène étoilé sans lune), la précision était plus grande et la rétention de la formation, meilleure. L'uniformité géométrique des estimations des observateurs s'est améliorée simplement par des exercices, ce qui n'a pas été le cas des estimations de distance. Cet effet de la formation a été constaté grâce à l'affichage de la même scène sur ordinateur de bureau, et l'effet a perduré pendant au moins un mois.

Importance pour la défense et la sécurité

1. La formation de validation permet d'améliorer l'estimation des distances effectuée à l'aide d'appareils de vision nocturne.

2. Cet effet de la formation dure deux semaines si la formation a lieu sous une scène éclairé par une demi-lune.

3. L'effet de la formation ne dure pas deux semaines si la formation a lieu sous une scène étoilé sans lune.

4. La formation de validation à l'aide d'une scène simulée permet d'améliorer l'estimation des distances pendant un mois.

5. L'uniformité de l'évaluation des distances augmente, peu importe que l'évaluation fasse l'objet d'une validation initiale ou non.

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1 Introduction

Night Vision Goggles (or NVGs) have been used in aviation and in surveillance for decades. NVGs are image-intensifier devices which amplify environmental light in the visible and the near-infrared regions of the electromagnetic spectrum. Photons arrive on one side of a plate, and they induce a cascade of electrons in the plate. Those who use NVGs do not see *through* the goggles; they look towards a plate. The many electrons induce the emission of many photons on the observer's side of the plate, and the photons appear as an amplified image of the environment. Vision through NVGs is indirect vision: rays of light do not proceed unbent or unbroken from the object to the eye. Observers who use night vision devices estimate distance accurately when given metric feedback on their reports of distance. They estimate distance more accurately, more consistently, and with less variability after such feedback. Weeks later the same observers again tell distance accurately without feedback in the same scene, though their accuracy depends on the illumination conditions under which metric feedback was first administered.

The effects of Night Vision Devices (NVD) on distance estimation by eye—and on flight performance with NVDs—have been a focus of concern since the 1970s. (MacLeod & Hilgendorf, 1973; Chisum & Morway, 1975; Sanders, Kimball, Frezell & Hofmann, 1976; Wiley, Glick, Bucha & Park, 1976; DeLucia, 1995). Users of NVDs have expressed concern about the use of these devices, including the use of second-generation devices. There has been ample documentation of users' concerns, including surveys at Hurlburt Field, Florida; Dover Air Force Base, North Carolina; Pope Air Force Base, North Carolina; Fairchild Air Force Base, Georgia; and Robins Air Force Base, Georgia (Donohue-Perry, Hettinger & Riegler, 1992; Donohue-Perry, Hettinger, Riegler & Davis, 1993; Donohue-Perry, Hettinger, Riegler & Davis, 1993b; Hettinger, Donohue-Perry, Riegler & Davis, 1993; Hettinger, Donohue-Perry, Riegler & Davis, 1993b; respectively). Dyer and Young (1998) provide a 30-year review of issues for ground forces.

What seems to be wrong with the visual perception of distance? Many researchers argue against the notion that the estimation of distance by eye is either natural or perfectable. (One may be surprised to learn that distance is perceived at all.) There are many misconceived ways to deny or mitigate the statement that distances may be seen. Many reasons are given that distance may not be seen—or seen for itself—or seen directly. The estimation of distance is an age-old topic in psychology; many theoretical considerations impend on any simple proposal about distance estimation by eye. Some theories bring to bear quasi-optical factors which affect the perception of distance—such as foreshortening or depth cues (Lappin, Shelton & Rieser, 2006; Aznar-Casanova, Matsushima, Ribero-Filho & Da Silva 2006, p. 280). Other theories posit a psychological scale or a space which provides a "form of intuition" for the perception of distance. Implicit in both kinds of theories is the notion that there is something which is better seen than distance in depth. There is something more immediate or direct, so the assumption goes, and on that basis we perceive distance (He, Wu, Ooi, Yarbrough & Wu, 2004). A perceptual datum is assumed to be integral to distance estimation, by those theories. Some pristine and inchoate item is assumed, upon which distance estimation rests. The ways people estimate distance by eye are not pristine and inchoate.

Some theories emphasize a difference between "egocentric" and "exocentric" distances (Wu, He & Leng, 2003; Neggers, Schölvinck, van der Lubbe & Postma, 2005; Li, Phillips & Durgin, 2011). Egocentric distances are those nearly "placed endwise to the eye"; exocentric distances are lengths marked out in fair perspective, particularly those placed sagittally to the observer. The distinction is inexact: egocentric

distances are those more severely foreshortened. Distances placed in fair perspective are not distinguished categorically from other, severely foreshortened distances. Foreshortening is a compression of distance in perspective, by a cosine function of the angle which the distance makes to the picture plane—by which a sagittal plane is often meant. There is a way that observers might be misled in judging distance while using night vision goggles: by the foreshortening of distance in perspective. Foreshortening may become salient if a scene is extremely impoverished of detail (Ono, 1966). The picture of a line segment that is tilted in depth will be shortened—foreshortened—by the cosine of the angle that the line makes to the picture plane. A large number of distances between point-sources of light are presented to observers in the experiments. The distances vary in proximity to the observer, in height relative to eye level, and in orientation to the observer's sagittal plane. Renner, Velichkovsky & Helmert (2013) provide a review of factors that seem to affect egocentric distance in virtual environments.

Some theories depend on the relation of distance to other quantities in perspective (e.g., Gregory, 1963; Coltheart, 1971; Barfield & Kim, 1991; Wolfe, Maloney & Tam, 2005; Tozawa & Oyama, 2006). In two-point perspective, an object in the foreground of a picture is larger than the same object depicted in the background. Similarly for non-anamorphic film: a sphere of fixed diameter which moves from foreground to background in the film will follow rules of perspective. The sphere's image varies regularly in size with the sphere's depth from the camera lens: its image shrinks on the film screen (it may also become elliptical, but few people notice until the ellipse is very eccentric). Then there is a rule, or a law of perspective, which relates distance (the distance of the sphere from the camera) to size (the size of the sphere's image on the screen). That is to say, distance is related to other quantities in perspective. Some psychological theories adopt those rules as regularities in the visual perception of depth, or even as candidates for laws of psychology (Goldfarb & Tzelgov, 2005; Imamura & Nakamizo, 2006). Such "laws" of psychology emerge from the rules of perspective: their connections and their regularity depend on the optics of perspective. The depth cue of relative size is one such regularity derived from a rule of perspective. There is a necessary connection, one might say, between size in an image and distance from a camera under certain conditions. That connection will not do as a rule of visual perception, in the absence of further evidence. (Epstein (1963,1965) and Haber & Levin (2001) claim size and distance judgments are independent or uncoupled, except under specific conditions.) The claim of a lawful connection between size constancy and retinal image size is an old one (Boring, 1940; Kilpatrick & Ittelson, 1953). Holway and Boring (1941) sought to provide experimental evidence of the connection in a classic experiment. Their paradigm persists: the experiment provided the model for Zalevski, Meehan & Hughes's (2001) work on the estimation of size with NVDs.

Some other theories invoke a notion of "visual space" (Gilinsky, 1951; Wagner, 1985; Erkelens, 2015). Visual space is meant to be distinct from physical optics (or else dioptrics). There have been a number of empirical approaches to the description of visual space. Those empirical approaches have meant to assess the geometric properties of visual space, leaving aside individual differences and methodological errors (for instance as listed by Higashiyama, Ishikawa & Tanaka, 1990, or Button, Schofield & Croft, 2016). Estimates of properties by eye, or adjustment to physical arrangements by eye, can be assessed for their correspondence to key geometric properties. Such empirical approaches take advantage of the growth of mathematics in the nineteenth and twentieth centuries, which included a proliferation and classification of geometries. The end or purpose of these empirical investigations is to align judgments made by eye with properties that serve to select one geometry or another. What happens then? Then we have two spaces, or two geometries: the geometry of physical optics and the geometry of visual space (Koenderink, van Doorn, Kappers & Todd, 2002). Not much is said in psychology about the mapping between one space and the other; visual space introduces a difficult problem, rather than a clear explanation of distance estimation. Though properties of visual space may be said to be apprehended immediately or directly,

what can that tell us about seeing distance in our environment? The original problem remains untouched, for which the notion of visual space was first introduced. Rather this attempt is confused from the outset as a concept.

However its description may be motivated by theory, the estimation of distance can be improved by minimal feedback training. Eleanor Gibson (Gibson, 1953) reported this as the result of a series of studies conducted for government purposes during World War II. The basic result was refined in a program of experiments (Gibson & Bergman, 1954; Gibson, Bergman & Purdy, 1955). Gibson (1953, p. 410) notes the finding that "unaided vision, after training, was more accurate than stadiametric estimation." (In the stadia method, distance is estimated using fixed angular subtenses and a telescopic sight.) Gibson & Bergman (1954) demonstrate that absolute judgments of distance are improved by feedback training, with good generalization to novel distances. They report that the training corrected their observers' initial errors, both of underestimation and of overestimation. Further they find that variability in observer's estimates is reduced considerably (their Table 2, p. 477). Gibson, Bergman & Purdy (1955) show that the training transfers from one field (a flat field of 300 yards, about 274 m.) to another of the same length. "Absolute estimation was improved even though Ss were not tested in the same field where they were trained, the targets were unfamiliar, and the distances varied." (Ibid., p. 105). Richardson & Waller (2005) also found that "absolute judgments" of distance—meaning estimates in metres—improved with feedback training, and the improvement persisted for at least a week. Observers' estimates improved for both exocentric and egocentric distances. Allen & Rashotte (2006, p. 178) showed that "various forms of feedback regarding distance to target were roughly equally effective in training distance estimation skill in the field and that such skill transferred to a new field setting..."; their tests ranged out to 300 metres. Waller & Richardson (2008) also found that brief interaction in an immersive virtual environment improved distance estimates there.

Reising & Martin (1994, 1995) proposed applying feedback training to improve distance estimation with NVD. They did train observers in that way, but they concluded that observers showed a residual and constant error in distance estimation after training. A subsequent review of their data showed their supposition of a constant error to be a simple artifact of arithmetic. Reising & Martin compared the distances between posts on the ground (i.e., the flat ground of the Sonoran desert), to observers' estimates of those distances before and after training. As their dependent measure, Reising & Martin used the absolute value of the difference between the observer's estimate of distance, and the distance on the ground. A different pattern of results became apparent when the arithmetic difference was taken, but the sign of that difference was retained (Niall, 1999). Call those signed differences "errors in estimate of distance." After training, errors by Reising & Martin's observers centred about zero, and the errors had appreciable variability across conditions. Though the average value of errors was zero in those conditions, the average of their absolute value is positive; it is positive and constant because the variability of the conditions was roughly equal. The signum (absolute value) operation confounds the mean and the variability of the conditions. A mean of zero is not possible in those conditions where there is variability, when the sign of the error is not retained. (Aznar-Casanova, Matsushima, Ribeiro-Filho & Da Silva (2006) use an absolute-value measure of error, as a root mean-square error or RMSE. Basevitch, Tenenbaum, Land & Ward (2015) use the absolute value itself.) The line of experimentation was continued in Niall, Reising & Martin (1999), who found that errors in distance estimation (with the revised dependent measure) were alleviated by feedback training. Distances within a 175 x 175 foot (53.34 m^2) grid were estimated well by eye, with a mean (group) error of one foot over a period of a week after training.

There are at least two ways observers might be misled in judging distance when using night vision goggles. (Neither one affects judgments of depth significantly given adequate training.) Observers might either mistake the relative size of halos around point-lights as a cue to depth, or else they might be misled by the foreshortening of distances in perspective. Point sources of light induce circular halos around their NVG image (Thomas et al, 2005). That is an artifact of electro-optics: advances in NVG electro-optics have reduced the diameter of these characteristic artifacts, but have not eliminated them. Halo size depends on the spectral content and power of a light source, rather than its proximity to the observer. Halo size has been suspected of presenting an unreliable cue to depth for the observer, in contrast to changes in relative size which are contingent on perspective. A disk in the foreground of a picture is larger than the same disk pictured further in the background. The disk's size diminishes regularly in perspective as it is pictured to lie farther away. (Conversely, a disk drawn low on the picture's foreground will indicate a smaller size in a perspective picture than the same diameter of disk drawn high on the picture's background.) The relative size of a disk is an indication of its depth in the picture—it is one indication of the disk's pictured distance from the viewer. Relative size is a cue to depth in that sense, as a predictable consequence of perspective. The size of NVG halos does not depend on distance from the observer, but on the power and spectral content of the point-light source. That is to say: there is some variation of halo size with distance from the observer, but that variation does not follow the rules of perspective (Zacher et al, 2007). Halo size does not vary with distance from the observer, for a moderate range of distance. (There is a far distance at which halo size may be reduced dramatically.) Large halos may result from distant light sources, and smaller halos from nearer sources: their size is not contingent on perspective first of all. Point-light sources of higher spectral energy (towards the blue end of the visible spectrum) produce larger halos than point-light sources of lower spectral energy (towards the red end of the visible spectrum). Then a more blue point-light source far from the observer can produce a much larger halo than a more red point-light source near to the observer. Their relative sizes are different from the relative sizes of near and far objects as expected by the rules of perspective. If the relative sizes of those halos were to be taken as a depth cue due to perspective, then the relative sizes of the halos would run counter to their anticipated relative size due to perspective. And then if observers were to apprehend halo size as a cue to distance in perspective, they would be mistaken when judging distance in several situations.

2 Experiment one

The first experiment sets out to determine the accuracy of distance estimation under night vision conditions, and the efficacy of feedback training in correcting errors. LED lights are presented at different distances and heights from the observer; two colors of LED lights are used for the generation of halos of different sizes. Halo size is meant to be a distractor to distance estimation in the experiment, rather than a help.

2.1 Method

2.1.1 Observers

Twenty-nine men and seven women participated as observers in the first experiment. Most were current employees of the Flight Research Lab (FRL), but several came from other National Research Council (NRC) branches and government departments (such as Transportation Safety) as well as the private sector. All had either normal vision (12 observers) or corrected-to-normal vision (23 observers), but were not screened for colour deficiency or colour anomaly. The experiment was approved by the DRDC Toronto Human Research Ethics Committee (HREC) and all subjects signed a declaration to indicate their informed consent to participation in the experiment. As with many forms of judgment, observer performance may be affected by many factors: the amount of sleep during the night before, the side effects of prescription medication, non-prescription medication, and over-the-counter drugs, excessive alcohol consumption, and the level of caffeine consumption. All accepted subjects were instructed not to change their habits regarding sleep, medications, alcohol or caffeine within 36 hours prior to participation in the study, and to avoid over-the-counter anti-nausea drugs like Gravol® 48 hrs prior to participating in the study, as such medications have been shown to change eye movements and vestibular responses.

2.1.2 Apparatus

All testing utilized a standard set of ANVIS-9 (Aviator Night Vision Imaging System) Gen lllA or Pinnacle, F4949 night vision goggle (NVG) system from ITT Night Vision, serial number 7317. Prior to testing, observers received specific training on NVG adjustment procedures using the Hoffman ANV-20 (Hoffman Engineering Corporation), a system widely used to ensure good NVG focus before night flying. The Hoffman ANV-20 utilizes the USAF-1951Tribar test to set goggle visual acuity. Subjects spent approximately 5–10 minutes adjusting and focusing their goggles and were tested to have a Snellen value of at least 20/30 visual acuity after NVG adjustment. The experiment was conducted in a 30 m indoor alley (known as an eye lane) in Building U-69 of the FRL at NRC's Uplands facility in Ottawa. Lighting in the eye lane was tightly controlled. Measures were taken to make it as dark as possible. The windows on the east side of the lane were blocked off, sealed with caulking, and painted in a flat black. The north and south walls of the lane were also painted in a flat black. The west wall of the lane was made of chain link and covered in black fabric. The west wall access door was closed during experiments. Since the west wall did not continue up to the ceiling, it was important to ensure that other doors in the building were closed to minimize the amount of light leaks from other areas of the building.

The subject was seated at one end of the eye lane with their head stabilized on a chin and forehead rest and their NVG mounted on a helmet visor. There were eight light posts on the left side of the eye lane and eight on the right side. The posts were staggered at irregular intervals. At each of these posts, three light emitting

diodes (hereafter referred to as "lights") were located at three heights from the ground (Lower = 0.622 m, Middle = 1.23 m, and Upper = 1.84 m. Lights that are higher in elevation may be perceived as being closer: Dunn, 1969). The NVG fixture and consequently the observer's eye height were set to 1.23 m. Figure 1 gives an oblique view of this arrangement, and Figure 2 gives its top view. Subjects were provided with a lamp, a flashlight, and a bottle of water. The experimenter was seated behind the subject at a desk. In order to minimize the amount of light contaminating the lane, the experimenter's Personal Data Assistant (PDA) and laptop were placed in a box covered with black fabric on the desk.

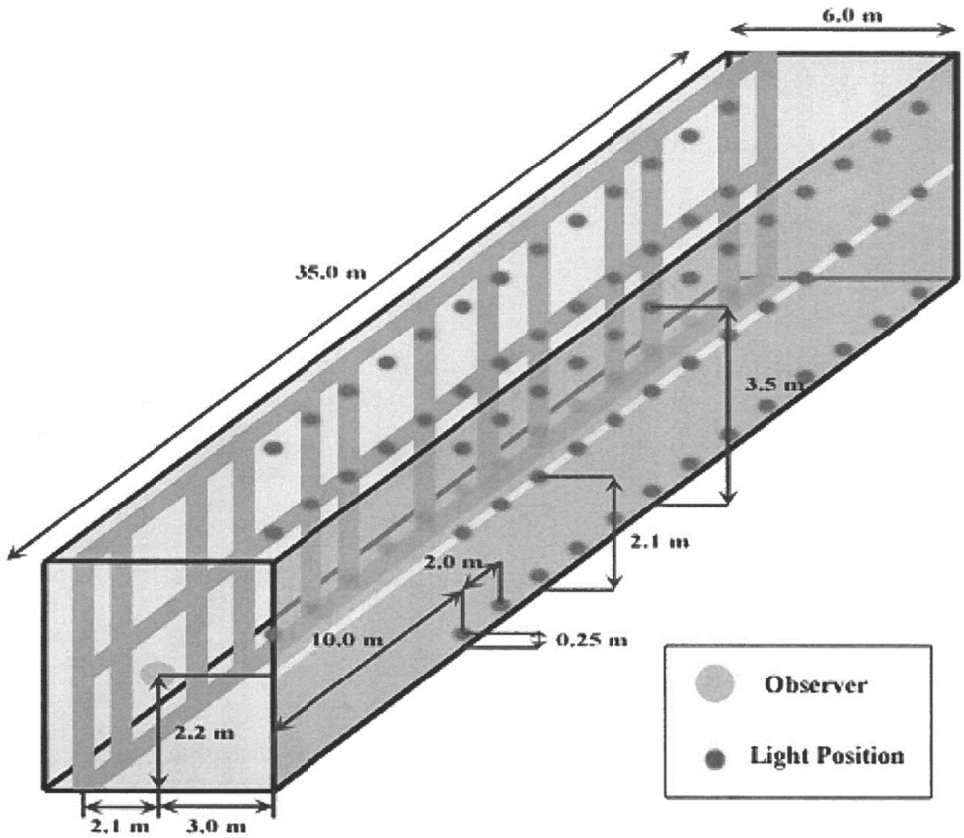

Figure 1: *Remotely-controlled LED lights were arranged along an 35 m eye lane at three different heights (0.25 m, 2.1 m, and 3.5 m). Two panels of the lights were set 6 m apart. The observer was stationed at one end of this arrangement, which is shown in oblique view.*

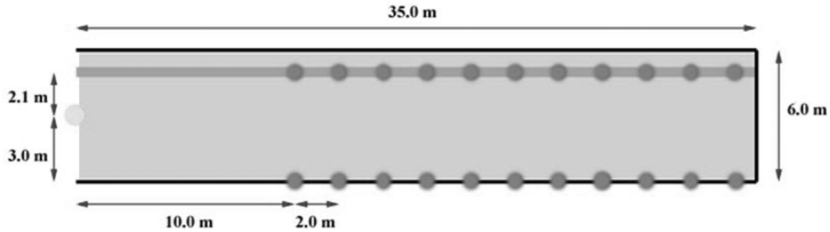

Figure 2: *The same eye lane is shown in top view.*

Illumination was controlled by 2856K pinhole light sources provided by the FRL and based on a design from the Air Force Research Laboratory at Wright Patterson Air Force Base (Dayton, Ohio). Luminance was tested through the use of a Hoffman 410 Series illuminance meter (ANV-410) provided by DRDC. In this study, half-moon illumination was duplicated by turning on one 2856K pinhole light sources. Only the ambient room light and two LEDs were used to simulate starlight illumination. The light source to produce the "half-moon" illumination was a square spherical source of 60 mLux, to produce 0.06 lux at the observation point. The light source to produce the "starlight" illumination was ambient light, plus two of the LED point sources, to produce 0.01336 lux at the observation point. A predetermined and random sequence of light illumination was programmed on the experimenter's PDA. Electrical signals from the PDA went to a blue tooth transmitter and then a receiver and light controller.

The stimuli of this experiment were Light-Emitting Diode (LED) point-lights of two distinct spectral types. Two LEDs of each type were placed at each position, and the two could be switched on or off independently. The point-lights were arranged on a scaffolding along a long passageway, so that the LED were placed at three heights and at several distances from the end of the passageway. The observer sat at a table at the end of the passageway, where night-vision goggles were fixed in place above the table.

Two different kinds of light emitting diodes (hereafter referred to as simply, lights) were installed at each position on the light post. Two were different colours of lights. The red light had a dominant wavelength of 624 nm with a 15° viewing angle and it produced a large halo under NVG viewing conditions. ("Super-Blue" GaN LED manufactured by SuperBright LEDs, St. Louis Missouri Part number RL5-B5515. Full width at half max: 25.5 nm; luminous intensity 5500 mcd @ 20mA.) By contrast, the blue light had a dominant wavelength of 467 nm, with a 15° viewing angle; it produced little or no halo under NVG viewing conditions. ("Super-Red" AlGaInP LED manufactured by SuperBright LEDs, St. Louis Missouri Part number RL5-B5015. Peak wavelength: 631 nm; spectral line half width: 13.5 nm; luminous intensity 5000 mcd @ 20mA.)

The arrangement of the LED is meant to enable variations in two properties of the point-lights, as they are seen through the night vision goggles: relative halo size, and inclination to the picture plane (Figure 3 gives an indication of three such pairs). Relative size varied with the spectral content of the two LEDs: both blue (meaning higher-energy and therefore larger halos), both red (meaning lower-energy and therefore smaller halos), or one blue and one red. The arrangement of the two LED lights also fixed an orientation in space, that is, a three-dimensional orientation (Figure 4 indicates the relative arrangement of all the lights at once.). The position of the observer and the fixed position of the NVGs specify an image plane, somewhat like a picture plane. Importantly, the orientation of the two LEDs in space fixed an inclination to the image plane, that is, an angle between the line of the two LEDs and the picture plane.

The lights were arranged in steps of approximately one foot. The six lights were arranged according to a randomized series of integers (representing feet) between 1 and 100, where the integers are chosen without replacement. One such series is [38 86 32 23 73 49]; another is [5 92 33 59 20 52]. A series in which the same number appears twice was not used. These lights were labelled implicitly with the nearest light being counted as the first. In each block of trials, every light was paired with every other light except itself. Fifteen verbal estimates of distances in metres between two lights were made on each set of six lights. These were explicit verbal estimates by the observer, in meters.

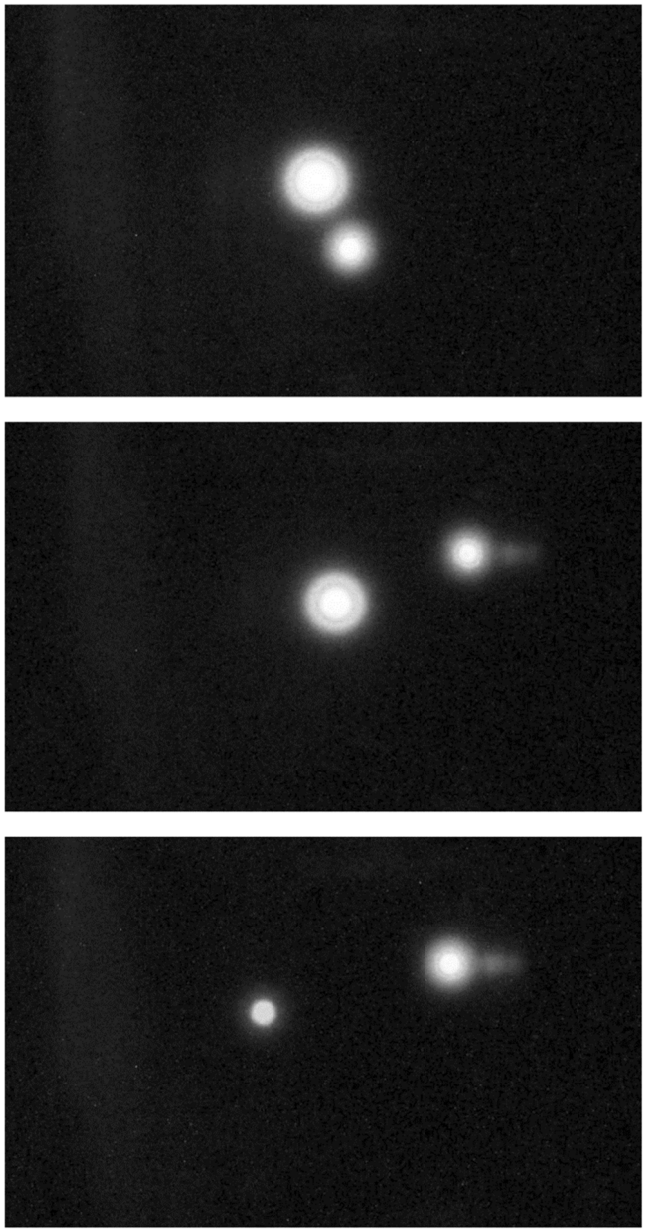

Figure 3: *Three pairs of lights are shown, each as photographed through the night vision device. Only one pair of lights was shown on a trial, and the observer was asked to tell the distance between the pair. A blue LED light produces a larger halo than a red LED light.*

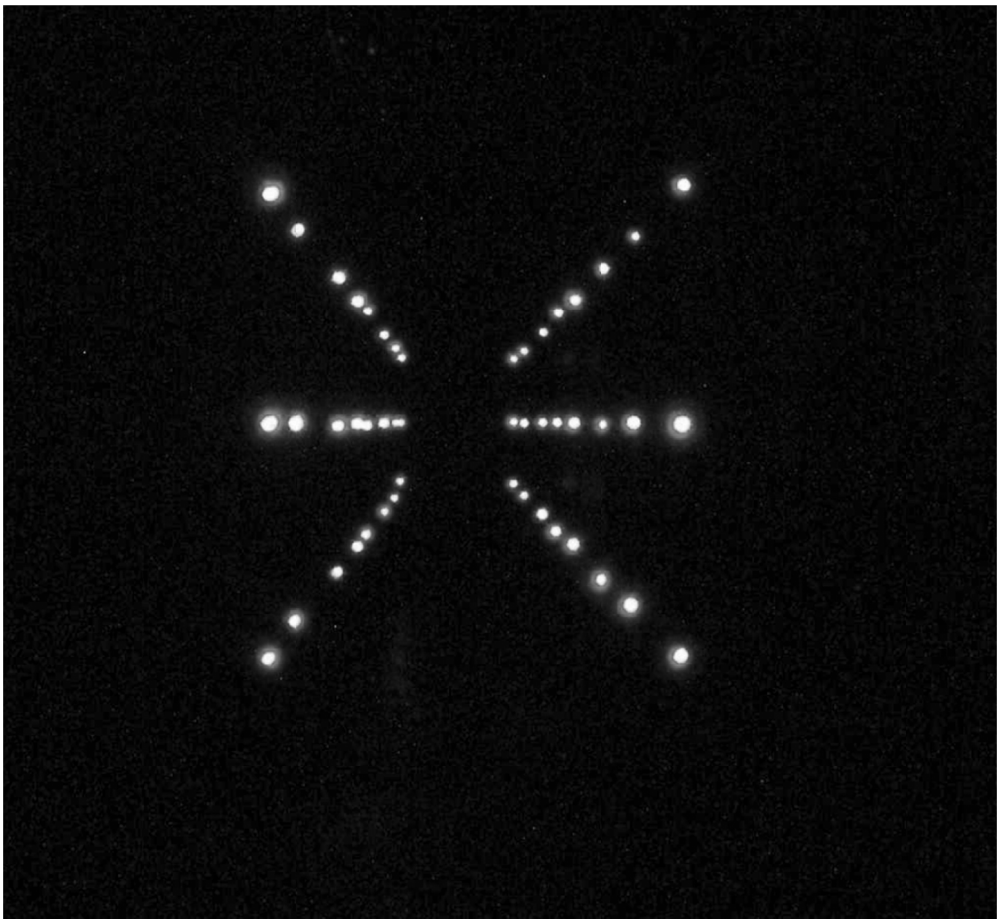

Figure 4: *The ordinary-light (non-NVG) view from the position of the observer is shown as all the LED sources are illuminated at the same time. The sources have a rectilinear arrangement that is subject to perspective.*

2.1.3 Procedure

Subjects were randomly assigned to one of four groups. Two experimental groups received feedback and two control groups received no feedback. One each of both the experimental and the control groups also received two different lighting conditions: Half-moon or Starlight. The light condition refers to the ambient illumination under which the participants conducted their estimates: half of the subjects were tested under an illumination equivalent to half-moon light (0.06 lux), and the other half under unclouded starlight (0.01338 lux). This made a total of four groups, each with nine subjects. (Note that effective visual acuity with NVDs is known to decrease as light level is reduced: Donohue-Perry, Task & Dixon, 1994, their Figure 6.) Figure 5 shows the entire arrangement of LEDs illuminated at once, as seen through the night vision device.

In feedback conditions of the experiment, the observer was given verbal feedback on their estimates. That is, after making an estimate, the observer was told the correct distance in metres between the two lights. This is called “feedback” rather than “training,” since this simple procedure falls short of more academic training methods that one might imagine. The experimenter was given a table of the comparisons between

lights to be made, where the order of the fifteen comparisons had been randomized. The experimenter was also given a table of the inter-point distances of the lights. This table was given so that the experimenter did not make errors in giving feedback in the relevant conditions of the experiment. Alternatively, the control groups did not receive feedback on the actual distances.

Each subject made a total of 180 inter-point distance estimates split among four sessions: pre-training, training, post-training, and two-week post-training, each with a block of 45 distance estimates. The first three sessions were run in one day and the fourth was run two weeks later. For each block of distance estimates, three arrangements of six lights were randomly selected so that within each set, each light was on a different post and there were equal numbers of different height positions and equal numbers of red or blue lights. By pairing each light with every other light except itself, a total of fifteen pair-wise distances was designated for each set of six lights. These three sets of fifteen distances were then randomized within each block to make the total of 45 inter-point distances to be judged per session of testing. A random order of presentation was not given to the same observer twice, and the repetition of random orders across observers was avoided.

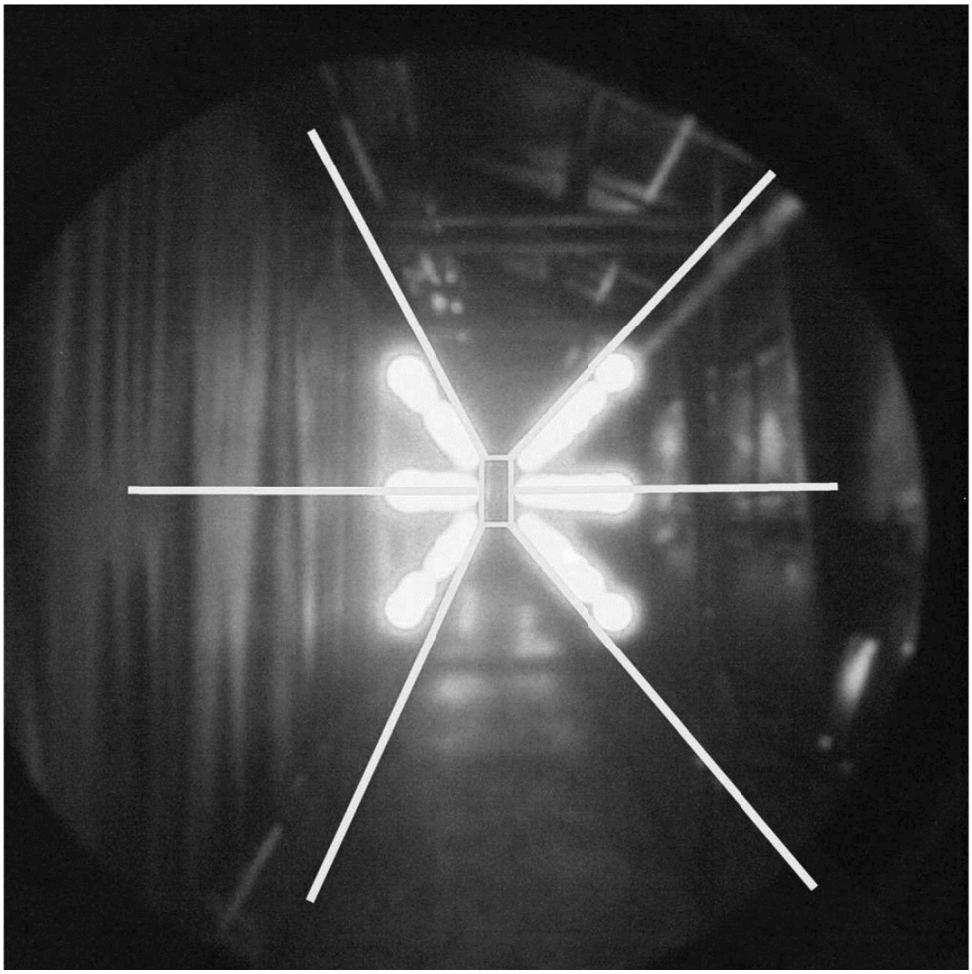

Figure 5: *The view from the position of the observer is shown as all the LED sources are illuminated at the same time. Here the scene was photographed through the night vision device. Lines are superimposed on the photograph to emphasize directions of the lines of LEDs in space.*

The fifteen estimates were randomly selected beginning with the selection of light posts. Six light poles out of 16 were chosen randomly with a random number generator, chosen fresh each time. Every possible combination of the six lights in was made, making 15 pairs and 45 in the total block. The poles were selected such that each pole was only chosen once per fifteen estimates. Therefore, it was never the case that there were two lights illuminated on the same pole. Distances were calculated in metres between the two poles using the Pythagorean Theorem; the calculations were accurate to two decimal places. These distances were calculated from the difference in x, y, and z coordinates of each pole. Once the 45 trials had been determined, they were rearranged randomly using a random number generator. For each testing block, a new set of 45 trials was selected to eliminate unwanted carryover effects.

2.2 Results

2.2.1 Dependent measures

The main dependent variable was the error of estimate between the observers' spoken estimate and the corresponding actual distance (estimated—actual). This error was signed, as the estimate could have been greater or less than the actual distance, resulting in a positive or negative value, respectively. A difference of zero between the estimated distance and actual distance would represent accurate judgment. Another dependent variable used to measure accuracy was the natural log ratio of the observer's distance estimate to the actual distance or $\log_e$(estimated/actual). (Da Silva, 1983, uses this ratio measure.) A ratio of one between the estimated distance and actual distance would represent accurate judgment, and similarly for a log ratio of zero, since the log ratio of one equals zero. Using log ratio is useful, as the measure is not susceptible to the effects of skew in observations like the error of estimate. The $\log_e$(estimated/actual) will hereafter be referred to as "log ratio."

Table 1: *Verbal feedback in fair conditions of illumination does improve estimates of distance with a night vision device. The improvement in estimate of novel distances will last for at least two weeks. Four conditions of the experiment are presented (by rows) with four times of testing (by columns: before training, during training, after training, and two weeks later). The signed error measure is estimated distance minus actual distance in metres. The log ratio error (meaning, ln(estimated distance/actual distance)) is also given.*

		Before training		Training		After training		Two weeks	
Condition		***Error (metres)***	***Log ratio***	***Error (metres)***	***Log ratio***	***Error (metres)***	***Log ratio***	***Error (metres)***	***Log ratio***
Half-moon	Feedback	**-3.59**	**-0.65**	**-1.18**	**-0.17**	**0.66**	**0.06**	**0.88**	**0.05**
Half-moon	No feedback	**-3.02**	**-0.58**	**-2.78**	**-0.62**	**-3.49**	**-0.67**	**-2.62**	**-0.48**
Starlight	Feedback	**-3.78**	**-0.79**	**-0.79**	**-0.11**	**-1.2**	**-0.1**	**-2.27**	**-0.44**
Starlight	No feedback	**-2.35**	**-0.5**	**-2.87**	**-0.52**	**-2.56**	**-0.5**	**-3.65**	**-0.67**

A mixed-model analysis of variance was applied to the data, with one between-subjects factor (Group), and one within-subjects factor (Session). There were four Groups (Group 1: half-moon illumination, feedback given; Group 2: half-moon illumination, no feedback; Group 3: starlight illumination, feedback given; Group 4: starlight illumination, no feedback) and four Sessions (Pre-training, Training, Post-training, and Two-week post-training). The main dependent variable was the error of estimate, meaning the estimated distance minus the actual distance. In the first analysis, a mean value was computed for the 45 observations by each observer in each session to produce one score. In the second analysis, a mean value was computed on the log ratio of the 45 observations by each observer in each session to produce one score. The purpose of taking the log ratio was to mitigate the effect of skew in some conditions. The Greenhouse-Geisser correction was applied to the ANOVA degrees of freedom in each case. The first analysis showed a significant Group by Session interaction ($F_{(9,96)} = 3.68$, $MS_e = 3.86$, adjusted df (6,67), $p \leq .005$), as well as an overall main effect of Session ($F_{(9,96)} = 4.70$, $MS_e = 3.86$, adjusted df (2,67), $p \leq .05$). The second analysis also showed a significant Group by Session interaction ($F_{(9,96)} = 4.93$, $MS_e = 0.09$, adjusted df (8,85), $p \leq .0001$), as well as an overall main effect of Session ($F_{(9,96)} = 7.62$, $MS_e = 0.09$, adjusted df (3,85), $p \leq .0005$). Average errors of estimate across observers are shown in Table 1 for all conditions. The difference between feedback conditions and non-feedback conditions is illustrated in Figure 6. Note that in Figure 6, the apparent departure from zero error at two weeks is the result of averaging over two feedback conditions (half-moon and starlight).

The significant effects of the ANOVAs plus the trend of the average estimates to zero provide an indication that feedback training does correct the underestimation that is characteristic of distance estimation in perspective. The effects of training last at least two weeks; they are better when the training is administered in conditions of higher illumination. The correction of distance estimation by feedback training is undeterred by the extraneous information provided by halo size. The question arises whether such training can be demonstrated when these conditions of night vision are simulated roughly on a

desktop device. (Emphatically, that is not to go so far as to say that the training should be administered with a desktop device.)

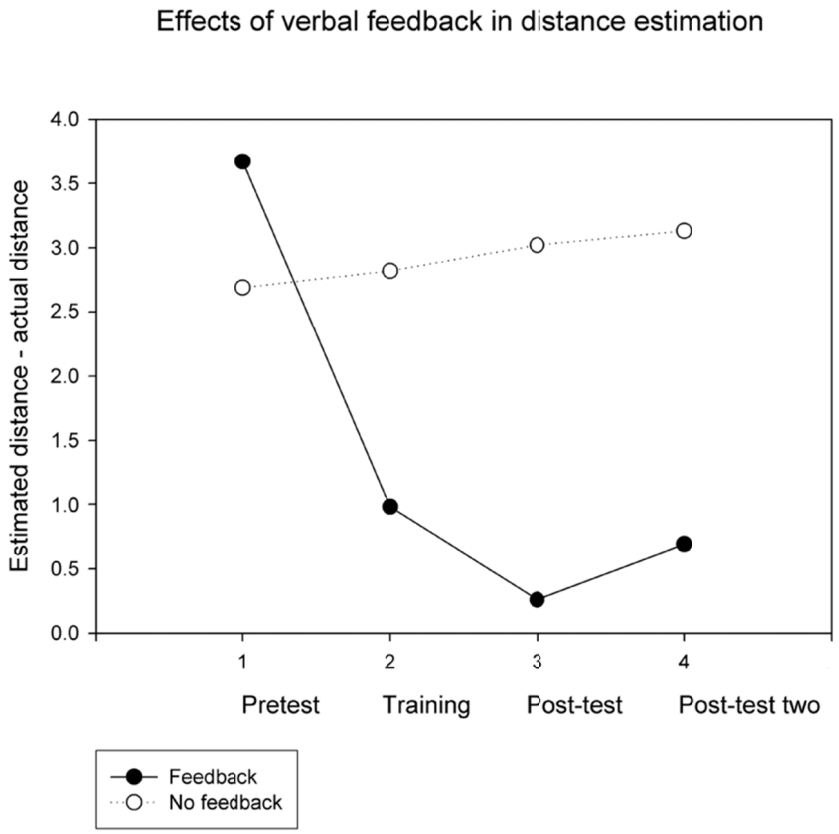

Figure 6: *Immediate verbal feedback decreases average error in distance estimation on novel distances, over a period of two weeks. Four sets of trials (untrained pretest, performance during training, performance just after training, and performance two weeks after training) are marked on the abscissa, while average error in distance estimation (the average of estimated distance minus actual distance in metres) is marked on the ordinate. Average estimates do not improve if feedback is not provided.*

3 Experiment two

In the second experiment, a desktop replication of the eyelane results was attempted. The aim of this second experiment is to show that distance estimation in virtual environments is also corrigible under conditions of feedback training. The estimation of distance by eye in actual environments can be contrasted with the estimation of distance in virtual environments. (Loomis & Knapp, 2003; Messing & Durgin, 2004). Yet the same relations of size and distance (size-distance invariance) has been claimed for both sorts of environments. (Nakamizo & Imamura, 2004). Field of view does not seem to be the primary difference: distance underestimation in virtual environments is not a result of a restricted field of view. (Knapp & Loomis, 2004). Peli (1998) claimed that several important visual effects of head-mounted displays were not functionally distinguishable from desktop displays; the quality of computer graphics rendering does not seem to contribute substantively (Thompson, Willemsen, Gooch, Creem-Regehr, Loomis & Beall, 2004).

3.1 Method

3.1.1 Observers

Fifteen men and twelve women (mean age of 26.5 years, SD 8.6) were recruited to be observers in the experiment. They came from DRDC Toronto, York University, and the surrounding area through distribution of posters, email, and by word of mouth. Two subjects were members of the Canadian Forces and the remaining 25 subjects were civilian. Two subjects had previous experience with night vision. All had either normal vision (6 observers) or corrected-to-normal vision (21 observers), but were not screened for colour deficiency or colour anomaly. As with many forms of judgment, observer performance may be affected by many factors: the amount of sleep during the night before, the side effects of prescription medication, non-prescription medication, and over-the-counter drugs, excessive alcohol consumption, and the level of caffeine consumption. Observers were therefore asked not to change their habits in these respects during the course of the experiments. They were instructed not to take over-the-counter medications like Gravol® 48 hrs prior to participating in the study, as such medications have been shown to change eye movements and vestibular responses. The experiment was approved by the DRDC Human Research Ethics Committee (HREC).

3.1.2 Apparatus and stimuli

Two identical Dell UltraSharp 19″ (48.3 cm) 1905FP flat screen LCD monitors with active matrix TFT (thin film transistor) display were used in this experiment. Observers were seated comfortably approximately 60 cm away from the monitor screen. Distance estimates were entered using the computer keyboard. All testing was conducted in a room with the lights off to more realistically simulate night vision conditions. However, the room was not pitch black because the window curtains on the other side of the room were open.

The simulation software was custom designed and developed for ADDNS-TDP by Array Systems Computing Inc. The simulated environment was created using MultiGen-Paradigm's Creator 3.0, which enabled the creation of a highly optimized, real-time, three-dimensional model. A model of an eye lane, or indoor alley, was constructed using digital photographs of the actual eye lane at the NRC Uplands facility that was used in the previously described field experiments. Dimensions of the long rectangular

eye lane were set to be equivalent to 35 m long and 6 m wide. The appearance of the eye lane was made to recreate the layout and feel of the actual experiment set-up in real life. Dark grey and stone-like texture served as the walls and ceiling, and wooden frames on the left side and ceiling of the eye lane provided depth cues for the eye lane. Positioning of the light emitting diodes (hereafter referred to as lights) at the three heights was adjusted to follow the perspective projection of the eye lane, and to simulate as close as possible to the viewed angles in the original experiment (Figure 7).

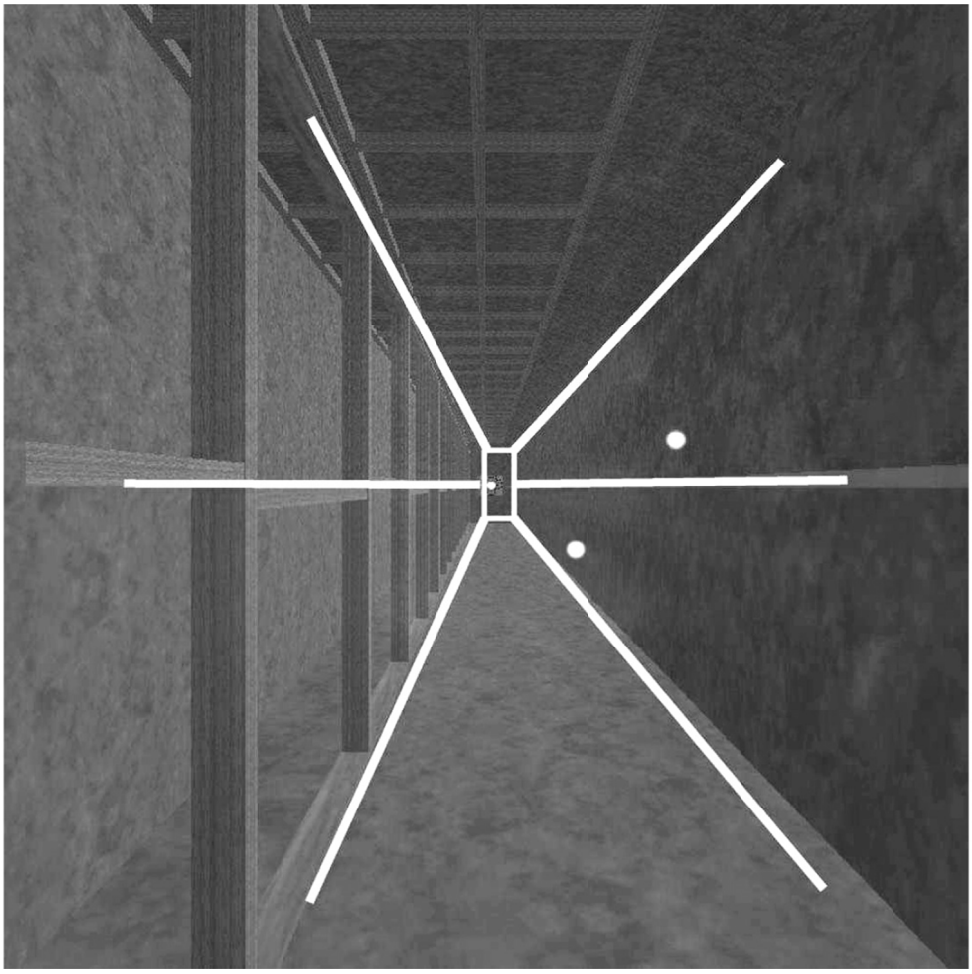

Figure 7: *Directions of the lines of LEDs are reproduced in a desktop simulation of the scene of the eye lane for a second experiment.*

A three dimensional (x, y, z) coordinates system was used to represent position in the eye lane, with the horizontal width of the eye lane as the x-axis, the distance longitudinally down the lane as the y-axis, and the height from the ground as the z-axis. Using the position of the observer as an origin, the view of the observer was set to be 0, 0, 2.2; equivalent to 2.2 m from the ground at the beginning of the eye lane, and centred along the hall's width. A line was created at eye level height (z = 2.2) along either side of the eye lane model as a horizon reference for the observer. Simulation included a wooden frame on which lights could appear on the left side of the eye lane at x = -2.1 and the right wall at x = 3.0. There were 13 distances along the y-axis at which lights could appear on either side of the alley, starting at 10 m from the observer (y = 10) and at every 2 m interval to 34 m from the observer (y = 34). There were also three

light positions of differing heights (x-values) at each distance interval: 0.25 m (low), 2.1 m (middle), and 3.5 m (high). These heights were chosen so the middle height would be near eye level, and the low and high heights could be differentiated from any distance interval, including those at the farthest end of the eye lane. Thus, with 13 distances, three heights and two sides on which lights could appear, there were a total of 78 different possible light positions.

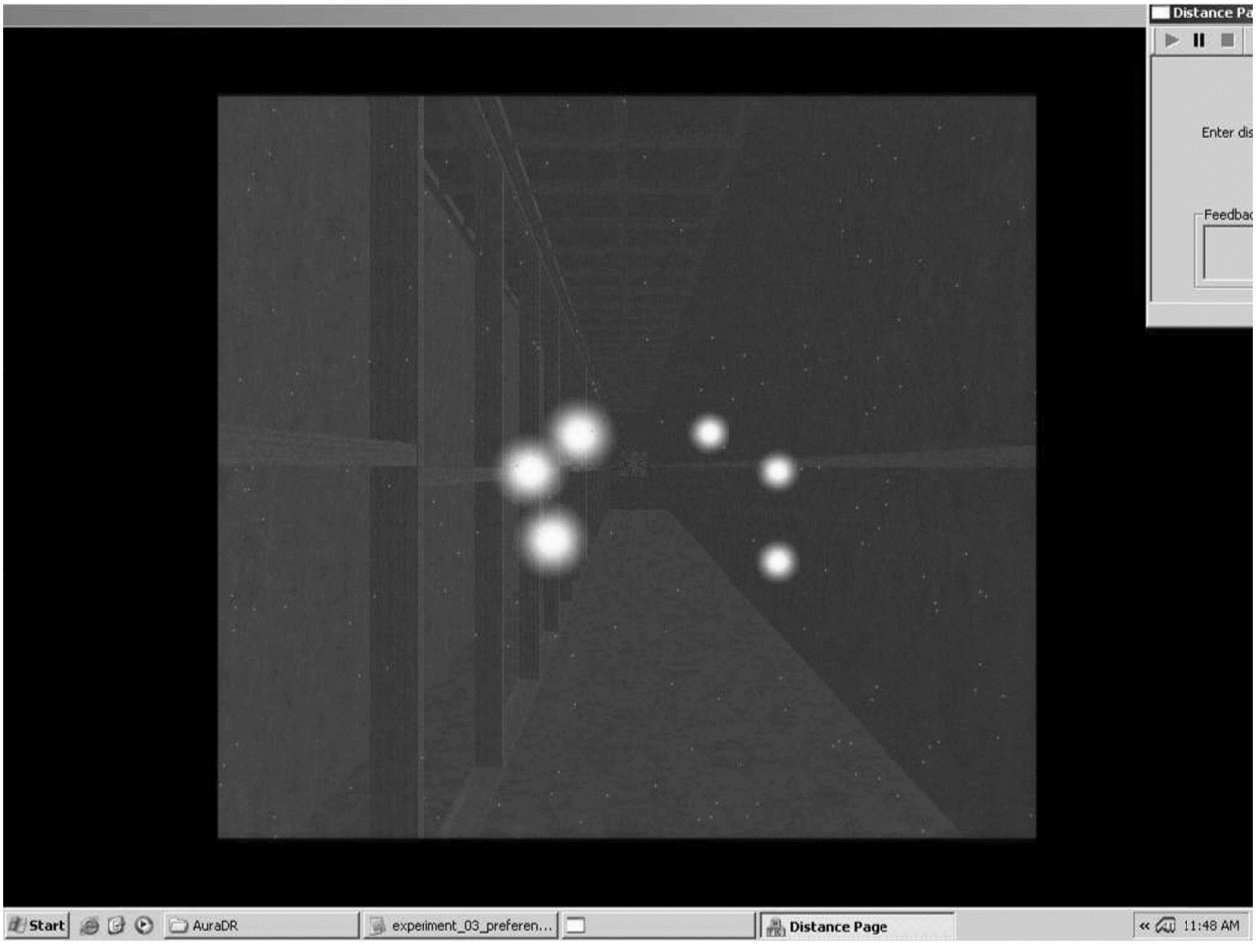

Figure 8: *As in the first experiment, only one pair of lights is presented on a trial. Over many trials an observer is asked to estimate all fifteen pairwise distances among a group of six lights, interleaved in order with a multiple of fifteen distances from other groups of six lights. Larger halos represent blue LED sources, while smaller halos represent red LEDs.*

A computer program for each block of trials in the experiment was made and run using Vega Prime 2.0.0, a run-time graphics engine also by Multi-Gen Paradigm**.** Settings for the screen resolution of the programs were at 1024 x 768, 32-bit colour depth and a screen refresh rate of 75 Hz. Image brightness of the monitors was at 250 cd/m^2. The field of view of the NVG was rectangular and set to be at 180° and 73% x 87% of the total screen (approximately 750 pixels x 670 pixels), with the remaining border of the screen showing as a plain black background. This was intended to simulate the view seen by an observer using NVG.

The halo textures for the lights were generated using Matlab based on a Gaussian model. The lights themselves were represented as two-dimensional images facing the observer position to minimize rendering time. Three halo sizes were used to represent lights of different night vision device compatibility. These were based on a scale proportional to the actual size of a halo measuring 0.2 radians, drawn as if it were 50 m away from the observer: 0.7 (large), 0.4 (medium), and 0.25 (small) radians.

Two different illumination levels were used for the simulated NVG environment: half-moon and starlight. These represented the lighting that would appear with NVG use in half-moon light and unclouded starlight. The illumination model used was a built-in functionality of Vega Prime and the levels were based on a fraction scale of the amount of light given by a full moon. Half-moon light was thus defined at 0.3 and starlight at 0.1. The NVG noise model used in the simulation software was injected into the final scene and consisted of two stages: a randomly generated 2-D static noise overlay, and a randomly generated particle system that simulates scintillation noise. This was an effects-based model to give the overall look and feel of NVG noise and was not based on the physics of actual NVG. The same level and characteristics of noise were used for both lighting conditions. However, higher levels of noise appeared to the observer in the starlight condition due to side effects of the darker illumination. This effectively simulated higher levels of NVG noise under low light conditions.

3.1.3 Procedure

The twenty-seven subjects were randomly assigned to three groups: 1) half-moon with feedback, 2) half-moon with no feedback, and 3) starlight with feedback. Therefore, there were nine subjects in each group. Group 2 (half-moon with no feedback) served as the control group. In contrast to the NRC eye lane experiment, an equivalent control group in starlight illumination conditions was not included in this experiment. There were five sessions: Pre-training, Training, Post-training, Two-week post-training, and One-month post-training. Observers in Groups 1 and 3 received feedback in the second session, thus labelling this session as “Training.” All the other sessions are named in relation to this session, with the Pre-training session occurring before the Training session, and the three post-training sessions occurring after this session. The first three sessions were completed consecutively on the first day, while the fourth and fifth sessions were run at their specified time periods after the first day (two weeks and one month, respectively). The Post-training session occurred immediately after training. Each session took approximately 10 minutes, making a total participation time of approximately 50 minutes for the whole experiment over the three days in which observers came in to participate in the study.

Each observer made a total of 225 inter-point distance estimates across the five sessions. For each subject at each session, one set of six light positions was randomly selected (cf. Figure 8). In each set, lights 1–6 were numbered so each light had a specific and static x-value and z-value, i.e., left or right wall and light height. Therefore lights 1–3 would appear on the left side of the eye lane and lights 4–6 on the right side, and two lights each of the six would be at the three different light heights: low, middle, or high. The distance coordinate (y-value) along the eye lane for each light was randomly selected with replacement; this means that two lights at the same distance interval and side of the eye lane could appear in one set only if they appeared at different heights. By pairing each of the six lights with every other light except itself, there were a total of 15 pair-wise distances. There were three of these blocks of 15 trials within each session to make a total of 45 distance estimates per session. The order of appearance of pairs of lights with a block was randomized and the order of blocks was also counterbalanced across subjects for each session.

Within each session, there were three cases in which the same set of six light positions was presented to the observer. Since there were varying halo sizes, each observer would see some pairs of lights that have equal halo sizes, and some which have combinations of large and medium halos. For each trial, observers were prompted to "enter the distance between the two lights (m)" using the number pad on the keyboard. Observers were allowed to make distance estimates as precise as they wanted (e.g., metres in integers or with any number of decimal places). In the training sessions, subjects in Group 1 (half-moon with feedback) and Group 3 (starlight with feedback) were given the actual inter-point distances by the program immediately after their estimates were entered. Subjects in Group 2 (half-moon with no feedback) were not given the actual distances. None of the subjects received feedback in any of the other sessions (i.e., Pre-training, Post-training, Two-week post-training, and One-month post training).

The program output generated the following information for each trial: actual inter-point distance, the observer's entered distance estimate, the error of estimate between the estimate and actual distance, the (x, y, z) coordinates of the two lights shown (side of the eye lane, distance along the eye lane, and light height), as well as the scale size of the halo for each of the lights.

3.2 Results

3.2.1 Dependent measures

The main dependent variable was the error of estimate between the observers' entered estimate and the corresponding actual distance (estimated minus actual). This error was signed, as the estimate could have been greater or less than the actual distance, resulting in a positive or negative value, respectively. Another dependent variable used to measure accuracy was the natural log ratio of the observer's distance estimate to the actual distance or $\log_e$(estimated/actual) calculated as ln(estimated/actual).

A mixed-model analysis of variance was applied to the data, with one between-subjects factor (Group), and one within-subjects factor (Session). There were three Groups (Group 1: half-moon illumination, feedback given; Group 2: half-moon illumination, no feedback; Group 4: starlight illumination, feedback given) and five Sessions (Pre-training, Training, Post-training, Two-week post-training, and One month post-training). The main dependent variable was the error of estimate, meaning the estimated distance minus the actual distance. In the first analysis, a mean value was computed for the 45 observations by each observer in each session to produce one score. In the second analysis, a mean value was computed on the log ratio of the 45 observations by each observer in each session to produce one score. The purpose of taking the log ratio was to mitigate the effect of skew in some conditions. The Greenhouse-Geisser correction was applied to the ANOVA degrees of freedom in each case. The first analysis showed a significant Group by Session interaction ($F_{(8,96)} = 2.6$, $MS_e = 8.8$, adjusted df (5,64), $p \leq .05$), as well as an overall main effect of Group ($F_{(2,24)} = 32.8$, $MS_e = 16.6$, $p \leq .0001$) and an overall main effect of Session ($F_{(4,96)} = 4.4$, $MS_e = 8.8$, adjusted df (3,64), $p \leq .01$). Scheffé contrasts showed that Group 2 performed significantly worse than Groups 1 and 3 overall, and that Group 2 was significantly different from Groups 1 and 3 in the two-week posttest session. An ANOVA of the same form on the variances of the 45 observations showed a significant overall main effect of Group ($F_{(2,24)} = 5.2$, $MS_e = 1324.7$, $p \leq .05$). These variance scores were significantly smaller in Group 2 (overall 17.9) than in Group 3 (overall 42.7). The results for individuals are plotted as light gray dots in Figures 9, 10, and 11. The three graphs have the same scale of abscissa. Mean values for each of the groups are indicated by connected dots (Figure 9: unfilled; Figure 10: filled; Figure 11: filled stars) in the graphs. It is clear that accuracy of distance estimation does not improve without feedback. The observers trained in the better illumination conditions do estimate distance well in the scene at a remove of a month. Observers trained in worse illumination conditions also improve in accuracy, but their performance is much more variable.

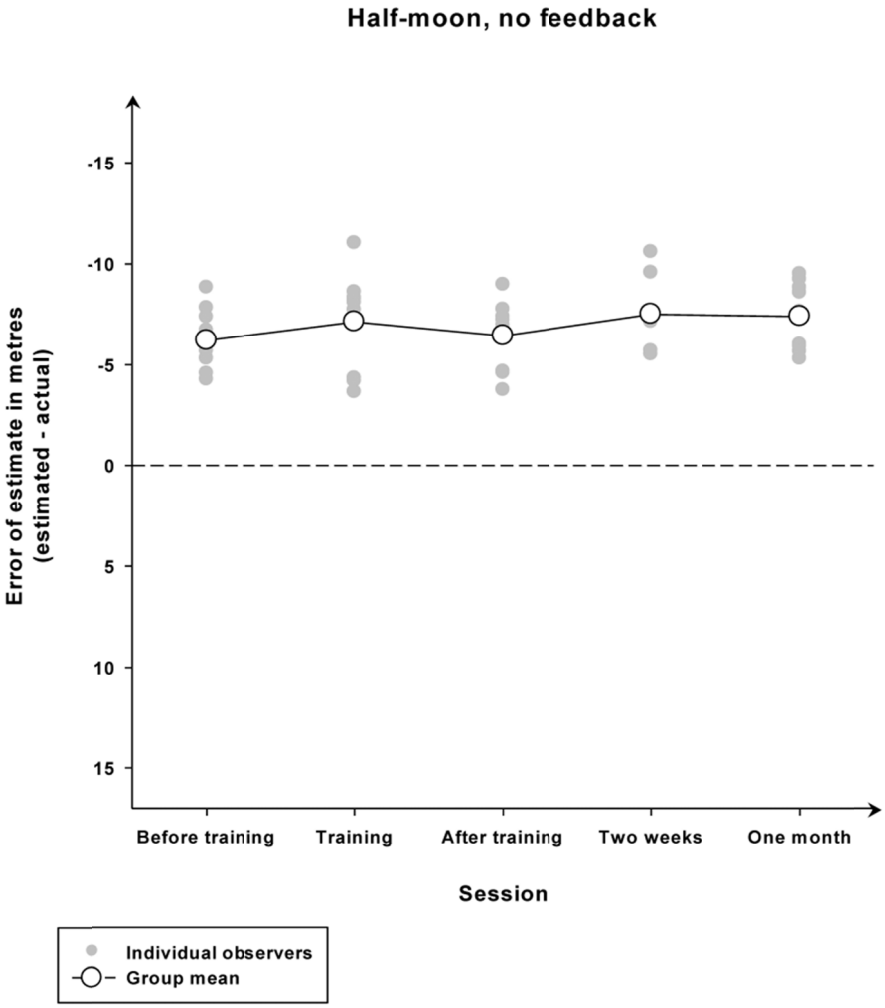

Figure 9: *Distance estimates do not improve over time in the absence of verbal feedback training with a desktop simulation that mimicked half-moon illumination. Observers were tested before being trained, during training, just after training, two weeks after training, and one month after training (as indicated on the abscissa of the graph). Average error in estimate of distance (estimated distance minus actual distance) is shown on the ordinate. The unfilled and connected circles indicate group averages, while gray dots indicate averages for individuals.*

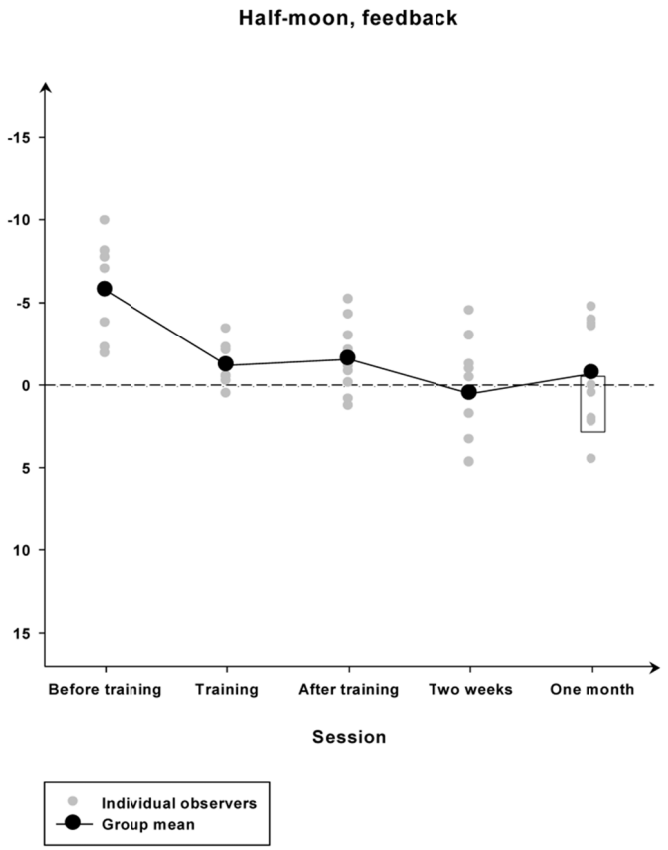

Figure 10: *Distance estimates improve over time with verbal feedback training in a desktop simulation that mimicked half-moon illumination. Observers were tested before being trained, during training, just after training, two weeks after training, and one month after training. Average error in estimate of distance (error as estimated distance minus actual distance) is shown on the ordinate. The filled and connected circles indicate group averages, while gray dots indicate averages for individuals. A small box is drawn to enclose average scores of individuals (one month after training) whose average errors were not different from zero*

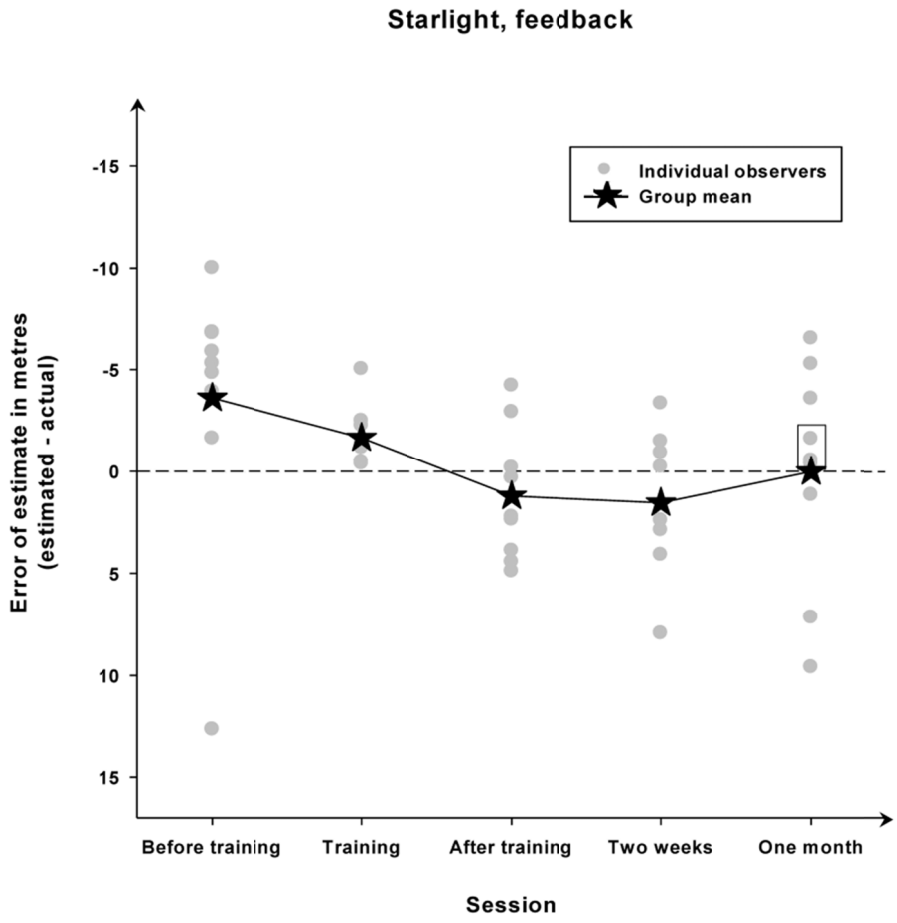

Figure 11: *Distance estimates improve over time with verbal feedback training in a desktop simulation that mimicked starlight illumination. Observers were tested before being trained, during training, just after training, two weeks after training, and one month after training. The filled and connected stars indicate group averages; gray dots indicate averages for individuals. Average errors in this condition were more variable than in the "half-moon" simulation.*

Table 2: *In each testing session distances were estimated between pairs of lights, from a connected set of six lights. Triads of distance judgments may or may not respect the triangle inequality. Violations of the triangle inequality are tabled for each testing session, as counts and as proportions (*p*) of triangle inequalities. There are sixty possible triangles in each session, for a total sum of 540 possible triangles among nine subjects in each group. The number (i.e., the count) of violations of the triangle inequality does decrease with practise.*

		Pre-training	Training	Post-training	Two week post-training	One month post-training
Half-moon feedback	*Count*	**224**	**144**	**121**	**127**	**152**
	p	.41	.27	.22	.24	.28
Half-moon no feedback	*Count*	**172**	**102**	**80**	**89**	**104**
	p	.32	.19	.15	.16	.19
Starlight feedback	*Count*	**172**	**159**	**109**	**98**	**113**
	p	.32	.29	.20	.18	.21

3.2.2 Triangle inequality

Each observer made 15 distance estimates for the set of six light positions. By choosing any three of those six lights and taking the distances between them, one could theoretically create a triangle. However, estimates of distance were not necessarily accurate, and their sense of physical space flawed. Thus, distance estimates between three light positions may not have joined together in three-dimensional space to make a triangle. This would occur if the theorem of triangle inequality was violated, where the measure of any given side in a triangle must be less than the sum of, but greater than the difference between, the other two sides. A count of the triangle inequalities was conducted. The number of triangles one could form with the 15 estimates of distance could be calculated with $\binom{n}{r}$ counting the unordered choice of r objects (r-combination) from a set of n objects, where $n = 6$ (number of lights) and $r = 3$ (distances to make a triangle). Accordingly, for each set of six lights, 20 different triangles could be created using the observers' 15 distance estimates. To determine whether three distances could create a triangle, an attempt was made to calculate the area formed by those three distances. If this area could be calculated, a triangle formed by those distances exists. If not, then triangle inequality is violated and the triangle does not exist. Since the distances were based on observers' estimates in their own sense of physical space, there were no coordinates for each of the distances; the area was calculated from the distance values themselves. By using the semi-perimeter, s, found from the three distances between the observer and the two lights, one could use the trigonometric formula in [1] to find the area, S. If the triangle does not exist, the answer for S would be an imaginary number, and therefore denotes a violation of triangle inequality.

$$s = \frac{OA + OB + AB}{2}$$
$$S = \sqrt{s(s - AB)(s - OA)(s - OB)} \qquad (1)$$
$$S^2 = s(s - AB)(s - OA)(s - OB)$$

A measure of geometric consistency for the observer's judgment was made by counting the number of times an observer's estimates created a violation of triangle inequality within the 20 different triangles for each set of 15 distance estimates. Since each session included three cases of differing halo sizes and each observer made three sets of 15 distance estimates, a total of 60 possible triangles could be formed. The higher number of violations of triangle inequality, the less consistent an observer's estimates were. The sum of counts for violations of triangle inequality for all nine subjects in each session for each group is tallied in Table 2 across the five sessions.

Table 3: *Numbers of accurate observers in a desktop simulation, by session (columns). Observers were considered accurate if their session's error of estimate mean was within –2.0 m to 2.0 m (the distribution of z-scores of estimates includes the value of zero within its 95% bounds). Each condition (rows) had nine observers, meaning that nine is the maximum number in each cell of the table. Some observers in feedback conditions could be considered to have accurate performance even one month after training. In the no-feedback condition, no observer was accurate in any session by this criterion.*

	Pre-training	Training	Post-training	Two week post-training	One month post-training
Half-moon feedback	**1**	**6**	**5**	**4**	**2**
Half-moon no feedback	**0**	**0**	**0**	**0**	**0**
Starlight feedback	**1**	**6**	**2**	**3**	**4**

In the second experiment, feedback training was found to correct for the underestimation of distance. The visual alley of the first experiment was simulated on a desktop computer, and feedback training was found to the effective in that situation. Once more, variations in halo size did not lead to biased estimates of distance on average. The effect of feedback training in this situation was found to last at least one month. The accuracy of distance estimates did not improve at the same time that observers' judgments became more consistent: unlike the accuracy of distance estimates, observers' judgments became more consistent with practise whether or not feedback training had been administered. Consistency does not guarantee accuracy, though accuracy entails consistency as a matter of geometry. Some but not all observers were trained to a criterion of $\pm$ 2 metres in accuracy by feedback training in this situation, but no observers achieved accurate performance without feedback training (Table 3). There is room to make training more effective, in other words. The sign of the errors that observers commit before feedback training is not a new finding, nor is it of interest for present purposes. The notion that observers overestimate distance in the absence of training is a commonplace observation in the literature (Gilinsky, 1951). It occurs as the effect of foreshortening in perspective. Attention to the form of those errors may distract the reader from the crucial point, which is that the errors can be corrected.

4 Discussion

No light, but rather darkness visible
Served only to discover sights of woe

Milton, J. (1667, ll. 63, 64).

Some have said that the effects of feedback training are context-dependent, meaning they may not transfer from one environment to another, or from some viewing conditions to others (e.g., Waller, 2006). In one sense this is plain: it is harder to judge distances in a cloud, or in mountainous terrain. In another sense it is an empirical matter: we can nearly always judge depth, though instruction may be needed, and new conditions may take a little getting used to. We perceive the properties of three-dimensional environments better—in a more primary way—than we perceive the pictorial properties of scenes (Attneave, 1972). The derivative judgment of properties of scenes in pictures is a difficult art to perfect, which may require extensive training to "recalibrate" (Kelly, Hammel, Siegel & Sjolund, 2014). Conversely Allen & Rashotte (2006) found that when distance estimates are improved by feedback with digital photographs or videos, acquired skill in distance estimation does transfer to estimates made in an outdoor field. In analogy to the use of carpentry tools, the eyes are used with greater skill once one has received instruction in their use. What can be achieved through vision is **best** known when observers have been trained. The estimation of distance after training—feedback training being only a paltry example—is a better characterization of the ability people can have to judge distance by eye, than is an ignorant guess from a first glance. Distance estimation is not a business of some "cognitive overlay" which impinges on a pristine perception, as when Allen & Rashotte (2006, p. 173) say: "The psychological mechanism mediating this improvement is posited to be a form of cognitive calibration in which metric values are imposed on the information in the optic array such that the characteristic compression of the visual gradient... is accomodated." That statement is unnecessarily complicated: instead, observers express the basic skill they have for estimating distance by eye when given instruction in good viewing conditions.

Distance estimation should not be a primary concern in the night vision curriculum. Distance estimation can be corrected relatively quickly and easily, and errors in distance estimation are not specific to NVD use (Foyle & Kaiser, 1991). Undue emphasis on distance estimation is bound to distract untrained users from important issues in the use of night vision devices. Some issues are associated with manufacture of the devices, such as restriction of the observer's field of view (Marasco & Task, 1998; Jennings & Craig, 2000; Thorndycraft, 2003; Fullenkamp, Trissell, Aleva, Dixon & Task, 2005), or the limitation on visual acuity which may be imposed by a limited density of elements on the photomultiplier plate (Kotulak & Rash, 1992; Davis, Donohue-Perry & Task, 1994; Macuda, Allison, Thomas, Truong, Tang, Craig & Jennings, 2005). The optical focus of the devices may not always be adjusted by strict procedure, either (DeVilbiss, Antonio & Fiedler, 1994; Task & Pinkus, 2003): a rule of thumb is that NVD focus should not be adjusted to stars at night, to make them seem sharp (cf. Kotulak & Morse, 1994). Optical and ergonomic interactions also play a role in NVD use, as in head-mounted displays (see Mustonen, Berg, Kaistiner, Kawai, & Häkkinen, 2013): the very weight of second-generation NVDs can cause neck injury if a device is worn for hours and days (Karlsson, 2000). Peripheral lighting (as found in an aircraft cockpit: Breitmaier & Reetz, 1985; Gibb & Reising, 1997) should not veil the NVD image or blind the user. Many issues inherent in vision with NVD do remain topics for instruction, such as changes in shadows over time (Kooi & Toet, 2005; Toet, Kooi, Kuiper & Smeenk, 2005), or contrast reversal due to environmental heating or cooling in some materials at dawn or dusk (Crowley, 1991). (The devices are

more sensitive to changes in heat than the human eye.) Distance estimation has only a minor role in instruction for NVD use among these other considerations (Berkley, 1992).

Simple feedback training does improve distance estimation with night vision devices in a single environment, for a matter of weeks. How can this elementary finding be extended? Improvements can be made in training technique, to make training more intelligent. Yet the more important direction for extension of the elementary finding may be its generalization to new environments, in the sense of new geography (cf. Nguyen, Ziemer, Grechkin, Chihak, Plumert, Cremer & Kearney, 2001). One might argue that feedback has a *graded* effect on distance estimation. It would not be surprising to learn that the effect of feedback may generalize to experience with similar environments, but which environments count as similar? The robustness or fragility of training effects should be measured in terms of similarity across many training environments and manoeuvres (Stewart, 1996)—the strength of the effect should be gauged against the similarity of those environments. Mountains and flatlands are different in many respects, but which geographic properties are relevant to this generalization of training? The real question is how efficiently—how, given only a few trials and missteps—an ability to judge depth may be established in a new environment (Teichner, Kobrick & Wehrkamp, 1955). How one adapts to judging distance in a new environment may depend on its similarity to familiar environments—though it is far from certain there is any useful metric of similarity to be had across environments (see Meng & Sedgwick, 2002). Skill in seeing requires a little practical experience in the use of one's eyes. Though we see many things, what we see is generally in front of our eyes (with some exceptions such as *mouches volantes*). In learning to judge distance by eye, what we see and what we judge lies in front of our eyes (and not behind them except by reflection). It is an error of intentionality to suppose that the psychology of distance estimation involves the establishment of a metric for visual space: *there is no measurement in visual space* (Wittgenstein, 1981, p. 266). Nothing in vision is quite infallible or immediate, though our ability to judge distance by eye can be excellent and we are quick to learn distances even in difficult environments.

5 Conclusions

The estimation of distance by eye may be improved by simple feedback training. Though many details may be added to the present assessment, several important points have been revealed in the work of these experiments. First, feedback training improves distance estimation with night vision devices. This effect of training lasts for at least two weeks when the training takes place under half-moon illumination conditions (to within one metre: cf. Table 1, top row). Feedback training on a simulated scene of the same arrangement improves distance estimation. The improvement lasts at least a month. The consistency of those distance judgments improves over trials, whether initial feedback is given or not. Errors in estimate of distance are correlated with distance, when or after no feedback has been given, taking magnitude of visual angle into account. None of the same correlations are found to be significant, when or after feedback is given. And finally, factors other than distance estimation should have priority for training in night vision device use.

The ability to see depth is a basic visual skill. The visual perception of depth takes precedence over judgments of depth in pictures, a fact which should hardly need mentioning (though see Kersten, 1997). Vision is best characterized as a light sense rather than a distance sense, but there is hardly any getting around the fact that we learn to estimate mid-range terrestrial distances by eye. (Non-terrestrial environments may have their own quirks: for the accuracy of verbal estimates under altered conditions of gravity, see Clément, Loureiro, Sousa & Zandvliet, 2016, their Figure 3A.) Consider distance estimation in golf: golfers learn to estimate distance on a fairway. They may learn to estimate distances on a driving range that has range markers (compare the visual indicators used by Allen & Rashotte, 2006, or by Kytö, Mäkinen, Häkkinen & Oittinen, 2013), or they may learn to estimate distance from the tee by eye, perhaps consulting their score-card a few times at first. Golfing skills are not specific to courses played already (though one may note that bean-bag tossers may be less adaptable than golfers: Jones, DeLucia, Hall & Johnson, 2009). Golfers may even seek out new courses for the difficulty of long fairways and uneven terrain; golfers put their skills to use when they choose a nine-iron over a five-iron (though some ask a caddy when in doubt). Fuijita, Shiihara & Noji (2005) allow accurate distance perception for the performance of soccer players. All that is to say: distance estimation is neither difficult, unusual, nor a cognitive achievement of the highest order. A few feedback trials on a driving range may not fix your golf game—but they may help (cf. van Lier, van der Kamp & Savelsbergh, 2011). It should come as a surprise to no one that the same moral applies to night vision devices.

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List of symbols/abbreviations/acronyms/initialisms

ADDNS	Advanced Deployable Day/Night Simulation
AlGaInP	Aluminum Gallium Indium Phosphide
ANOVA	Analysis of Variance
ANVIS	Aviator Night Vision Imaging System
DRDC	Defence Research and Development Canada
DSTKIM	Director Science and Technology Knowledge and Information Management
FRL	Flight Research Laboratory
GaN	Gallium Nitride
HREC	Human Research Ethics Committee
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
NRC	National Research Council
NVD	Night Vision Devices
NVG	Night Vision Goggle
PDA	Personal Data Assistant
R&D	Research & Development
RMSE	Root Mean Square Error
TDP	Technical Demonstration Project
TFT	Thin Film Transistor

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The unguided visual estimation of depth and distance with night vision devices is often inaccurate. Observers estimate distances more accurately when given metric feedback on their reports of distance. Observers were asked to estimate distances between LED point-lights as seen through night vision goggles. The point-lights varied in azimuth and in elevation to the observer. Two weeks later, observers told distance accurately in the same scene without further feedback. Higher illumination (half-moon conditions rather than starlight) when feedback was administered made for better accuracy and better retention of training. The geometric consistency of observers' estimates improved with practice alone, unlike the accuracy of their distance estimates. This effect of training was found with a desktop computer display of the same scene, and lasted at least a month.

L'estimation visuelle de la profondeur et de la distance est souvent erronée lorsqu'on utilise un appareil de vision nocturne sans assistance. L'observateur arrive souvent à estimer les distances avec plus de précision lorsqu'on lui offre la validation métrique des distances rapportées. On a demandé à des observateurs d'estimer la distance entre des sources ponctuelles de lumière DEL vues à travers des lunettes de vision nocturne. L'azimut et l'altitude des sources lumineuses étaient variables du point de vue de l'observateur. Deux semaines plus tard, les observateurs ont bien estimé la distance des sources observées dans la même scène, sans autre validation. Lorsque la validation était offerte aux observateurs sous une scène mieux éclairé (en présence d'une demi-lune plutôt que sous une scène étoilé sans lune), la précision était plus grande et la rétention de la formation, meilleure. L'uniformité géométrique des estimations des observateurs s'est améliorée simplement par des exercices, ce qui n'a pas été le cas des estimations de distance. Cet effet de la formation a été constaté grâce à l'affichage de la même scène sur ordinateur de bureau, et l'effet a perduré pendant au moins un mois.