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by William A. Monaco, O.D., Ph.D., Kent E. Higgins, Ph.D., and Joel T. Kalb, Ph.D.

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14. ABSTRACT
The U.S. Army acquisition community uses models of human and systems performance to evaluate materiel. One such model, used to assess equipment for the dismounted Soldier, is the Individual Warrior Simulation (IWARS). When Soldier modeling target acquisition, IWARS applies the ACQUIRE model to some portion of the visual scene, determines the probability of detecting a target if one is present, then repeats the process for a different portion of the field. ACQUIRE predicts the probability of visually acquiring a target presented anywhere within its field of view (FOV) without regard for the location of the target in the scene. Human visual performance varies dramatically across the FOV, with acuity decreasing rapidly as objects move away from the center of gaze or away from the central vertical and horizontal axes of vision. The current research used Gabor patches to characterize visual detection thresholds at various locations around central vision. Results showed a marked increase in contrast threshold for targets of a y of spatial frequencies ranging from 0.5 to 18.2 cycles/degree appearing greater than ±3°–4° horizontal eccentricity. These results can be used to intelligently constrain the portion of the visual field over which IWARS applies the ACQUIRE detection model.

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spatial contrast sensitivity, Gabor patch, spatial resolution, visual acuity

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1. Introduction

1.1 Purpose of the Study

Currently, combat simulations predict target detection and recognition performance by two models – ACQUIRE and DELPHI. The ACQUIRE model predicts the probability of visually acquiring a target presented anywhere within a scene without regard for the location of the target in the visual field of the observer; the DELPHI model predicts aspects of peripheral vision. Neither model incorporates actual variations of human vision threshold across eccentricities in measures of Soldier performance, yet tools including the Individual Warrior Simulation (IWARS) use such models to predict visual performance. The objective of this work is to provide appropriately scaled and specific vision threshold data that may be incorporated into visual acquisition models and simulations in a manner that improves their computational speed and predictive capability. These vision thresholds are derived from the measurement of the subject's visual capabilities using well-established scientific methodologies and state-of-the-art technologies to measure visual thresholds.

1.2 Background

A key mission objective for the Warfighter is to minimize fratricide risk while maximizing mission effectiveness by optimizing visual identification of friendly vs. enemy combatants under complex and stressful battlefield conditions. This mission objective must be accomplished without impinging on the Warfighter's combat and mission effectiveness, while reducing the potential for fratricide risk to neutrals, and noncombatants, or friendly Soldiers (*1*).

In order to meet this mission objective, the U.S. Department of the Army has challenged the research community to develop a way to quantify the Warfighters' visual performance while improving their ability to **identify** targets while maintaining a low probability for error. There has been a hierarchy of defined visual events that has led to target identification; these include the following:

- detection (initially distinguishing target from background)
- classification (animal vs. human)
- recognition (man)
- identification (adversary)

The U.S. Army modeling and simulation community has an approved system that seeks to simulate the likely performance of dismounted warriors. The Natick Soldier Systems Center (NSSC) and the U.S. Army Material Systems Analysis Activity (AMSAA) pursued infantry combat simulations independently until 2003, when NSSC and AMSAA agreed to collaborate on a constructive model to meet both agencies' needs. As a result, IWARS was created. A virtual environment was created in which Soldier behaviors could be simulated with a view to evaluating proposed equipment and troop deployment strategies.

A key factor in Warfighter combat performance is optimal use of unaided vision. Currently, the ACQUIRE model of target acquisition is used by the U.S. Army Natick Soldier Research Development and Engineering Command in IWARS to predict a Soldiers' visual target acquisition performance. Within the ACQUIRE model's predefined field of view (FOV), vision is homogeneously good, and the prediction of detection performance from the model is based on the assumption that an observer has sufficient time to examine the entire scene using foveal-quality vision. For some applications, the predefined size of ACQUIRE's FOV may not be important. However, size is important in IWARS, where the behavioral model moves a small FOV around a much larger field and applies the ACQUIRE model to the contents of the scene in each FOV. It is in this way that IWARS developers model the dynamics of visual search for a target. Thus, an important question arises: What is an appropriate value for the horizontal FOV for the ACQUIRE model when used by simulations such as IWARS? Figure 1 shows that one measure of vision, acuity, declines rapidly with increasing eccentricity.

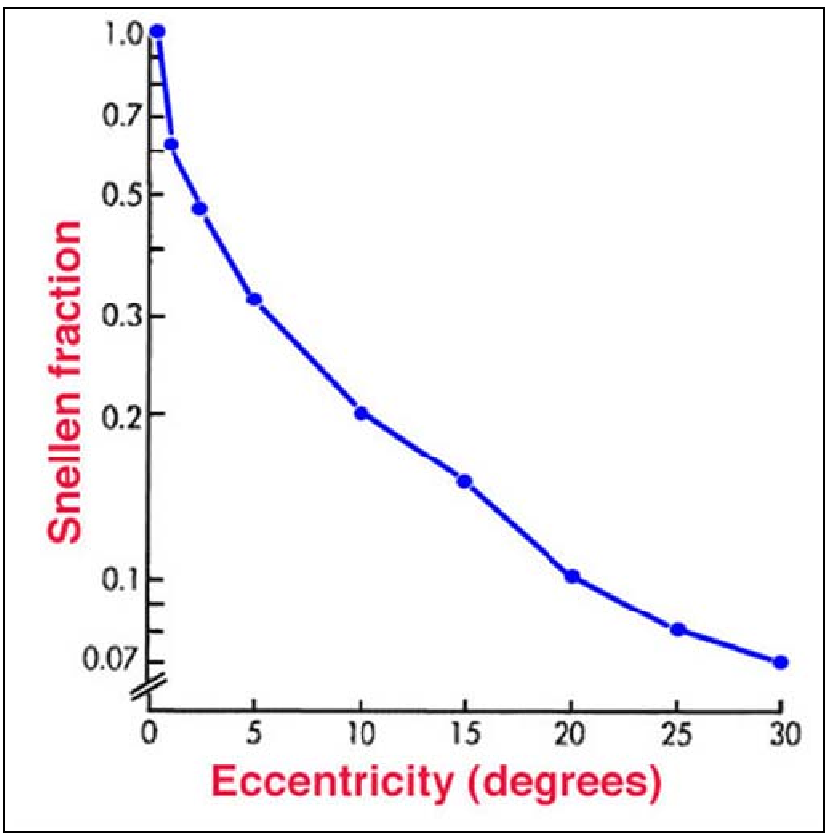

Figure 1. The effect of eccentricity on visual acuity (expressed in decimal notation) (*2*).

Figure 1 indicates that decimal acuity at about 4°–5° of eccentricity is ~0.33. This corresponds to a decline from 20/20 at the fovea to 20/60 at about 5°. Thus, the required minimum angle of resolution has increased by a factor of 3 from 1 to 3 min of arc. In the present research, the objective was to obtain specific vision threshold data describing the change in overall spatial contrast sensitivity (*3–5*) within the near-central retina. These data, in conjunction with those in figure 1, should provide an estimate of an acceptable lateral FOV for the ACQUIRE Model when used in IWARS, an FOV over which one can assume reasonably uniform and good, unaided vision.

2. Methods

2.1 Experimental Design

A three-retinal-eccentricity X, six-spatial-frequency, repeated-measures design was used for collection of the spatial contrast sensitivity data described in this report. Spatial contrast sensitivity was measured at spatial frequencies ranging from 0.5 to 18.2 cycles/degree and at horizontal retinal eccentricities of 1°, 2°, and 4°.

2.2 Subjects

Ten male and female subjects (mean age = 25.4 ± 1.6 years) were tested after informed consent was obtained from each using the Salus University institutional review board-approved procedures and consent form. Prior to testing, all subjects were evaluated to verify their visual status in the clinical skills lab of the Pennsylvania College of Optometry/Salus University. Subjects were excluded if there was a history of eye disease or visual disorder. Further, all subjects were required to have a corrected visual acuity of at least 20/20 in each eye, normal color vision in each eye (as measured by the Ishihara test), and a stereoacuity of at least 20 s of arc (as measured with a stereo optical Randot test).

2.3 Spatial Contrast Sensitivity Testing System and Procedure

The recently procured Metropsis (Cambridge Research Systems) testing suite was used exclusively for all testing. The Metropsis vision testing suite provides precise, repeatable, psychophysical threshold measurements for general research applications. Features include a high-resolution graphics engine capable of presenting spatial patterns with 14-bit contrast resolution, a choice of stimuli (sine-wave gratings vs. Gabor patches, three psychophysical staircase options [linear, logarithmic, and QUEST], and two forced-choice testing options (2-interval temporal vs. a 2 or 4 alternative spatial forced choice procedure).

Although much of the early research on contrast sensitivity was conducted using sharply-windowed, extended grating patterns (*3–5*), this option was rejected for the present study. Briefly, as Peli et al. noted (*6*), "extended gratings CSFs are unlikely to represent actual contrast sensitivity in free viewing of real-world images, and, therefore, may be inappropriate for vision simulation in normals." Indeed, more recent models (*5, 7, 8*) have relied heavily on results collected using Gabor patches as stimuli, i.e., spatial sine-wave gratings windowed by a two-dimensional (2-D) Gaussian envelope. Accordingly, all measurements in the present research were obtained using Metropsis' Gabor patch option.

At the calibrated 1-m viewing distance used for most measurements, the fixed size Gabor stimuli represented the product of a $5^{o} \times 5^{o}$ vertical sine wave grating having a spatial frequency from 0.5 to 9.1 cycles/degree and a 2-D Gaussian window function having a radial standard deviation of 1° of visual angle. The stimuli were displayed on a calibrated, high-resolution, 21-in Mitsubishi monitor at a mean luminance of 50 cd/m^2. The experimenter monitored the test's progress using a computer and associated computer display.

All subjects were tested under binocular viewing conditions using the 2-alternative spatial forced choice procedure. Subjects were instructed to maintain fixation on a small green fixation cross in the center of the display monitor. The start of a trial was announced by a brief tone following a stimulus pattern that was presented at a fixed eccentricity to the left or right side of the fixation cross. Each trial of the Gabor patch was presented for a total duration of 1200 ms. The contrast of the Gabor patch gradually increased and decreased over the 1200-ms interval. A raised cosine temporal envelope to minimize temporal transients associated with stimulus presentation followed since such transients were known to selectivity affect low spatial frequency sensitivity (*5, 6, 9*). The subject's task was to press a button on a response console indicating whether the pattern appeared on the left or right side of the fixation cross.

Starting contrast levels were selected to ensure that each spatial frequency would be easily visible to the subject at the beginning of the test. Threshold was measured at each spatial frequency and eccentricity by varying the contrast of the Gabor patch over a series of presentations using the Metropsis' default logarithmic staircase option. In this option, a single correct response produced a decrement in contrast while a single incorrect response produced an increment in contrast. The logarithmic option was selected since it provided the best option for ensuring that subjects would quickly reach near-threshold contrast levels (i.e., within 5–10 presentations at each spatial frequency). This, in turn, ensured that an estimate of threshold sensitivity could be achieved within a reasonable number (e.g., 30–40) of stimulus presentations. Each correct response to the first few presentations at each spatial frequency produced relatively large (1.5 dB) decreases in contrast. After the first incorrect response, each correct response produced a 0.2-dB decrement in contrast while each incorrect response produced a 0.6-dB increment in contrast. The staircase at each spatial frequency was terminated after 10 reversals in the direction of contrast change. Threshold was calculated as the mean of the final eight reversals.

Testing protocols were created using the menu-driven interface provided by the Metropsis system for two different test distances. Two sets of protocols were necessary since the spatial calibration of the Metropsis system assumed a default test distance of 1 m. At that test distance, the highest presentable spatial frequency (without aliasing) was 9.1 cycles/degree. Accordingly, three 1-m testing protocols (one/eccentricity) were created for testing spatial frequencies of 0.5, 1.0., 2.0, 4.0, and 9.1 cycles/degree. The difference between the three protocols was in the horizontal eccentricity at which the Gabor patches appeared (1°, 2°, or 4°). To measure contrast sensitivity at 18.2 cycles/degree, three additional testing protocols (one/eccentricity) were created to test sensitivity of a single Gabor frequency (the nominal 9.1 cycle/degree Gabor patch) using a 2-m test distance. This effectively doubled the spatial frequency of the highest frequency Gabor patch from 9.1 to 18.2 cycles/degree. The screen eccentricities at which the patterns were presented were doubled for the longer 2-m test distance to ensure that the retinal eccentricities were the same as for the 1-m testing distance (i.e., 1°, 2°, and 4°).

3. Results

For the statistical analysis, thresholds were expressed as the logarithm of the reciprocal of the threshold contrast. Thus, a threshold contrast of 0.01 (1%) represented a contrast sensitivity of 100 or a log contrast sensitivity of 2.0, and a threshold contrast of 0.10 (10%) represented a contrast sensitivity of 10 or a log contrast sensitivity of 1.0. The resulting table of log contrast sensitivities was then analyzed using the Statistical Package for the Social Sciences application.

The results of this analysis indicated statistically significant effects of spatial frequency [$F(5,45) = 156.7$, $p < 0.0001$] and eccentricity [$F(2,18) = 6.08$, $p = 0.01$]. Both effects seen in figure 2 show mean Gabor contrast sensitivity as a function of spatial frequency for each of the three eccentricities. Error bars ($\pm$1 SD) show the results collected at the 1° retinal eccentricity. Error bars for the 1° and 4° eccentricities were similar to those for the 1° eccentricity but were omitted for presentation clarity. The significant effect of spatial frequency was expected given that contrast sensitivity was well known to be an inverted U-shaped function of spatial frequency. In addition, it was well known that, on average, sensitivity decreased with increasing retinal eccentricity. In this study, the change with eccentricity, while significant, was small in magnitude.

It was also well known that high spatial frequency sensitivity should decrease more rapidly with increasing eccentricity when compared to low-frequency sensitivity, paralleling the well-known rapid decline in visual acuity. Indeed, the statistical analysis confirmed that the spatial frequency X eccentricity interaction was significant [$F(10, 90) = 4.4$, $p < 0.0001$]. The results in figure 2 show that with increasing eccentricity, there was a selectively greater loss in sensitivity at the higher frequency relative to the middle and lower spatial frequencies.

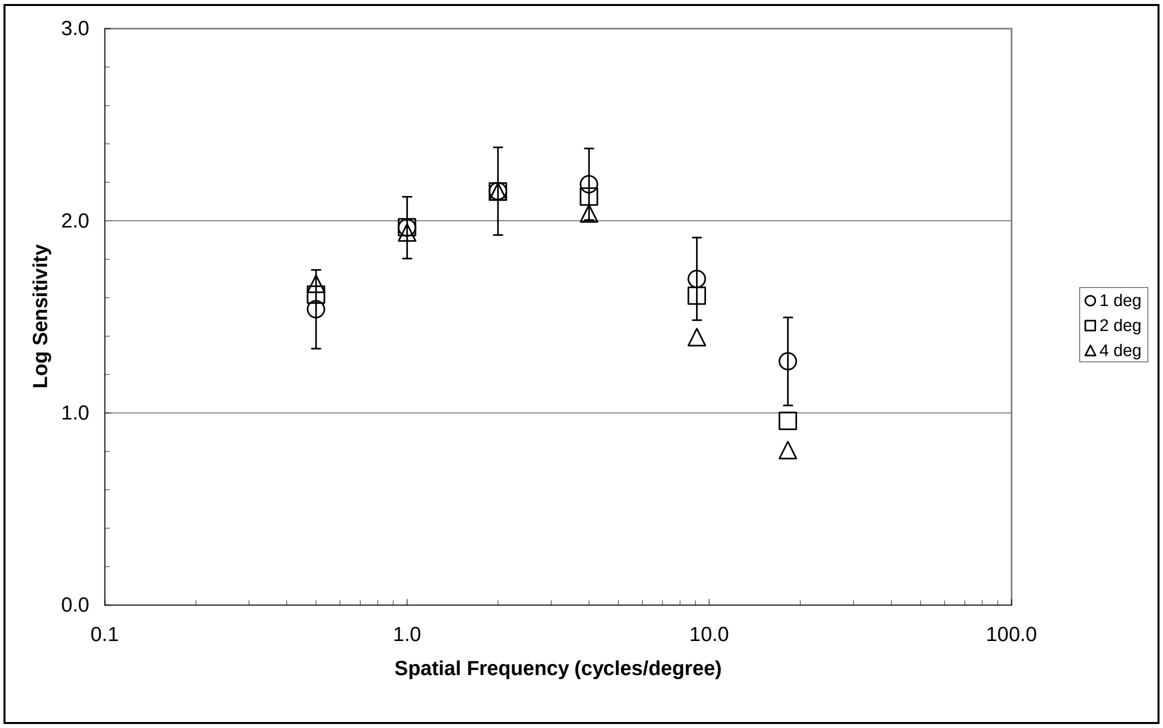

Figure 2. Gabor log contrast sensitivity vs. retinal eccentricity.

Finally, figure 3 shows the results from figure 2 plotted in semi-log coordinates. This type of plot is useful for estimating the high spatial frequency cutoff from thresholds collected at the higher spatial frequencies. This cutoff is intended to represent the highest spatial frequency that could be detected if presented at maximum (100%). This cut-off frequency was estimated by fitting straight lines (not shown) to the thresholds for the 4, 9.1, and 18.2 cycles/degree patterns at each eccentricity to determine the x-axis intercept. The three downward pointing arrows along the spatial frequency axis indicate cut-off frequencies. The cut-off frequencies for the 1, 2, and 4 eccentricity data were 37, 30, and 27 cycles/degree. These frequencies corresponded to minimum angles of resolution of 0.82, 1.00, and 1.11 min of arc. Thus, the total increase in the minimum angle of resolution at maximum contrast (vision loss) was by a factor of 1.35, not the factor of 3, as noted for Westheimer's acuity vs. eccentricity data.

4. Discussion and Recommendations

There are three features of the results that merit discussion. First, the fact that statistically significant results were obtained in this interim study is important because it suggests that relatively small samples are sufficient to delineate differences among conditions, at least for within-subject experimental designs. Second, the results are generally consistent with those reported by previous researchers using similar methodologies. At all eccentricities, contrast sensitivity was a roughly inverted-U-shaped function of spatial frequency.

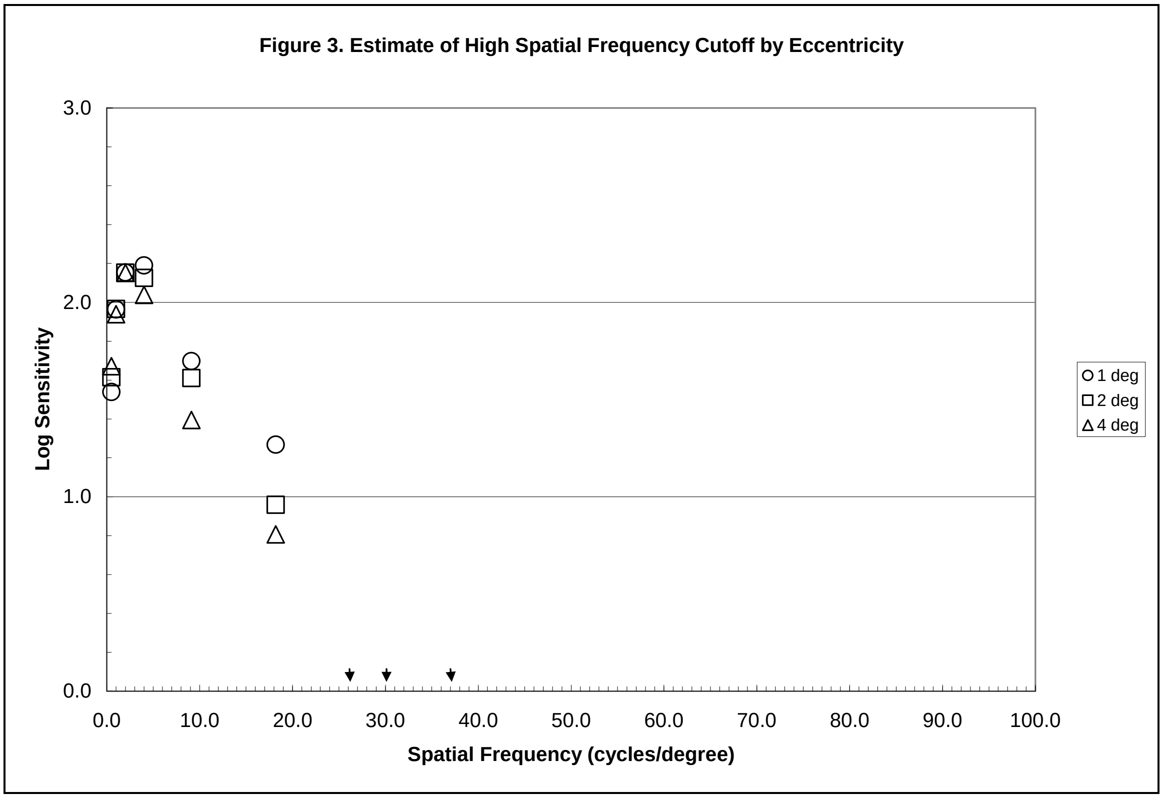

Figure 3. Estimate of high spatial frequency cutoff by eccentricity.

Third, the finding that increasing eccentricity produced an increasing loss in high spatial frequency is highly relevant to the application of ACQUIRE within a simulation such as IWARS. Although this finding is consistent with the well-known decline in visual acuity with increased eccentricity, the present results obtained using Gabor patches suggest that the loss may be more moderate than that suggested by the visual acuity results shown earlier in figure 1. However, it must also be noted that the total angular subtense of a 20/60 acuity target imaged at any eccentricity is limited to an extent, i.e., 15 min of arc (0.25°). In contrast, the effective angular subtense of the Gabor patches used in this study would, near threshold, have been at least 3–4× larger. Thus, even though the most extreme Gabor patch was centered at 4°, portions of the stimulus would have impinged on less eccentric and, therefore, more sensitive retinal regions. This may have contributed to a smaller estimate of resolution loss compared to that observed by Westheimer using acuity targets. Thus, in attempting to estimate an appropriate value for the horizontal FOV for the ACQUIRE model when used in IWARS, it would seem best to base this estimate on both measures of resolution, i.e., acuity and spatial contrast sensitivity (via high spatial frequency cutoff values).

Both acuity and contrast sensitivity measures indicate that maximum resolution declines with eccentricities as small at 4°. Westheimer's data suggest that acuity decreases from 20/20 and the fovea to about 20/40 at 2°–3° (factor of 2 resolution loss) and to about 20/60 (factor of 3 resolution loss) at 4°–5°. In contrast, the high spatial frequency cutoff data obtained using Gabor patches suggests a smaller estimate (factor of 1.35) of loss at 4°, implying that one may be able, at least with larger angular subtense images, to resolve detail with a better than 20/40 level of vision. At eccentricities larger than ±4°, this would not have been true. Specifically, the results shown previously represented mean sensitivities. It should be noted that about half of the subjects were pushing the limits of our system's ability to measure contrast sensitivity at the highest spatial frequency, i.e., 18.2 cycles/degree. That is, we would not have been able to measure the precise amount of additional high spatial frequency resolution loss at eccentricities greater than 4°.

Accordingly, it is recommended that the horizontal FOV of the ACQUIRE model used in IWARS be restricted to no more than ±3°–4°, or a total field not exceeding 6°–8°. Within this window, one can likely expect a level of vision of roughly 20/40 or better, a level consistent with the currently-prevalent minimum visual acuity standard required for an unrestricted driver's license (*10*).

Finally, there is one important issue that should be addressed in future research. Specifically, at present, IWARS is blind in all regions of the peripheral field beyond the pre-specified horizontal limits of the ACQUIRE model's central FOV. This means that IWARS' behavior model cannot use peripheral visual events to guide the FOV in a manner consistent with human behavior. Accordingly, it is recommended that research be conducted to determine the kinds of peripheral vision events and stimuli that might be critical for triggering IWARS to re-direct its relatively small, high-resolution FOV to inspect and search new regions of the visual environment. Spatially redundant stimuli like moving (or flickering) low-frequency sine wave gratings and Gabor patches provide one option for studying potential peripheral vision "triggering" events. In the event that such stimuli are selected for study, a series of papers on the "perimetry of contrast detection thresholds of moving spatial sine wave patterns" by Koenderink and collaborators (*11–14*) should provide an informative starting point. In addition, as part of this Technology Program Annex, the U.S. Army Research Laboratory created a software algorithm and testing paradigm for the tactical environmental simulator and was able to demonstrate proof of concept for the measurement of retinal motion sensitivity in the extreme periphery using a relatively simple stimulus configuration (dot displacement) (*15*). Importantly, any investigation of peripheral vision introduces a number of caveats that are normally not present in the investigations of central field visual function. These caveats concern such factors as the effects of practice (*16*), the potential task-dependent effects of practice (*17*), and the effect of attention (*18*) on peripheral visual performance.

These research paradigms could be implemented and extended using the ViSaGe-based system used in the current project. Such research would provide IWARS with the peripheral vision information (cues) necessary to direct and redirect ACQUIRE's FOV from one region of the visual environment to another through an efficient "top-down" or "event-driven" search strategy. Conducting such research would, however, require the addition of a MATLAB license to the existing ViSaGe workstation and a qualified programmer with expertise in vision science and MATLAB. The software provided with the ViSaGe system does not provide the measurement of sensitivity to moving stimuli.

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