

# Head and Eye Movements in Visual Search Using Night Vision Goggles

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**Background:** Night-vision goggles (NVGs) provide only a restricted field of view and have other characteristics that may affect the head and eye movements used in visual search. **Methods:** We measured head scan patterns, the magnitude and duration of gaze saccades, and fixation duration as subjects searched computer generated imagery either with or without NVGs. Subjects searched for either a large (6°) target on a low-detail background (high conspicuity condition) or a small (2°) target on a high-detail background (low conspicuity condition). **Results:** All subjects displayed head-scan patterns that were qualitatively similar to those reported in the literature. Although both head-scan speed and amplitude were higher for the NVG condition as compared with the no-NVG condition, the difference was not statistically significant. Head-scan speed did vary significantly with target conspicuity, however. Gaze saccade amplitude varied with target conspicuity but only when NVGs were used. Fixation duration did not vary with either NVG use or target conspicuity. A two-parameter (exponent and scaling parameter) power function was fitted to the amplitude-duration data. The power-function exponents varied from about 0.30 to 0.44, but there was a concomitant variation in the scaling parameter, and the result was no significant difference in the form of the power functions fitted to the data. **Conclusions:** NVG use did not significantly affect any of the individual head or eye movement variables involved in searching the computer-generated imagery studied here. However, the decrease in gaze-saccade amplitude with increased target conspicuity when NVGs were used is evidence of the sensitivity of the head and eye movement measurement techniques used here, and suggests that all available measures of response efficiency be considered when evaluating NVGs using complex stimuli.

**Keywords:** NVG, eye movements, gaze-scanpaths, visual search.

A DIMLY ILLUMINATED visual scene can be intensified by night vision goggles (NVGs) so as to provide a retinal illumination sufficient to perform many of the visual tasks required of pilots and other flight personnel during night flight. Although NVGs provide significant visibility under reduced lighting conditions that might otherwise preclude the performance of many visual tasks, they do not "turn night into day," as is sometimes claimed. NVGs have characteristics that place limitations on their use, and that may require modification of normal, daytime visual behaviors (18). For instance, in addition to image color, the NVG image may differ from a naturally illuminated scene in contrast, clarity, and the addition of high-frequency noise in the form of scintillation. Changes in image contrast can affect global object recognition, and they can reduce spatial detail by decreasing the local contrast among adjacent features of the image. Changes

in spatial detail may be expected to affect the eye movements used to acquire information from a visual scene. In addition, because NVGs have a 40° restricted field of view, pilots have to move their head more often and in a more deliberate manner (compared with daylight) in order to assess the full visual field and to maintain spatial awareness. It has been reported that proper scanning patterns can break down, and may be replaced by prolonged fixation. This phenomenon appears to be associated with channeling of visual attention, and is often referred to as "tunneling." Tunneling is most common during weapons delivery and has been implicated in several aircraft mishaps. Also, the weight of the NVG, and its forward center of gravity, could alter the user's normal head movements. It is evident that the various characteristics of NVGs and their imagery have effects on perception, cognition, and behavior.

Under normal viewing conditions, visual search involves the use of both head and eye movements to direct the subject's gaze to objects of interest (8,27). The rapid changes in eye position, known as saccades, are a major component of visual search. Saccades are limited, however, to about  $\pm 60^\circ$  from their centered (i.e., straight-ahead) position relative to the head, are generally less than 15°-20° in amplitude, and average only about 5° (3,12). Therefore, when the visual field to be searched is large, head movements become more important in that they serve to reduce the average size of the required eye movements. The general characteristics of head and eye movements during visual search have been described (9,23), but few details are available

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14. ABSTRACT

**Night-vision goggles (NVGs) provide only a restricted field of view and have other characteristics that may affect the head and eye movements used in visual search. METHODS: We measured head scan patterns, the magnitude and duration of gaze saccades, and fixation duration as subjects searched computer generated imagery either with or without NVGs. Subjects searched for either a large (6 degrees) target on a low-detail background (high conspicuity condition) or a small (2 degrees) target on a high-detail background (low conspicuity condition). RESULTS: All subjects displayed head-scan patterns that were qualitatively similar to those reported in the literature. Although both head-scan speed and amplitude were higher for the NVG condition as compared with the no-NVG condition, the difference was not statistically significant. Head-scan speed did vary significantly with target conspicuity, however. Gaze saccade amplitude varied with target conspicuity but only when NVGs were used. Fixation duration did not vary with either NVG use or target conspicuity. A two-parameter (exponent and scaling parameter) power function was fitted to the amplitude-duration data. The power-function exponents varied from about 0.30 to 0.44, but there was a concomitant variation in the scaling parameter, and the result was no significant difference in the form of the power functions fitted to the data. CONCLUSIONS: NVG use did not significantly affect any of the individual head or eye movement variables involved in searching the computer-generated imagery studied here. However, the decrease in gaze-saccade amplitude with increased target conspicuity when NVGs were used is evidence of the sensitivity of the head and eye movement measurement techniques used here, and suggests that all available measures of response efficiency be considered when evaluating NVGs using complex stimuli.**

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as to eye movement characteristics such as saccadic amplitude, saccadic duration, and fixation duration.

Both head and eye movements are known to be affected by the visual task being performed as well as the spatial properties of the target and background (1,10,16). In the present study, we have measured various characteristics of the head and eye movements used to perform exploratory visual search with and without NVGs. All visual imagery was computer generated, and the effects of image properties were studied by varying the size of the target and the amount of detail in the background image.

## METHODS

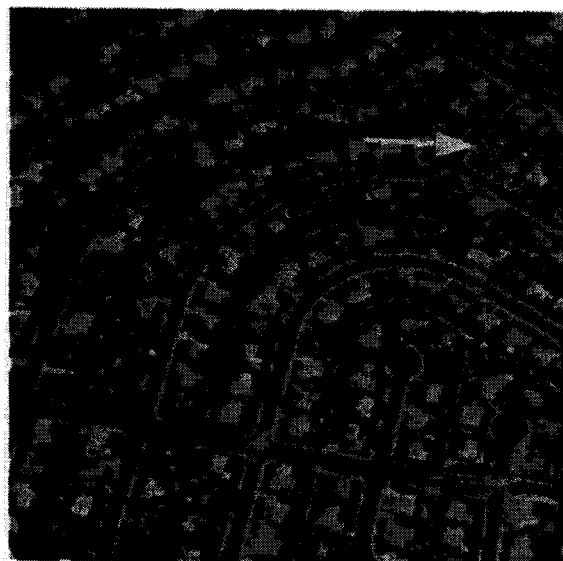
### Subjects

We tested 10 subjects, 5 under the NVG condition and 5 under the no-NVG condition. The 10 subjects ranged in age from 34–49 yr and had no previous experience in laboratory studies of visual search. Three subjects (S4, S8, and S9) were female. Among the subjects in the NVG condition, one (S1) had 8 yr of experience with NVGs as a helicopter (UH-1) pilot, one (S2) had 5 yr of experience with NVGs as a C-130 pilot, and two (S3, S4) had Air Force flight training but used NVGs only in a research setting. All subjects had visual acuity of between 20/15 and 20/20 as determined by a Snellen chart, and none wore glasses or contact lenses.

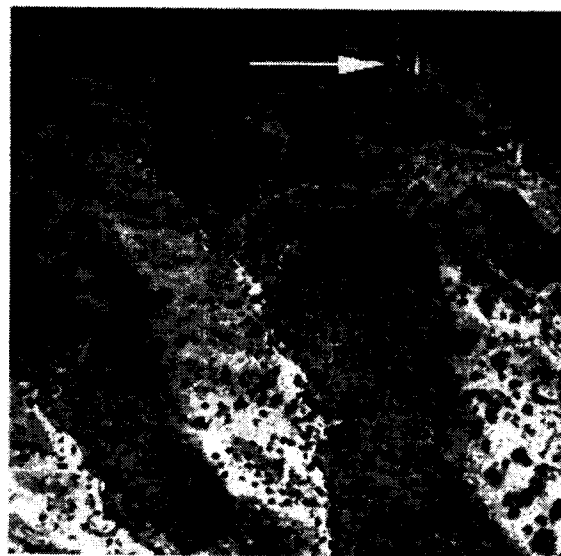
### Stimuli and Apparatus

The target and background stimuli used in the present study are shown in Fig. 1. The combinations were 6° target/*desert* background and 2° target/*city* background. The *desert* and *city* backgrounds consist of relatively low and relatively high spatial detail, respectively, and so the 6° target on the desert background was much easier to see than the 2° target on the city background. The two stimulus combinations were therefore referred to as the *high conspicuity* and *low conspicuity* conditions, respectively. The background images were obtained from photographs that were digitized at 1024 × 1024 × 8-bits. The images were displayed so as to subtend 68° on a side from a viewing distance of 1.5 m. The mean luminance of the background imagery was approximately 1.5 fL, both with and without NVGs. The test targets were obtained by multiplying a cosine luminance distribution by a circularly symmetric gaussian function that effectively smoothed the edges of the target. The spatial frequency of the luminance distribution was three cycles/target measured at the half height of the gaussian. The targets were circular, extended to  $\pm 2\sigma$  of their respective gaussian envelopes, and consisted of 32 × 32 and 96 × 96 pixels for the 2° and 6° targets, respectively. Examples of the 2° and 6° targets as they appeared at one position in the *desert* and *city* background images, respectively, are shown in Fig. 1 (their location is indicated by the arrows). On each trial, target contrast was increased following a randomly chosen delay of between 0 and 5 s. The target contrast varied from zero to its maximum level of about 0.8 over a 15 s interval.

The instantaneous field-of-view (IFOV) of the single



Low Conspicuity  
(2° target / *city* background)



High Conspicuity  
(6° target / *desert* background)

**Fig. 1.** The target and background stimulus combinations used in each condition. Upper: low conspicuity condition (2° target/*city* background); Lower: high conspicuity condition (6° target/*desert* background). In each case, the target is indicated by the arrow.

NVG used (Model F4949C, SN:405, ITT Industries, Roanoke, VA) was about 40°. The NVG weighed about 0.7 kg. The same IFOV was provided in the no-NVG condition by apertures placed approximately 1.5 in in

front of each eye and centered on each pupil. The aperture views were fused by the subjects, giving the visual impression of a single, 40°-diameter aperture centered on the subjects' line of sight. The NVG was adjusted prior to each experimental session using standard procedures (2) that were modified slightly to take account of our experimental viewing distance and imagery. Acuity was not measured while our subjects wore the NVG, but previous data have shown visual acuities of about 20/50 for subjects with 20/20 vision using this device under illumination conditions similar to those of the present study. All stimuli were displayed on a rear-projection screen using the green channel only of a Model 801 CRT projector (Barco, Inc., Kennesaw, GA). The background imagery was displayed and the test stimuli were controlled by a SGI Indigo Elan workstation.

Head movements were measured in two-dimensions (pitch and yaw) using a 3Space Fast-Trak system (Polhemus, Inc., Colchester, VT). Changes in roll angle and three-dimensional head translation were insignificant in the present experimental context. Eye movements were measured using an Series 2000 eye tracking system (El-Mar, Inc., Toronto, Canada). Head- and eye-movements were sampled at 120 Hz and all data collection was controlled by a PC. Head data was acquired through the PC serial port while eye position data was acquired through two 12-bit A/D channels (Model DT-2801A, Data Translation, Inc., Marlboro, MA). All data acquisition was synchronized to the head tracking system. Special-purpose software was used for both real-time display of eye and gaze (i.e., head + eye) position, and for off-line data analysis.

#### Procedure

The subjects acclimated to the ambient light level of the experimental room by viewing one background image for 8–10 min while the head- and eye-movement systems were calibrated. The subjects were then shown the test target for which they would be searching in the upcoming series of trials. They were informed that the target would initially be invisible and would then increase gradually in contrast until they indicated detection by pressing a mouse button. The subjects were also informed that the target could appear anywhere within the background image. Each trial began when the subject was asked to begin searching for the test target.

Both levels of target conspicuity were tested in each experimental session. The order in which the conditions were tested was randomized for each subject. For each condition in a given session, the subjects searched for the test stimulus in 10 separate trials that lasted until either the test stimulus was detected or the allotted 35 s search time was exceeded. Data collection was automatically terminated after 35 s although subjects were occasionally allowed to continue their search after data collection ended. The average time from the beginning of the trial until the target was detected was about 26 s.

#### Analysis of Head and Eye Movement Data

Gaze saccades were generated as a vector sum of the recorded horizontal and vertical head and eye move-

ments. Gaze saccades were then analyzed based on trend, velocity, and duration of movement. A movement was considered a valid gaze saccade if its duration was between 17 and 180 ms, its average velocity was between 30 and 400° · s<sup>-1</sup>, and the fixation duration preceding and following it was at least 50 ms. Saccades were identified by a computer program written for that purpose. The accuracy of the program was verified by comparison with saccadic identifications made by one of the authors who has had extensive experience in eye movement analysis.

A power function of the form:

$$\text{Duration} = a \cdot (\text{Amplitude})^b \quad \text{Eq. 1}$$

was fitted to the gaze-saccade amplitude-duration data. The scaling parameter, *a*, and the exponent, *b*, were estimated using nonlinear regression (Sigma Plot Scientific Graphing Software 4.0, Jandel Scientific). An analysis of variance (ANOVA) was performed using SPSS 8.0 (SPSS, Inc.).

## RESULTS

### Head and Gaze Scanpaths

Head and gaze (head + eye) scanpaths for all NVG subjects tested under the low conspicuity condition are shown in Fig. 2. These scanpaths are typical of all conditions tested here and were for the most part composed of some combination of horizontal and vertical head and gaze movements. The gaze scanpaths are generally larger than the head scanpaths.

Mean head scan amplitudes and speeds for the NVG-Use and Target Conspicuity conditions are shown in Fig. 3a and 3b, respectively. The increase in head scan speed with target conspicuity was statistically significant ( $F_{1,8} = 17.6$ ,  $p < 0.003$ ), whereas the increase with NVG use was not ( $F_{1,8} = 0.21$ ,  $p > 0.66$ ). Head scan amplitude did not vary significantly with either target conspicuity or NVG use ( $F_{1,8} < 0.2$ ,  $p > 0.1$ ).

### Fixation Duration

Fixation duration averaged for the five subjects for each experimental condition are shown in Fig. 4a. Fixation duration did not change significantly with either NVG use ( $F_{1,8} < 0.001$ ,  $p > 0.98$ ) or target conspicuity ( $F_{1,8} = 3.1$ ,  $p > 0.11$ ).

### Gaze-Saccade Amplitude and Duration

The filled bars of Fig. 4b show gaze-saccade amplitude averaged for the five subjects for each of the conditions tested. The initial factorial ANOVA indicated no significant effects of either target conspicuity or NVG use on gaze-saccade amplitude ( $F_{1,8} < 0.28$ ,  $p > 0.14$ ). There is, however, an interaction evident in the data in that gaze-saccade amplitude decreases with increased target conspicuity in the NVG condition, whereas it increases with target conspicuity in the no-NVG condition. This interaction was found to be statistically significant ( $F_{1,8} = 15.3$ ,  $p = 0.004$ ), and therefore one-way ANOVAs were run on the NVG and no-NVG data separately. The change in gaze-saccade amplitude with

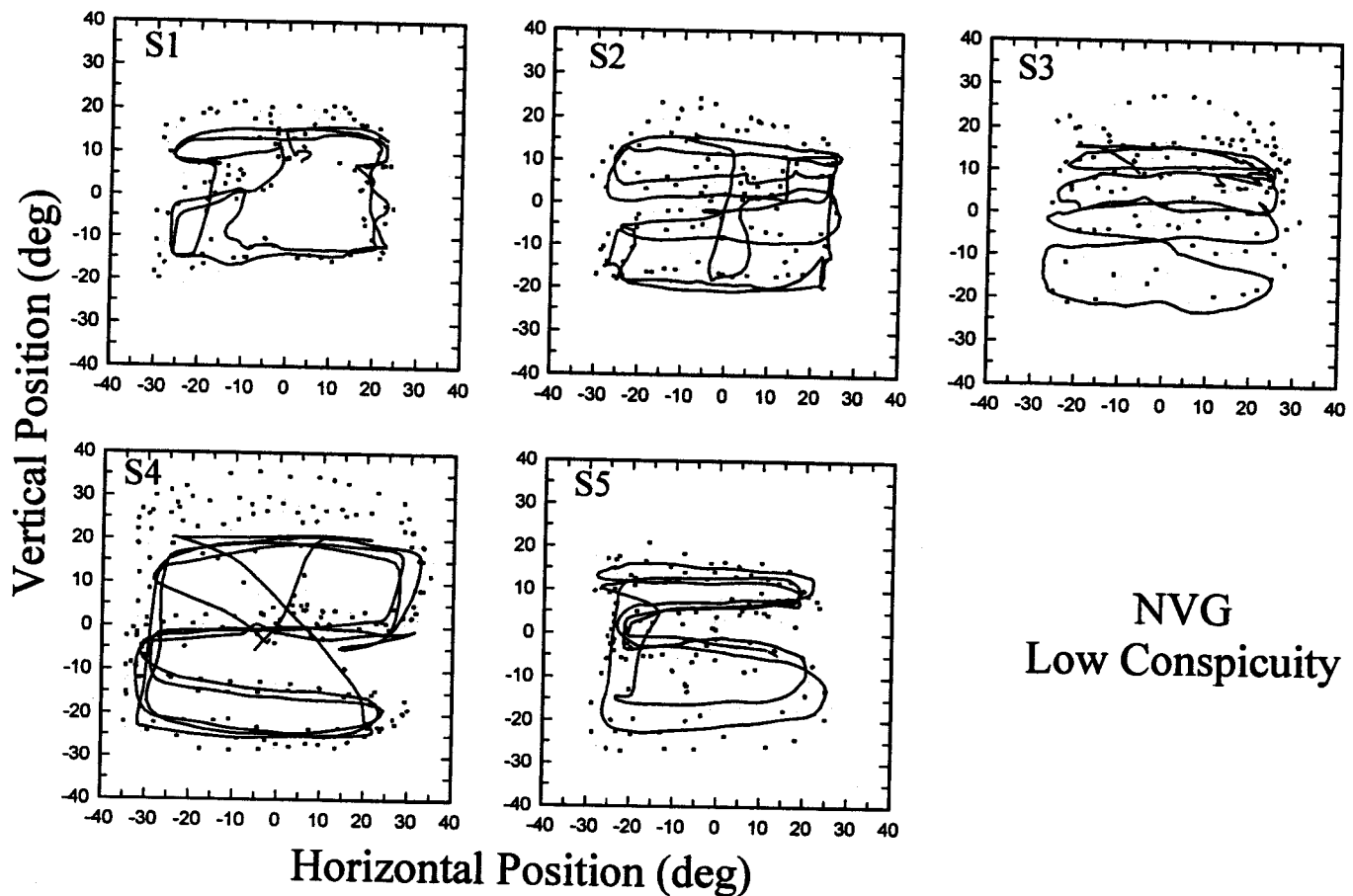


Fig. 2. Head (solid lines) and gaze (head + eye, dotted lines) scanpaths for one trial of each subject searching for the low conspicuity target under the NVG condition.

increasing target conspicuity was statistically significant for the NVG data ( $F_{1,4} = 37.2, p = 0.004$ ), but not for the no-NVG data ( $F_{1,8} = 2.8, p = 0.17$ ).

The relationship between gaze-saccade amplitude and duration for the NVG subjects tested under the low conspicuity condition is shown in Fig. 5. These data were fitted with the power function given in Eq. 1. The best-fit parameter values (i.e.,  $a$  and  $b$  of Eq. 1) for the plotted functions are also shown in Fig. 5. The best-fit parameter values and associated  $R^2$  values for power-function fits to the data for all subjects and all experimental conditions are summarized in Table I. An ANOVA on the power-function exponents showed a significant effect of NVG use ( $F_{1,8} = 8.6, p = 0.02$ ) but not target conspicuity ( $F_{1,8} = 2.9, p > 0.12$ ).

## DISCUSSION

### Head and Gaze Scanpaths

When asked to view a visual scene, most subjects show a characteristic gaze pattern known as a scanpath (26). Scanpaths have been used to study visual and cognitive function (7,14,15,20,22), and as measures of skilled behavior and workload (17,24,25). Gaze patterns that are in some ways similar to scanpaths have also been found when subjects search for objects in the visual field. For instance, Enoch (9) described the scan-

paths used by his subjects as they searched for various targets in aerial photographs. He identified general search patterns which were both idiosyncratic for a given subject and consistent over a wide variety of targets and background imagery. Enoch described these search patterns as "lateral back and forth," "up and down," "spiral," "closed square," or "non-directional." Stark, Yamashita, Tharp, and Ngo (23) also measured scanpaths for subjects searching for targets on various background images. They described the scanpaths they found as "vertical," "horizontal," "circular," "oscillating vertical," or "oscillating horizontal," which is in general agreement with the descriptions given by Enoch (9). The head and gaze scanpaths shown in Fig. 2 are similar to those reported by both Enoch (9) and Stark et al. (23).

Head-scan amplitude can only be reduced without adversely affecting visual search if there is a concomitant increase in saccadic amplitude or if the nature of the task or of the relevant visual stimuli are such that foveal inspection is not required. The finding that neither head-scan amplitude nor gaze-saccade amplitude changed with target conspicuity suggests that foveal inspection is required to detect even the larger (i.e.,  $6^\circ$ ) target used in the present study. Head-scan speed, however, was significantly lower for the lower level of target conspicuity. Clearly, the efficiency of visual

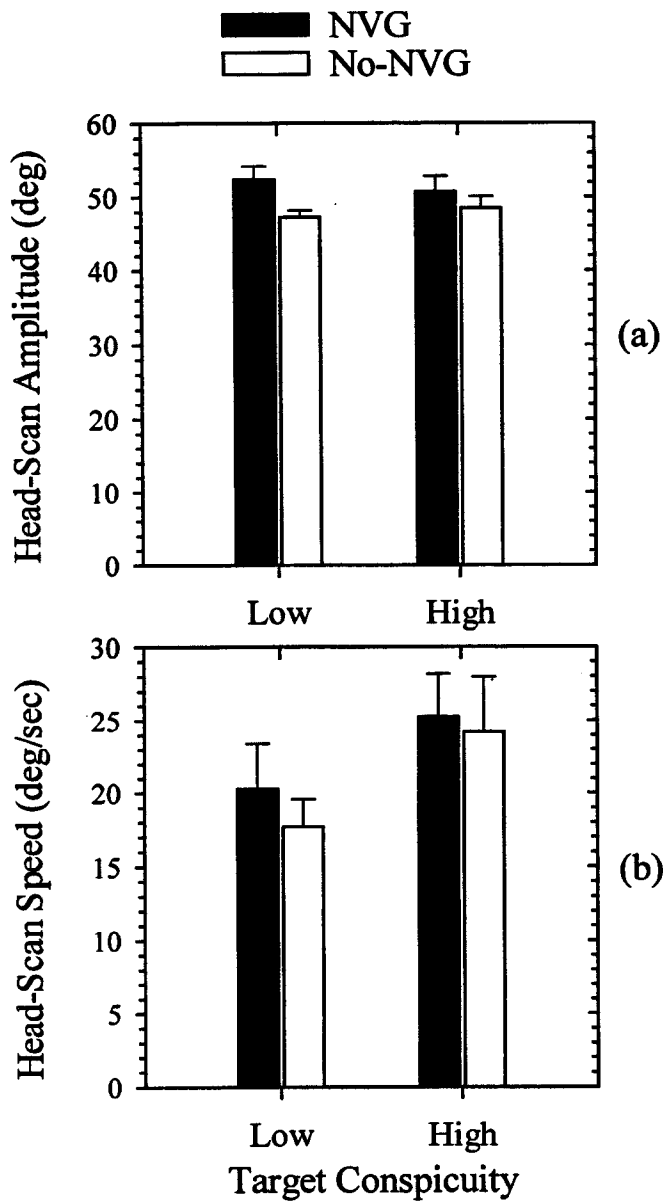


Fig. 3. Mean head-scan amplitude (a) and speed (b) for the NVG (black bars) and no-NVG (white bars) conditions and both levels of target conspicuity. The error bars represent standard errors of the mean for the data of the five subjects in each condition.

search will be increased if less time is spent inspecting portions of the visual scene which contain less spatial detail. Thus, head-scan speed is a measure that warrants further study in that the present data suggest that it reflects the rate at which information is processed during visual search.

*Fixation Duration*

As discussed earlier, saccades are the basic eye movement mechanism by which a visual scene is scanned during visual search. The actual visual inspection takes place, however, during the time between saccades while the eye is fixated on some portion of the visual scene. Thus, fixation duration is the eye movement parameter most likely to be affected by the spatial char-

acteristics of the visual scene. It is surprising, therefore, that fixation duration was not affected by target conspicuity, especially given the increase in head-scan speed described above. What appears to be an inconsistency, however, may simply be evidence that head and eye movements, while correlated, are not directly coupled when complex tasks are performed. This would not be surprising given the relative complexity of the visual search task studied here as compared with those typically used to study head and eye coordination (19,27).

Of more practical significance, however, is the fact that NVG use did not significantly affect fixation duration. One of the practical issues involved with NVG use is that some of the many visual tasks performed by pilots, for instance, which do not require NVGs may be compromised when NVGs are used. The present result

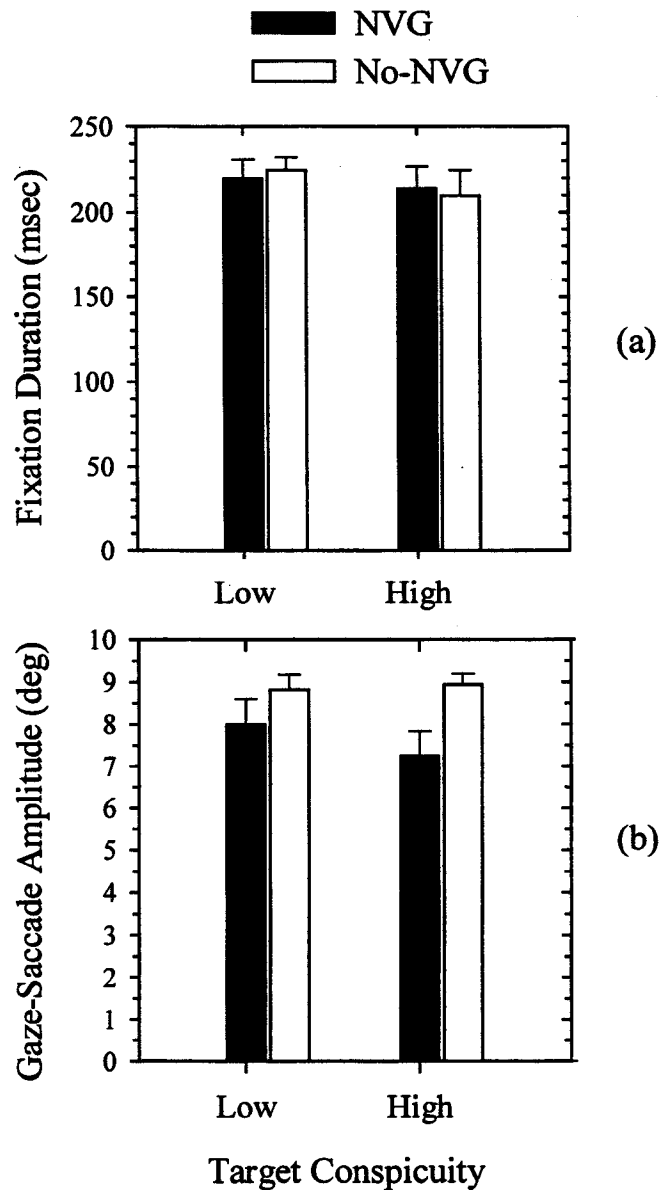


Fig. 4. Fixation duration (a) and gaze-saccade amplitude (b) for the NVG (black bars) and no-NVG (white bars) conditions and both levels of target conspicuity. The error bars represent standard errors of the mean for the data of the five subjects in each condition.

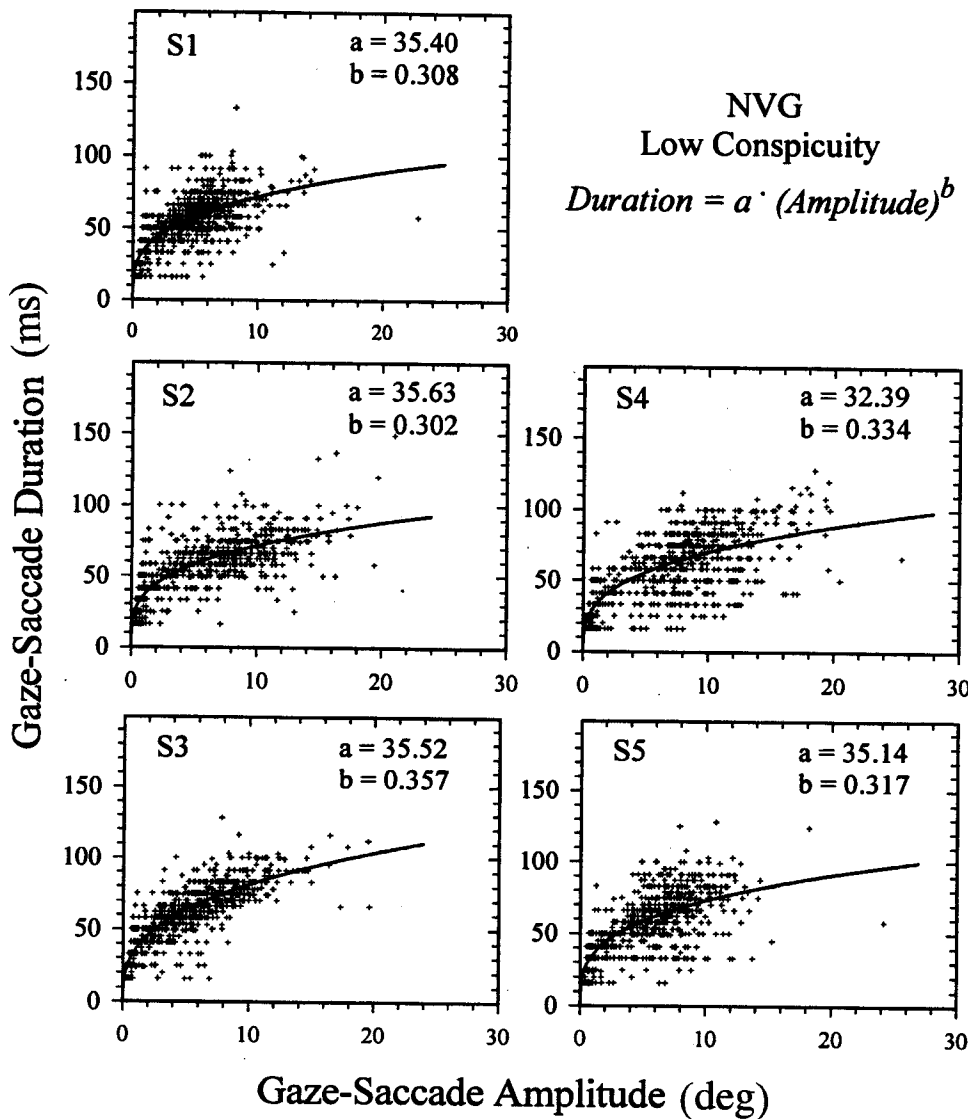


Fig. 5. Gaze-saccade, amplitude-duration plots for each subject tested under one experimental condition (NVG/low target conspicuity) showing the typical form of these data. The relevant parameters derived from data like these are summarized in Table I for all four experimental conditions.

thus may lend limited support to the contention that NVGs do not adversely affect complex tasks that depend on visual information obtained over several successive fixations.

*Gaze-Saccade Amplitude and Duration*

There was a significant change in gaze-saccade amplitude with target conspicuity when NVGs were used. However, it would be expected that optimum search performance would be associated with an increase in gaze amplitude with target conspicuity, whereas the data of Fig. 4b (filled bars) show a decrease. This finding suggests that some aspect of the NVG imagery has adversely affected the search behavior as indicated by the gaze responses of the present subjects. Although it would not account for the decrease in gaze-saccade amplitude with target conspicuity, the high-frequency scintillation present in the NVG image would be expected to make the low-conspicuity background appear more like the high-conspicuity background, which

would in turn tend to equalize the gaze responses obtained under the two conditions.

Although most visual processing occurs during the fixation period between saccades, efficient visual search also requires that the locations chosen for fixation be those that are most likely to provide the visual information relevant to the search task. The location chosen for successive saccades is most directly indicated by the amplitude of the gaze saccade. Clearly, the gaze saccade must be executed in a finite time, and it would be expected that larger gaze saccades will generally take longer to execute. The specific form of the relationship between gaze-saccade amplitude and duration can reveal more subtle aspects of the eye movement control system as well as how eye movement characteristics change with changes in the visual scene. There is general agreement in the literature that a power function best defines the relationship between saccadic amplitude and saccadic duration (4,6).

In the context of the data of Fig. 5, a flatter function indicates that there is a generally smaller increase in

TABLE I. EXPONENTS (b), SCALING FACTORS (a), AND R<sup>2</sup> VALUES OBTAINED FROM FITTING THE POWER FUNCTION,\* TO THE PRESENT DATA.

Target Conspicuity	NVG Condition Subjects					Mean, S.E.M.
	S1	S2	S3	S4	S5	
Low						
<i>b</i>	0.308	0.302	0.357	0.334	0.317	0.323, 0.010
<i>a</i>	35.40	35.62	35.52	32.39	35.14	34.82, 0.612
R <sup>2</sup>	0.478	0.613	0.670	0.446	0.474	—
High						
	0.303	0.315	0.339	0.304	0.315	0.315, 0.007
	34.73	34.85	36.36	34.31	35.67	35.18, 0.367
	0.479	0.545	0.510	0.316	0.519	—
Target Conspicuity	No-NVG Condition Subjects					Mean, S.E.M.
	S6	S7	S8	S9	S10	
Low						
<i>b</i>	0.384	0.308	0.344	0.332	0.367	0.347, 0.013
<i>a</i>	29.89	32.95	32.47	32.22	32.35	31.98, 0.536
R <sup>2</sup>	0.602	0.488	0.546	0.667	0.753	—
High						
	0.384	0.323	0.438	0.370	0.426	0.388, 0.206
	30.94	32.63	26.57	30.77	28.35	29.85, 1.067
	0.582	0.422	0.631	0.789	0.719	—

\* Duration =  $a \cdot (\text{Amplitude})^b$ .

gaze-saccade duration for a given increase in gaze-saccade amplitude. This in turn means that gaze-saccade velocity would increase more for a given amplitude increase. As little or no useful visual processing occurs during the gaze-saccade, a higher average velocity means that relatively more time is spent fixating, and hence visual search efficiency would be greater. However, as can be seen in the data summarized in Table I, NVG use resulted in lower power function exponents but higher scaling factors. As the product of these two parameters determine the slope of the amplitude-duration function as a given point, the result is that the fitted functions for the NVG and no-NVG conditions are of similar form. Thus, the data of Fig. 5 and Table I are consistent with those of Fig. 4 in indicating that NVG use did not significantly affect the gaze-response characteristics of the subjects tested here.

#### Visual Search with NVGs

There is apparently no consensus in the literature as to whether visual search performance can be improved by training subjects to use specific, formalized scanning patterns. Several early studies concluded that subjects tended to use scan patterns that did not adequately cover the area being searched (9,12). Clearly, formalized scanning would solve this problem, but it does not necessarily improve search performance (5,13,24). Banks et al. (5) also noted that many subjects do not scan efficiently, and further suggested that operators using night-vision devices be trained in specific search techniques that include using rectangular search patterns and a variable scanning rate. The utility of head movement training in this context has also been investigated (21). The subjects in the present study were not trained in any way and yet used generally consistent

scan patterns under diverse viewing conditions. This would suggest that formal head-scan training is not necessary unless the scanning behavior chosen is shown to be inefficient. Although more study is required on this issue, we are not aware of experimental evidence of such inefficiency.

The data reported here indicate that NVG use did not significantly affect the head and eye movements used to perform exploratory visual search. This was the case despite the fact that the NVGs altered the viewed image somewhat. Full and accurate NVG simulations are difficult to implement, and techniques for doing such simulations are not currently standardized. We, therefore, chose as our test stimuli simple computer generated images that could be easily replicated. A disadvantage of this approach is that the test imagery did not provide all of the spatial detail available in most real-world scenes. It might be expected that real-world imagery will differ from their NVG counterparts more than did the imagery used here. The present study, therefore, represents a conservative test of whether NVG use affects the head and eye movements used to perform exploratory visual search. Additionally, the field-of-view in the present study was much smaller than that available in most military aircraft. The present field-of-view was large enough to require head movements to scan the entire image, but those head movements were much smaller than might be required by some real-world search tasks. Additional research will be required to assess the implications of this difference for generalizing the present results to visual search in real aircraft.

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