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Night Vision Enhancement Systems for Ground Vehicles: The Human Factors Literature

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13. ABSTRACT ***(Maximum 200 Words)***

This report summarizes applied human factors studies of vision enhancement systems (both night vision goggles and LCD-based systems) and related topics for driving at night. Research recommendations are given based on gaps in the literature

Studies are grouped by dependent measure and task (target detection, distance/gap estimation, driving performance, subjective workload and preference, and other) and independent factor categories (display, sensor, environment, and the driver). Display characteristics include aided vs. unaided, viewing, image-display mapping (field of view, magnification, focal length), image polarity, stereoscopic vs. monoscopic systems, and color vs. monochromatic images. Sensor characteristics include the sensor position and panning, type, fusion, reliability, and quality. Environmental characteristics include lighting and visibility, road, traffic and glare, speed, gap size, target characteristics, and task. The driver variable examined is age. For each one of these independent measures, results from all relevant studies are described.

In addition, the report includes a short summary of each paper reviewed. As supplemental material, the appendix includes illustrations of military night vision systems.

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NIGHT VISION ENHANCEMENT SYSTEMS FOR GROUND VEHICLES: THE HUMAN FACTORS LITERATURE

UMTRI Technical Report 2002-05
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1 Open Issues in the Vision Enhancement Systems Literature

	Open Issues (**X** = More research needed)	Target Detection	Distance / Gap Estimation	Driving Performance	Workload / Situation Awareness	Preference
Display	What are the optimal magnification and field of view for vision enhancement systems? Are they different from those recommended for remote driving?	X	X		X	X
Display	What are the advantages of enhanced imaging features (e.g., color, stereoscopic vision, and adjustable polarity)?				X	X
Display	How well do users perform when using head-mounted displays and wearable computers?	X	X	X	X	X
Sensor	How do different vision enhancement systems (e.g., thermal, NIR) compare?			X	X	X
Sensor	What is the optimal sensor position and how much does it matter given practical limitations?	X	X		X	
Sensor	What are the advantages of sensor fusion of various input types? Is sensor fusion ready for real-time use?			X	X	X
Environment	What are the effects of the type of road, amount and form of traffic, and the driver's task? How do drivers using vision enhancement systems fit in traffic?	X	X	X	X	X
Environment	What are the effects of driving speed on performance with vision enhancement systems?	X	X		X	X
Driver	How do the driver's age, driving experience, experience with vision enhancement, and risk averseness characteristics affect performance?			X	X	X
Field Studies	Does the use of vision enhancement systems reduce crashes?	Crash data, interviews				
Field Studies	What is the usage pattern (e.g., frequency, purpose) and system acceptance among various drivers?	Observations, interviews				
Basic Research	Improve existing models of driving, detection of obstacles, pedestrians and other vehicles and apply them towards the use of vision enhancement systems.					
Military Specific	What design differences result from the difference in tasks between military and civilian?	Convoy driving, terrain, black-out, extreme fatigue				

2 Tabular Summary of References in this Review

		Dependent Measure				
	Independent Measures	Target Detection	Distance / Gap Estimation	Driving Performance	Subj. Workload and Preference	Other Measures
System / Display	Aided vs. unaided	**Barham '98** **Blanco '01** **Bossi '97** **Hollnagel '01** **Gish '99** **Nilsson '96** **Staahl '95** **Ward '94a**	**Barham '98** **Ward '94b**	**Barham '01** **Hollnagel '01** **Nilsson '96** **Stanton '00** **Ward '94a** *Oving '01* *Padmos '96*	**Barham '01** **Hollnagel '01** **Nilsson '96** **Staahl '95** **Ward '94a**	Risk compensation: **Stanton '00** **Ward '94a**
	Field of view, magnification, focal length	**Hollnagel '01**	*Brown '86* *Conchillo '96*	**Hollnagel '01** *Glumm '92* *Oving '01* *Padmos '96* *Smyth '01* *Sudarsan '97* *van Erp '97 '98*	**Hollnagel '01** **Aguilar '99** *Glumm '92* *Smyth '01* *van Erp '99*	Motion sickness: *Glumm '92* *Oving '01* Head movement: *van Erp '97*
	Polarity (FIR)	**Brickner '93** **Sinai '99a** **Sinai '99b**	**Ward '94b**			
	Stereoscopic or monoscopic		*Holzhausen '93*	*Drascic '91* *Holzhausen '93* *van Erp '99*	*van Erp '99*	
	Color or monochromatic	**Krebs '99** **McCarley '00** **Sinai '99a** **Sinai '99b** **Toet '97** **Waxman '96**	*Miller '88a '88b*		*Miller '88a '88b*	
Sensor	VES type	**Blanco '01** **Collins '98a** **Meitzler '00** **Piccione '97**		**Best '98** **Piccione '97**		
	Goggle type (monocular, binocular, bi-ocular)			*van Winsum '99*	*CuQlock, '95* *CuQlock '96* *van Winsum '99*	Vis. resolution: *Wiley '89* TCT and errors: *CuQlock '95* *CuQlock '96*
	Sensor fusion type	**Krebs '99** **McCarley '00** **Sampson '96** **Sinai '99a** **Sinai '99b** **Toet '97** **Waxman '96**			**Aguilar '99**	
	Sensor / camera position and panning camera		*Miller '88a '88b*	*Glumm '97* *Padmos '96* *Smith '70* *van Erp '97 '98*	*Glumm '97* *Miller '88a '88b*	

	Independent Measures	Target Detection	Distance / Gap Estimation	Driving Performance	Subj. Workload and Preference	Other Measures
Sensor	System reliability	**Ward '94a**		**Stanton '00** **Ward '94a**	**Ward '94a**	Risk comp.: **Stanton '00** **Ward '94a**
	Sensor quality (noise in image, resolution, frame rate, delay)	**Hollnagel '01** **Meitzler '00** **Ruffner '98**	*van Erp '98*	**Hollnagel '01** *Sudarsan '97* *van Erp '98*	**Hollnagel '01** **Ruffner '98** *van Erp '98*	
Environment	Visibility illumination, contrast, and type of weather	**Bossi '97** **Meitzler '00** **Nilsson '96** **McCarley '00** **Waxman '96**		**Nilsson '96** **Stanton '00**	**Nilsson '96** *CuQlock '95* *CuQlock '96*	Risk comp.: **Stanton '00** TCT and errors: *CuQlock '95* *CuQlock '96* Vis. resolution: *Rabin '96*
	Type of road					
	Other traffic / glare	**Gish '99** **Krebs '99** **McCarley '00**				
	Driving speed		**Ward '94b**			
	Gap size		**Ward '94b**			
	Target type and location	**Barham '98** **Blanco '01** **Bossi '97** **Gish '99** **Meitzler '00** **Staahl '95** **Sinai '99b**	**Barham '98**		**Staahl '95** **Aguilar '99**	Glance behavior: **Collins '98b**
	Task (speed monitoring / navigation)	**Gish '99**				
Driver	Age	**Blanco '01** **Gish '99**	**Ward '94b**			
General discussion		VES: **Hahn '94, Kiefer '95, Lunenfeld '91, Parkes '95, Tijerina '95** VES Products: **Barham '99, Galaxy Scientific '98, Martinelli '00, Pencikowski '96, Schwalm '96, Shelley '01** NVG: *Biberman '92, Gawron '01, Hudson '86, Ruffner '97, U.S. Army '98a* Fusion Algorithm: **Das '00, McCarley '00, Simard '00, Toet '97** Remote Driving: *Padmos '95* Night Driving and the Need for VES: Owens '93, Ruffner '97, Sullivan '02, U.S. Army Safety Center '97 Head mounted displays: Bakker '00, Davis '97, Geri '99, Glumm '98, Padmos '99, Venturino '90				

Formatting code for main topic of experiment:

VES (Small caps) | **Sensor fusion (Bold)**

NVG (Small caps italicized) | *Camera View (Italicized)*

GLOSSARY OF ACRONYMS, ABBREVIATIONS, AND COMMON TERMS

AMLCD	Active matrix liquid crystal display
ANVIS	Aviator night vision system
ARFF	Airport rescue fire fighting
Black Hot	In thermal images: Hot objects appear darker
BST	Barium strontium titanate ferroelectric detector material
CCD	Charge-coupled device
DEVS	Driver's enhanced vision system
Ditch	A vertical change of 3 feet or less
Drop-off	A vertical change of more than 3 feet
DVAN	Driver vision at night (night vision product)
DVE	Driver's vision enhancer
FARS	Fatality Analysis Reporting System
FIR	Far infrared (8 to 12 microns, 8000 to 12000 nm)
FL	Foot Lambert
FLIR	Forward looking infrared
FOV	Field of view
HDD	Head down display
HFOV	Horizontal field of view
HLB	Halogen low beam headlamps
HMD	Head mounted display / helmet mounted display
HMMWV	High mobility multipurpose wheeled vehicle
HUD	Head-up display
HUD eye box	The portion of the road scene ahead that is enhanced
Human eye sensitivity	0.4 to 0.7 microns (400 to 700 nm)
IR	Infrared (light)
IR-TIS	Infrared thermal imaging system
IVHS	Intelligent vehicle highway systems
LWIR	Long wavelength infrared
M SD SE	Mean, standard deviation, standard error
MIR	Middle infrared (3 to 5 microns, 3000 to 5000 nm)
MIT	Massachusetts Institute of Technology
MTBF	Mean time between failures
NASA TLX	Task workload index developed by NASA
NHTSA	National Highway Transportation Safety Administration
NIR	Near infrared (0.8 to 2 microns, 800 to 2000 nm)
NR	Non responsiveness (of LCD)
NU	Non uniformity (of LCD)
NVG	Night vision goggles
RMS error	Root mean square error

SD	Standard deviation
SWIR	Short wave IR (see NIR)
TNO	The Netherlands Organization for Applied Scientific Research
TTC	Time to collision
UFPA	Uncooled focal plane array
UMTRI	University of Michigan Transportation Research Institute
UV	Ultraviolet (light)
VES	Vision enhancement system
VFOV	Vertical field of view
White Hot	In thermal images: Hot objects appear whiter

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INTRODUCTION

Vision enhancement systems (VES) for night driving commonly are either night vision goggles (NVG) or in-vehicle displays. Several authors have reviewed the human factors literature on vision enhancement systems (Hahn, 1994; Kiefer, 1995; Lunenfeld and Stephens, 1991; Parkes, Ward, and Bossi, 1995; Tijerina, Browning, Mangold, Madigan, and Pierowicz, 1995), with the period covered ending in the mid-90s. This review was written to cover the gap since then as well as prior publicly available research performed by the U.S. military, which was largely ignored by previous reviews. In addition, research in related fields is covered, to provide answers to essential questions not yet answered by research on vision enhancement systems. This includes research on remote driving, driving with indirect view, and sensor fusion.

The objectives of this report are to provide an entrée into the human factors literature for readers unfamiliar with the topic, to identify gaps in current knowledge, and to provide a resource for those developing driver interface design guidelines.

Intended readers of this reported research include experts in the field of vision enhancement systems, human factors engineers and designers of such systems, and non-technical users and decision makers.

HISTORY

Night vision enhancement systems have been available for more than half a century, primarily for military use. Most use some mechanism to intensify the image from available light. The first starlight enhancement systems were used in World War II on sighting scopes. Night vision goggles (NVG) were first introduced in the 1960s for use by ground forces, mainly in the Vietnam War. Later, in the 1970s, night vision goggles were used by helicopter pilots. Although technological advancement has provided lighter-weight goggles with significantly better image intensification characteristics, the general concept of operation of the wearable goggles–along with their physical shape and their inherent limitations–has not changed much until recently. (See Miller and Tredici, 1992 for a more detailed summary of the history of NVG.)

The performance of current night vision goggles is far from perfect. The produced image is monochromatic. Depth perception is limited and visual acuity and focal range are restricted. The limited field of view requires special scanning techniques. The performance of night vision goggles is affected greatly by varying amounts of light due to position and size of the moon, weather, and artificial lighting. Moreover, the goggles are very susceptible to rapid changes in luminance, causing blooming of part or all of the field of view. Wearing the device for prolonged durations is likely to cause visual fatigue due to imperfections of the lenses and muscle fatigue due to the weight of the device on the user's helmet.

Despite the limitations mentioned above, it is more than likely that soldiers in the foreseeable future will continue to make extensive use of night vision goggles. A U.S. Army training document (U.S. Army, 1998b) states night vision goggles allow soldiers to "Read, patrol, provide medical aid, drive, walk, [and] observe the enemy," essentially everything a soldier needs to do. Using night vision goggles as an aid for night driving allows military drivers to perform tasks that could not be done unaided. Since vehicle headlamps are not needed, visibility to the enemy is reduced.

Vision enhancement systems based on FLIR (forward looking infrared) concepts were developed in the 1960s. At the end of the 1970s, uncooled systems, which were better adjusted for the requirements of the modern battlefield, were demonstrated to the U.S. Army. Uncooled FLIRs have since been used primarily for target detection and recognition. In 1984, the U.S. Army began to use FLIRs mounted on the Apache attack helicopter (AH-64A) for flying. FLIR systems were mounted on military vehicles in the late 1990s.

While both NVG and FLIR are used to enhance the driver's ability to see at night, they provide different information. The main difference stems from the method of operation of the two types of systems. NVG intensifies low levels of reflected light to provide a day-like image. FLIR is based on differences in heat emitted by objects in the environment. Typical NVG images are therefore easier to interpret but are more susceptible to brightness differences in the environment. They normally provide good detail of the path being driven and allow detection of obstacles on the road ahead. FLIR images are extremely sensitive to body heat in cold nights, thus allowing early detection of humans and animals, but the picture is not always easy to interpret and some information that users are used to seeing may not exist in the scene. Since the system relies on differences in emitted temperatures, FLIR is very susceptible to changes in the outside temperature and its performance may vary significantly as a function of time of night.

In the last decade or so, image processing technology and improved hardware capabilities have promoted the creation of real-time sensor fusion – methods for presenting images combining information from two or more types of sensors. Sensor fusion takes the good of both methods by providing images that are not only as intuitive as daylight images but allegedly better in detection of people and animals. Sensor fusion has promise for improving vision enhancement system usefulness, but there are a few implementation-related hurdles to overcome.

While vision enhancement technology has been applied quickly in the military area, that has not occurred in the civilian markets for several reasons. First, the immediate benefits to drivers using vision enhancement systems are not obvious in terms of "mission effectiveness" and personal safety. Second, the production and maintenance costs have been too high for mass sales in the civilian market. Third, less expensive off-the-shelf devices (such as NVG) still have significant performance limitations (such as limited field of view, and glare from the lights of oncoming traffic and in the car) and packaging constraints. Finally, the liability exposure of manufacturers and suppliers associated with the negative effects of such devices in the event of a crash is uncertain.

The only vision enhancement system marketed for production civilian vehicles thus far is the Raytheon 'night vision' system, an option on GM Cadillac model 2000 and newer vehicles. It is promoted as a safety enhancement feature for detecting pedestrians and deer while driving. Although formal information on the success of the product is not available to the public, GM representatives say they can easily sell the entire production capacity.

WHAT ARE THE HUMAN FACTORS ISSUES FOR VISION ENHANCEMENT SYSTEMS?

The aspects of a vision enhancement system that are most important depend upon the users and their tasks. For example, a military vision enhancement system is likely to be used for off-road driving and for path detection, and almost exclusively by younger drivers. On the other hand, a vision enhancement system for the civilian market would be targeted towards older drivers (the most likely purchasers) for on-road use, where the detection of objects such as pedestrians is important. Accordingly, Table 1 provides an extensive list of the human factors issues that need to be considered in designing and evaluating systems. Issues pertain to the device (the sensor and the display), the environment, and the driver. Developers may find this list useful when writing system specifications. Researchers may find this list useful when pondering potential research topics.

In research conducted to guide the development of system specifications, numerous human performance measures have been examined. (See Table 2.) For driving, measures pertain to controlling the vehicle (especially when visibility is poor), detecting objects (target detection time and accuracy), and higher level tasks and other considerations (e.g., risk compensation). Most of the research on vision enhancement systems has concerned vehicle control and object detection (Parkes et al., 1995). A good vision enhancement system should improve the driver's performance in at least one of these aspects without causing detrimental effects on the other aspects.

Table 1. Human factors issues related to vision enhancement systems

Device related	Environment related	Driver related
Sensor 1. Sensor type (thermal vs. near infrared) 2. Multiple sensors (fusion) 3. Image polarity (thermal) 4. Sensor position 5. Magnification ratio and field of view 6. System gain; signal to noise ratio 7. Susceptibility to bright light 8. Image realism 9. System reliability **Display** 10. Display type: HUD contact analog, HUD inset, HDD 11. Display size and location (retinal FOV, visual resolution, accommodation distance) 12. Image alignment 13. Distortion (curvilinear windshield, image not displayed straight ahead) 14. Transparency (reduces contrast of direct view) 15. Monochromatic vs. color 16. Stereoscopic vs. monoscopic (in NVG: Monocular vs. bi-ocular, and binocular) 17. Brightness and contrast 18. If worn on head: eye relief, exit pupils, weight, and balance 19. Optimal phosphor decay time to reduce smudging of moving objects while maximizing dynamic range 20. Calibration techniques and success levels 21. Controls	**Environment** 1. Weather (rain, haze, fog, snow) 2. Visibility (illumination, dust, smoke) 3. Vibration (sensor, display, driver) **Task** 4. Type of road (rural, highway, city, w/ street lights) 5. On-road vs. off-road 6. Convoy driving: Distance, speed, lights **Traffic** 7. Other traffic (oncoming traffic, following traffic) 8. Traffic with mixed technologies 9. Glare from oncoming traffic	**Individual characteristics** 1. Vision (acuity, depth perception, night vision, resting point of accommodation, presbyopia) 2. Expertise with the system 3. Age (as a confound with other factors) 4. Susceptibility to fatigue 5. Risk perception 6. Speed preference 7. Scanning techniques utilized 8. Anthropometry (eye height, focal distance, risk for facial injury) **Outcomes that may vary among different users and scenarios** 9. Comfort (may need to use for long periods of up to 12 hours) 10. Ability to direct attention 11. Tendency for spatial disorientation 12. Behavior under emergency situations 13. Crew coordination

Table 2. Human performance measures used to assess vision enhancement systems

Aspect of driving	Measure
Controlling the vehicle	Lane keeping and speed keeping
	Distance and gap estimation
Detecting objects	Probability to detect obstacles (fixed and moving) and events
	Time and distance to detect obstacles
	Recognition of road signs and traffic lights
Other	Speed choice
	Course completion time
	Number of crashes
	Risk compensation (tendency to take more risks to compensate for reduction in risk afforded by VES)
	Workload and fatigue
	Ability to perform additional tasks (such as use of a navigation system, talking on phone, etc.)
	Reliance on system (ability and willingness to drive without it)
	Spatial orientation
	Motion sickness due to using the vision enhancement system
	Night vision adaptation (ability to switch to unaided night driving in the event of a system failure)
	Visual resolution
	Glance behavior (Where do drivers look? For how long?)

EXPERIMENTS ON VISION ENHANCEMENT SYSTEMS

To establish the feasibility of vision enhancement systems for ground vehicles, several experiments compared these performance measures with and without enhancement (Barham, Oxley, and Ayala, 1998; Blanco, Hankey, and Dingus, 2001; Bossi, Ward, Parkes, and Howarth, 1997; Gish, Staplin, and Perel, 1999; Nilsson and Alm, 1996; Stanton and Pinto, 2000; Ward, Stapleton, and Parkes, 1994a, 1994b). Other studies examined performance differences between various sensors and different levels of sensor and image quality (Best, Collins, Piccione, and Ferret, 1998; Collins, Piccione, and Best, 1998b; Meitzler et al., 2000; Piccione, Best, Collins, and Barns, 1997; Ruffner, Massimi, and Choi, 1998). A few of these studies have focused on the effects of weather and visibility (Bossi et al., 1997; Meitzler et al., 2000; Nilsson and Alm, 1996; Stanton and Pinto, 2000), while others have addressed the types of targets to be detected and their characteristics (Barham et al., 1998; Blanco et al., 2001; Bossi et al., 1997; Collins, Piccione, and Best, 1998a; Gish et al., 1999; Meitzler et al., 2000).

Table 3 presents the reviewed vision enhancement system experiments organized by the factors that were studied (independent measures) and the performance aspects that were examined (dependent measures). A summary of findings from all these experiments, organized by the manipulated independent measures, follows.

Table 3. VES experiments categorized by dependent and independent measures

	Dependent measures					
Independent measures	Target detection	Distance / gap estimation	Driving performance	Subjective workload and preference	Risk compensation	Glance behavior
System / display						
Aided vs. unaided	Barham '98 Blanco '01 Bossi '97 Hollnagel '01 Gish '99 Nilsson '96 Staahl '95 Ward '94a	Barham '98 Ward '94b	Barham '01 Hollnagel '01 Nilsson '96 Stanton '00 Ward '94a	Barham '01 Hollnagel '01 Nilsson '96 Staahl '95 Ward '94a	Stanton '00 Ward '94a	
Field of view, magnification, focal length	Hollnagel '01		Hollnagel '01	Hollnagel '01		
Polarity (FIR)		Ward '94b				
Sensor						
VES type	Blanco '01 Collins '98a Meitzler '00 Piccione '97		Best '98 Piccione '97			
Sensor / camera position						
System reliability	Ward '94a		Stanton '00 Ward '94a	Ward '94a	Stanton '00 Ward '94a	
Sensor quality (noise in image, brightness contrast)	Hollnagel '01 Meitzler '00 Ruffner '98		Hollnagel '01	Hollnagel '01 Ruffner '98		
Environment						
Visibility illumination and type of weather	Bossi '97 Meitzler '00 Nilsson '96		Nilsson '96 Stanton '00	Nilsson '96	Stanton '00	
Type of road						
Other traffic / glare	Gish '99					
Driving speed		Ward '94b				
Gap size		Ward '94b				
Target type and location	Barham '98 Blanco '01 Bossi '97 Gish '99 Meitzler '00 Staahl '95	Barham '98		Staahl '95		Collins '98b
Task (navigation /speed monitoring)	Gish '99					
Driver						
Age	Blanco '01 Gish '99	Ward '94b				
General discussion	Hahn '94, Kiefer '95, Lunenfeld '91, Parkes '95, Tijerina '95					

Are Vision Enhancement Systems Beneficial? The Aided Versus Unaided Question

Overall, research favors the use of vision enhancement systems in vehicles due to improvements in obstacle detection. Gish et al., using a near infrared (NIR) sensitive camera, found an increase in detection distance of small targets from 90 to 120 m and of large targets from 120 to 180 m. Similarly, Staahl et al. (1995) and Barham et al. (1998, 1999) found that the use of an NIR VES increased the mean detection distance of a pedestrian from 61 to 95 m and for a few older drivers from under 30 m to over 100 m. An increase was also observed in detection distance of an adult dummy from 24 to 63 m and for a child dummy from 19 to 47 m. In a more recent study of an FIR system, Barham (2001) found an increase in headway distance, lower probability of crashing into a lead vehicle making an emergency stop, and lower probability of lane departure when using the system. However, significant increases in detection distance were not found under all circumstances. For example, Barham et al. (1998) found no increase in detection distance for road signs. Similarly, Ward et al. (1994a) found no significant difference in target detection time with a vision enhancement system. Finally, Gish et al. (1999) found no benefit for older drivers, partially because the information was displayed on an in-vehicle head-down display, which older subjects were reluctant to use extensively.

In terms of distance estimation, Barham et al. (1998) found that subjects using a vision enhancement system were unable to detect differences in distance of up to 2 m when viewing three wooden poles positioned 44 m in front of them. While driving, however, no significant difficulties in perceiving depth were noted. An overestimation of distance was observed for all targets at a distance greater than 30 m but was less marked when using a simulated vision enhancement system. Ward et al. found that the black-hot FIR device they used promoted a greater number of correct rejections of gaps deemed acceptable to pass through but fewer correct gap acceptances than a visible light image. The correct decisions on gap size were made sooner with the FIR camera (5.2 s before impact) than with the visible light camera (1.9 s).

While vision enhancement systems seem to improve detection distance and the estimation of physical sizes, they were found to degrade peripheral target detection and identification performance outside of the HUD image frame (Bossi et al., 1997), but only in certain lighting conditions, i.e., at night vs. dusk.

The presence of a vision enhancement system does not change driving performance considerably. Stanton and Pinto (2000) found an increase in speed when using a vision enhancement system before a simulated system-failure occurred. In contrast, Ward et al. (1994a) found slower speeds with a vision enhancement system (55.5 vs. 61.5 km/hr) and greater speed variation.

Does the Type of Sensor Matter?

In a recent experiment, Blanco et al. (2001a, 2001b) compared detection and recognition distance using an FIR system with several types of headlamps. They found the IR thermal imaging system allowed drivers to detect most objects at a greater distance than any of the conventional headlamps (210 vs. 150-180 m). Tire treads and a child's bicycle, which are hard to see using thermal imagery, were detected at shorter distances than with low-beam headlamps. Also, the recognition distance (as opposed to detection distance) was not significantly better than low-beam headlamps (the baseline).

In a comparison of sensor polarity (for thermal imagery), Meitzler et al. (2000) found braking time to obstacles in black-hot images faster than white-hot, which in turn were faster than a normal black-and-white camera view. Ward et al. (1994a) found comparable accuracy in time-to-collision (TTC) estimation between the black-hot setting and the visible matched scenes, but lower accuracy in the white-hot setting.

Collins et al. (1998a) and Piccione et al. (1997) compared a military FIR thermal system (Driver's Vision Enhancer or DVE) and NVG (using NIR). They found no differences in detecting known drop-offs and no differences in elicited driving errors. NVG had an overall advantage over thermal imagery under high illumination conditions, where it performs best. The NVG allowed for faster driving with greater reported confidence.

<u>Does the Sensor Quality Matter?</u>

Meitzler et al. (2000) found that when viewing a black-hot thermal image, Gaussian noise in the image (added by software to simulate degradation caused by sensor noise) decreased the probability of braking at the correct time to obstacles on the road from 100 to 91%. In fog conditions, where the image was not as clear to begin with, adding noise did not decrease the probability of correct braking. The addition of noise to visible black-and-white images with fog resulted in much larger changes (75% without noise and 38% with noise). In another experiment with degraded images, Ruffner et al. (1998) found no statistically significant differences in the percentage of objects identified or in response times between four display conditions. In those conditions, the uniformity of the display (up to 33% luminance variation distributed over the entire display) and the responsiveness of the pixels (65 of 640x480 pixels were off) were varied. Although the image quality was reduced, the response times were only slightly, and not significantly, lower for the non-uniform conditions. Additionally, subjects did not show large preference towards any of the devices although the non-uniform cases were somewhat less preferred.

<u>How Do Drivers Behave When a Vision Enhancement System Fails?</u>

Stanton and Pinto (2000) tested the effect of a system failure on driving performance. They found that before a system failure, speed was similar to daytime driving, and after the failure, speed was reduced to be similar to driving in the daytime in fog conditions.

<u>What Are the Effects of Ambient Illumination and Weather?</u>

Nilsson and Alm (1996) found that subjects increased their speed in fog conditions when using a vision enhancement system but drove more slowly than in the clear condition. The variance in lateral position was highest when using VES in the fog and lowest when driving in fog without VES. The reported workload level, however, did not vary.

Bossi et al. found better peripheral target detection at dusk than at night. This difference was greatest in the positions that were farthest from the center.

In a comparison of a military thermal system to NVG, Piccione et al. found that DVE had an advantage over NVG at night when smoke was present.

<u>What Are the Effects of Traffic and Glare?</u>

Gish et al. (1999) found detection distance in the presence of glare from low-beam headlights of a single oncoming vehicle to be similar for aided and unaided vision. They note that the maximum viewing distance that could have been obtained by viewing the vision enhancement system exclusively in the presence of glare was between 30 to 100 m in front of the vehicle. Since the glare significantly increased the drivers' workload, they felt uncomfortable looking down at the display and using the information on it. Also, since the field of view of the display was limited to 6 degrees horizontally, use of the display for driving was impractical.

<u>What Are the Effects of Target Type, Location, and Movement?</u>

As may be deduced from the literature on unaided night vision, detection and recognition distances varied considerably depending on the target type. For example, Blanco et al. (2001a) verified that pedestrians wearing white clothing were detected at greater distances than pedestrians wearing black clothing (250 vs. 100 m, respectively). Similarly, a black tire thread was detected only at very close distances (64 m).

While Blanco et al. did not find movement of the object to be a significant factor in detection range with thermal imagery, Meitzler et al. (2000) found moving objects more likely to be detected earlier than stationary objects. Bossi et al. found peripheral target detection to decrease with increasing target eccentricity regardless of the illumination.

In the only experiment that examined where drivers look when they use a vision enhancement system (Collins et al., 1998), found that drivers spend the majority of their visual search time looking at the center two-thirds of a (10-inch diagonal) display mounted about 10 inches in front of them. When searching for a drop-off, there is a shift up towards the horizon, but when not searching, most fixations are to the near field (bottom third of the display).

Piccione et al. (1997) found that vehicles, personnel, and obstacles were all detected earlier with thermal imagery than with NVG.

What Is the Effect of User Age?

A surprisingly small number of studies have formally tested age as a factor associated with performance. Barham et al. (1998) found a very significant benefit to the older population in using NIR images displayed on a HUD. In contrast, Gish et al. (1999) did not find older subjects benefited from vision enhancement system utilizing an in-vehicle head-down display (HDD). Most of the older drivers (ages 55 to 70) did not utilize the mockup vision enhancement system. While some did not see the display, others only used it to detect curves, or used it all the time but were uncomfortable with it. The added workload and risks associated with scanning down to the in-vehicle display were unacceptable to the older drivers.

EXPERIMENTS ON NIGHT VISION GOGGLES (NVG)

Night vision goggles are used ubiquitously in the military but are scarcely used for nonmilitary purposes. The exact frequency of use of NVG as an aid for driving by the military is unreported but is assumed by the authors to be prevalent. Nevertheless, only a handful of NVG experiments relevant to driving have been identified in this review. Because of the large number of aviation human factors studies on NVG and some similarities between driving and flying (both are time-shared tracking tasks), some might suggest that studies of driving with NVG are redundant. In fact, the scene detail, goals of the primary task, and user populations are quite different.

A few NVG-related studies are highlighted here to provide a sense of the questions that have been addressed and the findings. Although several papers discuss the potential use of NVG for ground vehicles, only one empirical experiment (van Winsum and Kooi, 1999) deals directly with driving with NVG. Table 4 lists the reviewed studies and the measures that were manipulated in them.

Table 4. NVG studies

	Dependent measures				
Independent measures	Task completion time	Errors	Driving performance	Subjective workload and preference	Visual resolution
Goggle type (monocular, binocular, bi-ocular)	CuQlock '95 CuQlock '96	CuQlock '95 CuQlock '96	van Winsum '99	CuQlock, '95 CuQlock '96 van Winsum '99	Wiley '89
Visibility	CuQlock '95 CuQlock '96	CuQlock '95 CuQlock '96		CuQlock '95 CuQlock '96	
Luminance and contrast level					Rabin '96
General discussion	NVG: Biberman '92, Gawron '01, Hudson '86, Ruffner '97, U.S. Army '98a				

General Discussion of NVG

In 1986, Hudson summarized design requirements for the development of NVG for military night driving. While some of his assumptions, based on “common sense,” were challenged in later scientific experiments, his early attempt to lay out the major human factors requirements was timely and essential. (Several of these design factors appear in Table 1 on page 4.)

Biberman and Alluisi (1992) conducted a review of the difficulties associated with night vision and display equipment in helicopters and fixed-wing aircraft. Besides providing a summary of relevant basic research, they discussed some operational problems associated with the use of NVG, based on interviews with high-ranking experienced military personnel. Improper scanning techniques are cited as associated with more than a third of all accidents reported. Maintenance and training are addressed as extremely important issues in maintaining high quality of vision using NVG.

Gawron and Priest (2001) discuss perceptual problems and other limitations of using NVG in aviation, based on their experience of more than a decade. Such issues as narrow field of view, reduced visual acuity, and poor distance estimation, as well as concerns about fatigue due to weight and imbalance, are mentioned.

Ruffner, Piccione, and Woodward (1997) report on a development of night driving training aid simulator software. In an analysis of 160 ground-vehicle crashes that involved night vision devices (mostly NVG), they found that over half of the crashes were attributable to either drop-offs or ditches. An additional 10% of the crashes were rear collisions with another vehicle.

The U.S. Army manual for NVG driving techniques and procedures (U.S. Army, 1998a) raises several considerations for driving with NVG. First, weather, visibility and illumination considerations are crucial. Second, the tendency to drive faster than one’s true capabilities needs to addressed. Third, convoy driving with NVG increases the demands on the driver. Finally, visual fatigue builds faster than without NVG and needs to be considered as well.

How Does the Type of Goggle Affect NVG Use?

Van Winsum and Kooi (1999) conducted a field experiment to compare driving performance in rough terrain with monocular and binocular NVG. They found no serious problems related to discomfort of wearing either type of goggles, though the visual comfort for the monocular goggles was rated lower than that for the binocular goggles. Driving with monocular goggles resulted in equally good driving performance but some of the drivers were not able to complete the two-hour session, implying that binocular goggles are more suitable for prolonged driving.

In a military setting experiment of soldiers navigating on foot, CuQlock-Knopp, Sipes, Torgerson, Bender, and Merritt (1995) (see also CuQlock, Torgerson, Sipes, Bender, and Merritt, 1996) compared performance with monocular, bi-ocular, and binocular goggles similar to those available for driving. In agreement with the conclusions reached by van Winsum and Kooi in the driving context, CuQlock-Knopp et al. found that binocular goggles yielded better performance (participants moved 10% faster and made 40% fewer errors of contact with hazards, decreased walking pace, request for assistance or stumbling, and stopping). The binocular goggles were preferred to the other two types of goggles. No consistent difference was found between the bi-ocular goggles and the monocular goggle even when, in a second experiment, a target-detection task was added. With the added task, the relative advantage of the monocular goggle was proposed to be due to the ability to use the free eye (not available in the bi-ocular goggles); something that did not occur.

In a laboratory study of visual resolution, Wiley (1989) found that stereopsis (the ability to perceive depth based on the relative differences between both eyes) was eliminated in monocular, bi-ocular, and binocular NVG. In fact, it was no better than the threshold obtained with unaided monocular viewing, suggesting that no advantage exists in depth perception for binocular versus bi-ocular and monocular. Spatial resolution capability (the ability to distinguish between small targets) with all of the goggle systems was superior to performance at night with unaided vision. Visual acuity with the goggles was approximately 20/50 but only for high contrast targets and simulated full moon ambient light levels. Any differences in visual performance between monocular, bi-ocular, and binocular goggles were assessed as not operationally meaningful for infantry use. No specific reference to driving was made.

How Does Ambient Illumination Affect NVG Use?

CuQlock-Knopp et al. (1995) found the ordering of performance with monocular, bi-ocular, and binocular was not affected by moon illumination.

How Does Display Luminance and Contrast Level Affect NVG Use?

Rabin (1996) found that display luminance did not in itself account for the level of acuity (visual resolution) achieved with NVG when viewing letter charts on a color monitor that was filtered green. Rather, an attenuation of contrast due to lower display luminance better explained the decrease in visual resolution.

EXPERIMENTS ON SENSOR FUSION

Sensor fusion is a promising technology that is likely to improve vision enhancement systems in coming years. By fusing images from different types of sensors, the viewer can take advantage of a combined image that is usually more informative. One apparent combination of sensor types for vision enhancement systems is thermal images with NIR images. This combination has the prospect of providing a day-like image, which is easy to interpret, with high contrast pedestrians and other live and moving obstacles. The fusion of information from various sensors should utilize the advantages of each sensor while avoiding the disadvantages.

Table 5 lists key references concerning the effects of sensor fusion on performance.

Table 5. Studies of sensor fusion and sensor type

	Dependent measures	
Independent measures	Detection speed and accuracy	Expert evaluation
Sensor type (and fusion present or absent)	Krebs '99 McCarley '00 Sampson '96 Sinai '99a Sinai '99b Toet '97 Waxman '96	Aguilar '99
Color or monochromatic	Krebs '99 McCarley '00 Sinai '99a Sinai '99b Toet '97 Waxman '96	
Field of view		Aguilar '99
Task / target	Sinai '99b	Aguilar '99
Glare	Krebs '99 McCarley '00	
Illumination	McCarley '00	
Polarity	Brickner '93 Sinai '99a Sinai '99b	
Contrast	Waxman '96	
Fusion algorithm	Das '00 McCarley '00 Simard '00 Toet '97	

<u>What is the Effect of Sensor Type on Performance with Fused Images?</u>

Krebs et al. (1999) compared target detection under six different formats: visible light, short-wave infrared (SWIR), two chromatic sensor-fused formats, and two achromatic sensor-fused formats. They found all sensor-fused formats for driving produced sensitivity to target detection equal to or better than that produced by either single-band (non-fused) format under conditions of low beam and high beam, respectively. SWIR was significantly worse than the other five formats, especially under the high-beam glare condition. In a follow-up study, McCarley and Krebs (2000) found sensor-fused imagery to be better than thermal or visible imagery. In their conclusions, however, they urge caution in the design and testing of any fusion system and algorithm that is meant to function under a broad range of environmental conditions such as that of driving.

Toet, Ijspeert, Waxman, and Aguilar (1997) found that color fused imagery leads to improved target detection over all other formats tested (achromatic-fused images and non-fused images). The lowest number of missed targets was obtained in the color-fused imagery (about 1.7%). The gray level images were next with 4.7%. The thermal image had 8% misses and the charge coupled display (CCD) had 20%. Similarly, Waxman et al. (1996) found that color fused imagery supports consistent detection while non-fused formats result in less consistent detection because they are much more susceptible to contrast changes in one of the formats.

Sinai, McCarley, Krebs, and Essock (1999b) found no significant difference between formats in response time to appearance of targets. Sampson (1996) found, contrary to expectation, that sensor fusion decreased task performance. This was caused by a local impact on the target contrast after applying the fusion to the imagery, suggesting that the details of implementation of sensor fusion must not be ignored.

Is There a Performance Difference between Color and Monochromatic Images?

Krebs et al. (1999) found that color rendering of sensor-fused imagery did not improve performance relative to that obtained with achromatic rendering. Similarly, Sinai et al. (1999b) did not find any significant difference in response times between formats.

Waxman et al. (1996) found the color fusion results to be consistent across all contrast levels, whereas the grayscale formats were inconsistent across the different contrast levels of each of the combined images. Some gray formats had increased reaction time when the visible contrast was low, and some when the IR image contrast was low.

Does the Field of View Matter for Fused Images?

Aguilar et al. (1999) compared detection and identification of targets using a wide and narrow FOV. Their data support the notion that the difference in detection due to FOV in low-light visible imagery is almost wiped out in the color-fused imagery.

Does the Type of Target Matter for Fused Images?

As mentioned above, performance differences are apparent when the task is varied and when different targets are used. Brickner and Zvuluni (1993) found polarity effects in segments where the targets were vegetation, natural terrain, or square buildings, but no polarity effects among other human-placed objects or among heat-emitting objects. Sinai et al. (1999b) found that across all sensor formats, people were detected faster than vehicles. Finally, Aguilar et al. (1999) found differences in performance when the evaluators changed the tasks or observed different targets.

Do Glare and Illumination Matter for Fused Images?

Krebs et al. (1999) found that reaction times with low glare were shorter than with high levels of glare. McCarley and Krebs (2000) found a reduction in sensitivity to the presence of a pedestrian in the scene under glare conditions when using simple fused as well as visible imagery. When using principal components fused imagery (a fusion method that attempts to improve image quality by manipulating the relationship between red and cyan pixel values), they found no degradation in sensitivity due to glare. However, this method did result in some degradation under very low-light conditions.

Polarity

Brickner and Zvuluni (1993) found some polarity effects, but not in a single direction. Sometimes black-hot was better and other times white-hot was better. They recommend allowing the operator (referring to skilled helicopter pilots) to choose polarity based on the specific task performed. Sinai et al. (1999b) found the least errors in detecting vehicles and people in the color-fused, white-hot format. Black-hot gray and color followed, and white-hot gray was last.

Does the Contrast Matter for Fused Images?

Waxman et al. (1996) varied contrast in the original images and showed that performance with the fused imagery was not affected much. Sampson (1996) found degradation in response times to fused images because their local contrasts were lower than in the original images.

Does the Fusion Algorithm Matter?

Several fusion algorithms have been suggested and compared. Toet et al. (1997) (from TNO and MIT) found the MIT algorithm for image fusion somewhat superior to the TNO algorithm. MIT had a lower number of missed targets (1.5 vs. 1.9%, respectively) and had lower mean distance error than the TNO images (17 vs. 26 pixels, respectively). Non-fused images had higher errors than any of the fused images.

Simard (2000) (not affiliated with either MIT or TNO) tested application of three fusion algorithms and concluded that the MIT-based algorithm generated some undesirable effects such as contrast reversals. This algorithm was also computationally intensive and relatively difficult to tune. He found the TNO-based algorithm more flexible and able to predictably preserve certain synthetic features that could be used to support obstacle detection.

McCarley and Krebs (2000) compared a simple fusion algorithm and a principal component fusion algorithm. They found the principal component fusion more robust to glare from the headlights of an oncoming vehicle, but slightly less sensitive under low illumination.

Das and Zhang (2000) propose a new algorithm. In contrast to other existing methods, which are intrinsically color-processing schemes, the new method performs grayscale or monochrome fusion to obtain a gray image first and then separate colors that image for further enhancement. The study does not compare performance of the new algorithm with other methods.

EXPERIMENTS ON REMOTE DRIVING AND DRIVING WITH INDIRECT-VIEW

Experiments on remote driving and driving with indirect-view have been performed since the early 1970s. While not all of their findings can be directly transferred to the context of vision enhancement systems, they provide valuable complementary information. For both types of systems, the driver views a projected image of the road scene. Similar issues arise, such as the optimal field of view and magnification, the camera position, the quality of the image, etc. The difference between remote driving and vision enhancement systems is that in most remote driving experiments drivers were outside of the vehicle, thus lacking proprioceptive feedback. Also, the remote driving tasks tend to be more military like (off-road, slow driving) and the participants in the experiments are mainly young soldiers. Nevertheless, as mentioned above, this field of research complements the study of vision enhancement systems and provides valuable answers to essential questions. Table 6 lists the key references grouped by the independent measures manipulated and the dependent measures examined.

Table 6. Studies of driving with indirect view

	Dependent measures			
Independent measures	Distance / gap estimation	Driving performance	Subjective workload and preference	Motion sickness
Field of view and magnification	Brown '86 Conchillo '96	Glumm '92 Oving '01 Padmos '96 Smyth '01 Sudarsan '97 van Erp '97 '98 '99	Glumm '92 Smyth '01 van Erp '99	Glumm '92 Oving '01
Camera position		Glumm '97 Padmos '96 Smith '70 van Erp '98	Glumm '97	
Stereoscopic or monoscopic	Holzhausen '93	Drascic '91 Holzhausen '93 van Erp '99	van Erp '99	
Color or monochromatic	Miller '88a '88b		Miller '88a '88b	
Panning camera	Miller '88a	van Erp '97	Miller '88a '88b	
With or without a camera		Oving '01 Padmos '96		
Image quality: Resolution, frame rate, image delay,	van Erp '98	Sudarsan '97 van Erp '98	van Erp '98	
General discussion	Padmos '95			

Brown and McFaddon (1986) varied the field of view, system magnification, and retinal size by manipulating the display size and viewing distance. They presented video recordings made during a vehicle's straight approach to a target and asked subjects to estimate coincidence time after the video was stopped at preset distances in various speeds. Subjects made undershoot errors, which were greater with limited HFOV (14 degrees) than with the wider HFOV (26 degrees). This study supports the use of wider fields of view but does not decisively identify a single optimal magnification level or viewing distance for reducing estimation errors.

In a study that varied retinal FOV while holding the camera FOV, Conchillo, Nunes, Recarte, and Ruiz (1996) found neither retinal size nor peripheral field restriction to affect speed estimation in laboratory settings.

Glumm, Kilduff, and Masley (1992) varied the focal length of a camera used to remotely drive a golf cart in an indoor test course. They found that speed and accuracy were significantly greater when a 6 mm lens (55 x 43 degrees; 2.75x) was used compared to a 12 mm lens and a 3.5 mm lens (with about half or twice the FOV, respectively). The 12 mm lens, while providing a much greater FOV, was worst in an obstacle avoidance course and was much less preferred by subjects. The differences between the 6 mm and 3.5 mm lenses were less profound than the differences from the 12 mm lens, though the 6 mm was recommended. The authors stressed the importance of the wider camera FOV because of the details available to the driver (e.g., seeing some of the car in the FOV) over the importance of image resolution, which varied with magnification.

Oving and van Erp (2001a, 2001b) tested the effectiveness of a head-slaved camera system for driving an armored vehicle using a head-mounted display. A wide HFOV of 88 degrees with high minification (0.44x) did not improve driving performance and tended to shorten estimated distances relative to a narrower HFOV of 40 degrees with no magnification (0.96x).

Padmos and van Erp (1996) varied the position (front-low at 0.4 m above the driver and rear-high at 1.4 m above the driver and 1.7 m behind the driver) and field of view (46 degrees; 1x and 80 degrees; 0.5x) of a monochromatic camera used for driving a vehicle. They found significant effects of field of view and camera position but these effects were not quite consistent for different tasks and different performance measures. For example, while lateral control with a wider view was less stable on straight sections and moderate curves, it was more stable on sharp curves. Overall, wide field of view with 0.5x magnification at a high position was most preferred and most likely to produce better driving performance. Normal field of view with 1x magnification at the high position was the worst.

Smyth et al. (2001) conducted a field experiment to study the effect of FOV on the ability of soldiers to drive an HMMWV with external vehicle-mounted camera array and panel-mounted video displays. They varied the magnification level (0.73x, 0.54x, and 0.43x) and displayed the image on a three-screen display of 110 degrees. Driving speed decreased with increasing magnification following a power function: Speed=22.3*compression^-0.332 (compression=1/magnification). The number of barrels struck increased with the level of compression. Subjective ratings did not vary at all between the conditions.

In a simulator study, Sudarsan, Du, Cobb, Yager, and Jacobus (1997) found the time to complete a course to increase when FOV was limited.

In a remote-driving simulator study, van Erp and Padmos (1998) varied the camera position (low at 1.4 m above the ground, above the driver, and high at 2.8 m above the ground and 1.7 m behind the driver), HFOV (40 and 80 degrees), and magnification (1.0x and 0.5x). They found the best overall performance and least difficulty rating with an 80 degree FOV and 1.0x magnification. Magnification of 1.0x resulted in better driving performance than 0.5x on sharp curves and in a lane change maneuver. The 0.5x minification also resulted in distance and forward speed overestimation.

Van Erp and Kappé (1997) found driving performance in a simulator with a 40 degree horizontal field of view to be inferior to that with 160 degrees. They recommend using a field of view greater than 40 degrees if there is a need to negotiate curves.

Figure 1 summarizes the camera FOV and magnification levels reported in the above studies. There is no single combination of FOV and magnification that all researchers agree is best. In fact, some studies with very similar settings make contradicting recommendations.

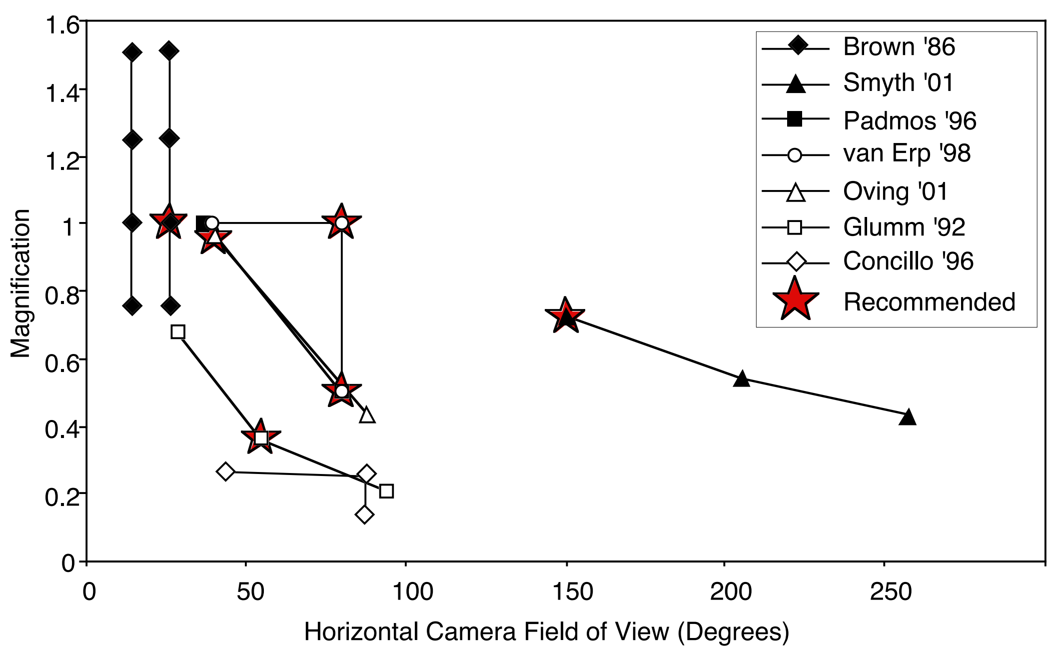

Figure 1. Field of view and magnification levels in various studies.
(Recommended values are denoted by a star.)

Where Should the Camera Be Positioned?

Camera position was studied extensively by Glumm, Kilduff, Masley, and Grynovicki (1997). They informally compared several possible camera positions, and then tested the three best positions. A computer program was written to calculate optimal camera positioning as a function of the height of the vehicle's hood, vehicle width, vehicle length, and the FOV of the camera lens system. In the formal comparison of the three different positions, the preferred camera position, with the least number of errors, was low in the back of the vehicle, so as to provide the best view of the sides of the vehicle (3.8 m behind the front of the hood, 1.4 m above the front of the hood, and aimed 10 degrees under the horizon). An additional good option was high in the front of the vehicle, to provide a good view of the ground in front of the vehicle (3.1 m behind the front of the hood, 1.7 m above the front of the hood, and aimed 10 degrees under the horizon). Subjects were divided in their preference between these two camera positions, suggesting that each has advantages and the trade-offs are not agreed upon.

Padmos and van Erp (1996) compared driving performance in the field with several combinations of field of view and camera position. Overall, a wide field of view with magnification of 0.5x at a rear-high camera position (1.7 m behind and 1.4 m above the driver) was most preferred and most likely to produce better driving performance.

Van Erp and Padmos (1998) compared driving performance in a simulator with several combinations of field of view and two camera positions (low at 1.4 m above the ground, above the driver, and high at 2.8 m above the ground and 1.7 m behind the driver). On sharp curves, there was an interaction between the camera position and field of view. While wide field performance was slightly better in the rear-high camera position, in normal field it was much worse. The high position of the camera lead to underestimation of lateral position, which was aggravated by the normal FOV because of the restricted lateral view and the lack of points of reference in the image.

These studies indicate that camera position has to be chosen carefully to provide an optimal image for certain driving tasks. Furthermore, position interacts with the magnification and FOV. Finally, when choosing camera position, it is not the actual position of the camera that matters, but inclusion of parts of the vehicle, namely the hood and side, in the image.

Should the Image Be Stereoscopic or Monoscopic?

Holzhausen, Pitrella, and Wolf (1993) studied the effects of mono- and stereoscopic viewing on driving performance of a remotely operated vehicle. They found that driving time with the stereoscopic view was shorter, suggesting that the driving task was easier to perform. The stopping distance from an obstacle without a collision was less as well.

In a study of the same issue, Drascic (1991) found stereoscopic video easier to learn than monoscopic. When stereoscopic depth cues were important, the benefits of stereoscopic vision lasted longer. (For difficult tasks, which depended on stereoscopic depth cues, the benefits of stereoscopic vision were still apparent, even after a great deal of practice.)

Van Erp and van Winsum (1999) found the difficulty rating (on a scale of 1 to 5) increased from 1.9 using binocular vision to 2.9 using restricted monocular vision. No significant effects were found, however, on task completion time in these conditions.

Should the Image Be Color or Monochromatic?

Miller (1988a, 1988b) studied distance and gap estimation using camera view with a monochrome and color monitor. He found the overestimation of distance to be larger for subjects using color rather than monochromatic imagery. Mean target height estimations in the color conditions were larger than in the monochromatic condition (6.3 vs. 5.0 ft, respectively). He concluded that color displays might aggravate the estimation problems that frequently occur under remote driving conditions.

Miller and McGovern (1988) compared the detection range of various objects in real-time remote driving of a Jeep to watching a prerecorded video of the driving task in color and in monochrome. In the video viewing condition, the color images provided greater detection ranges than monochrome.

Should the Camera Be Fixed or Steering-Slaved?

Miller and McGovern (1988) examined the advantages of a panning camera with 42 degree HFOV that was slaved to the steering wheel. In the video viewing condition, detection range was better with the steering-slaved panning camera than with either of the fixed cameras. In the actual teleoperation condition, however, the steering-slaved camera was only as good as the fixed black-and-white camera, possibly because of the jitter of the camera due to mounting hardware issues.

Van Erp and Kappé (1997) compared the unrestricted view (160 degrees horizontally) to two combinations of a panning camera with a 40 x 40 degrees image. In the first, the image was displayed on a fixed screen in front of the driver. In the second, the image was projected on the screen in the correct orientation from the driver's eyes. They found driving performance when the image was fixed to be worse than the other two conditions. In addition, they found that drivers utilized the panning camera less when the display was fixed than when it was variable. In the event that a fixed display is presented, they recommend adding vehicle references while minimizing occlusion of the area close to the front of the car.

Is There a Difference between Direct and Indirect Viewing?

Oving and van Erp (2001a) compared performance in direct view to periscope and to an HMD. Generally, they found the direct view to be superior to the HMD view in that the number of pylons (path edge markers) hit and track completion time were reduced. However, the camera view was better than the periscope view because of the elimination of dead areas in the field of view, due to more flexible positioning and movement of the camera.

Padmos and van Erp (1996) found differences between camera view and direct view in several performance measures. First, control of lateral position was moderately worse under the camera view, increasing the lateral distance to road markings and variability of lateral position 50%. Second, performance of braking tasks suggested a relative overestimation of distance under the camera view. Finally, driving with the camera view was rated as more difficult than with direct view (2.6/5 vs. 1.6/5, respectively).

<u>What Are the Effects of Image Quality (Resolution, Frame Rate, Image Delay)?</u>

Van Erp (1998, see also van Erp, 1996) studied the effects of spatial resolution and update rate on remote driving performance in a simulator. Performance at 10 Hz and 256x242 pixels was similar to baseline driving. Requirements on spatial and temporal resolution were task dependent. On sharp curves and in lane changes, a minimum update rate of 5-10 Hz was required. On braking, speed estimation, and distance estimation, 3 Hz was sufficient. No interaction was found between spatial and temporal resolution, suggesting that a higher level on one factor cannot compensate for a lower level on the other factor.

Sudarsan et al. (1997) tested the effects of several frame rates and frame lags on task completion time. They found that the time to complete the course increased exponentially as a function of frame rate and frame lag.

Padmos (1995) reviewed the available literature on remote driving. Based on the reviewed literature, he recommends mounting the camera in the rear of the vehicle over the lateral center of the vehicle. Camera motion is only recommended if a head-slaved camera combined with an HMD is available. The recommended field of view for fixed cameras is 70-90 degrees. Visual resolution of 20/200-20/80 is sufficient for road following, although for other driving tasks 20/40 may be needed. A magnification of about 1 is suggested to prevent distance and speed overestimation resulting from high minification.

NIGHT DRIVING AND THE NEED FOR VISION ENHANCEMENT SYSTEMS

Of the vast literature on night driving, a few representative studies are cited here in an attempt to show the need for vision enhancement systems and to identify where they will most likely be beneficial.

Owens and Sivak (1993) studied the role of reduced visibility in nighttime road fatalities. In an analysis of 100,000 accidents during twilight zones, fatal accidents were found to be overrepresented during darker portions, but unrelated to time of day, day of week, or alcohol consumption. Twilight was chosen because it allowed the unconfounding of illumination that occurs when day and night are compared. Reduced visibility was also indicated by higher overrepresentation of fatal accidents in low illumination under adverse atmospheric conditions and with pedestrians and pedalcyclists (both difficult to detect) as opposed to all other accidents. Reduced visibility was more important than drivers' drinking as a contributor to fatal pedestrian and pedalcycle accidents. The reverse was true for all other fatal traffic accidents.

In another UMTRI study, Sullivan and Flannagan (2002) estimated the influence of ambient light level on fatal pedestrian and vehicle crashes based on crash data from 1987 to 1997. They found that scenarios involving pedestrians were most sensitive to light levels, showing between 3 to 6.75 times more risk when dark relative to daytime light (with time of day held constant). Single-vehicle run-off-road crashes on dark curved roads showed little, if any, sensitivity to light level.

Ruffner et al. (1997) analyzed 160 military ground vehicle crashes, reported by the U.S. Army Safety Center, that involved night vision devices during the period of 1986-1996. Over two-thirds of the 160 crashes were attributable to three categories of terrain and roadway hazards/obstacles: drop-offs (34%), ditches (23%), and rear collisions with another vehicle (11%). One-third (34%) of the crashes involved an HMMWV, 18% involved the M1 Abrams Tank, and 14% involved the M2/M3 Bradley fighting vehicle. The most commonly occurring environmental conditions cited as contributing factors were dust (24%), blooming from light source (9%), and smoke (8%). Failure to detect a hazard or obstacle accounted for 43% of crashes, followed by misjudgment of size, depth, or location (19%).

Findings from these studies highlight the need for vision enhancement to reduce fatalities. Furthermore, it is clear that an enhancement system that could help in detection of pedestrians and pedalcyclists would be a major advantage. In the military context, drop-offs and ditches are the major concerns in off-road driving.

HEAD MOUNTED DISPLAYS AND WEARABLE COMPUTERS

Research in the last decade, especially at MIT and Carnegie Mellon University, has elevated interest in using head-mounted displays (HMD) for presenting nonguidance information. In an attempt to provide users with augmented information wherever they are, wearable computers may soon transition from interesting research ideas to commodity products. Since some of these systems already have a certain level of vision augmentation and enhancement, and since they are intended to be worn whenever the user is awake, it is only a matter of time before wearable computers with HMDs are used in vehicles. While no specific research has been done on the use of wearable computers with HMDs for driving, a few articles have dealt with field of view and head movements.

Researchers at TNO have rigorously studied the use of HMDs to present a camera view of the road scene, especially for army vehicles. (Some of their work is reported in the remote driving section of this report.) Bakker, van Erp, and van Winsum (2000) reviewed the human factors literature related to driving with head-slaved camera systems. They discussed the importance of field of view, mainly for steering, and visual acuity, mainly for detection of objects. Padmos (1999) studied the effects of head-slaved displays, and specifically HMDs, on driving performance and subjective difficulty ratings in a simulator. Padmos concluded that HMDs have negative effects on driving performance and on the subjective ratings of difficulty. By comparing driving with an HDM to a baseline condition in which the field of view was limited but an HMD was not used, he concluded that the limited field of view was not the reason for the degradation in driving performance and the increase in difficulty. Rather, the physical characteristics of the HMD (weight and image delays) are reported as more probable causes. If an HMD is used, it is recommended to apply vehicle references on the image. This can be done either by allowing see-through capabilities or by adding virtual computer-generated references directly on the HMD image. Van Erp and van Winsum (1999) compared driving an armored vehicle using an HMD to direct view with similar field of view restrictions and to unrestricted direct view. They found course completion time with the HMD was longer than in the other conditions (3.2 vs. 2.4 min). Drivers also rated it as more difficult than the other conditions (3.5/5 vs. 2.3/5 and 1.3/5, respectively). Each condition was also performed with monocular vision. HMD was most affected by monoscopic vision, suggesting some advantage to stereoscopic view when image quality is reduced.

A book chapter by Davis (1997) discusses several of the basic visual requirements for HMDs. These requirements are directly related to the requirements of any in-vehicle vision enhancement system and are summarized in detail later in this report.

Venturino and Wells (1990) studied the relationship between head and eye movements and the immediate field of view. Of interest were head movements made by subjects as they found and memorized the position of targets located around them with several FOV levels (20, 45, 60, 90, and 120 degrees). When slow search was performed, small FOVs produced more head displacement and lower head velocities than did the large FOVs. In the fast search trials, head velocity increased with increasing FOV. The faster search times associated with larger FOVs were due to subjects moving their heads less, but at higher velocities. With a large FOV, subjects could point their heads and use their eyes to scan within a large area to obtain the location of targets relative to one another and relative to their head position.

Geri et al. (1999) measured combined head and eye movements of observers wearing an HMD with limited FOV (10, 20, and 40 degrees). Similar to Venturino and Wells, they found that increasing the FOV resulted in a decrease in the magnitude of head movements and a concomitant increase in the magnitude of eye movements. They also found that only about 10 degrees of the visual periphery were effectively used in the visual search, which suggests that when actively searching, a FOV of 40 degrees is not fully utilized. However, as the authors note, the wider FOV does allow for detection of events in the periphery.

Glumm et al. (1998) studied soldier performance of land navigation and other daytime mission tasks using current navigational equipment integrated on a HMD. The results indicated that the soldiers traveled less distance between waypoints and experienced lower levels of mental workload using information presented on the HMD than they did using current navigational equipment.

Given the likely broad adaptation of wearable computers over the next decade, a program of focused research to determine design recommendations for in-vehicle use is required. Key issues will include likely communication architectures with the vehicle, the types of information to supply, management of driver workload, use of input mechanisms to interact with such devices, integration of vision enhancement sensors, and many other topics. Such work should keep a close eye on the civilian market as the use of ruggedized versions of wearable computers intended for the civilian market could be an attractive option of military use. There is no data on use of HMDs for both guidance and data processing (e.g., system access) while driving; timesharing issues should be the focus.

SUMMARY AND RECOMMENDATIONS FOR FUTURE STUDIES

While a fair amount of research on vision enhancement systems exists, there are a few major gaps that still need to be filled. First, none of the reported experiments on vision enhancement systems studied display and sensor parameters such as field of view, magnification factor, focal length, camera position, polarity of thermal image, and the use of a color image. Additional innovations for enhancing field of view (such as panning the camera or using multiple cameras) and for enhancing performance (such as stereoscopic images) should be studied as well. Second, research of HMDs and wearable computers and how they fit in the civilian night driving context is needed. Third, environmental factors such as the type of road, the level of traffic, and the driver's chosen speed have not been studied in the specific context of vision enhancement systems. Fourth, performance differences between drivers have not been studied extensively. In many studies only young subjects, with no experience using vision enhancement systems, were tested. While a few studies have dealt with two or three age groups (Blanco et al. 2001; Gish et al. 1999; Ward et al. 1994b), most studies have not looked at the effects of driver age, experience, risk averseness, and other personal characteristics on driving performance, risk compensation, workload, and preference.

On a different level, there has been a tendency to focus on measures that are easy to analyze (such as detection distance) while ignoring other measures that may also be important. For example, workload and distraction have not been addressed thoroughly. Similarly, where people look when they use vision enhancement systems of various kinds has been addressed in only one study (Collins et al., 1998a).

Most of the reviewed experiments were empirical in nature, performed either in the laboratory or on test tracks, and fairly applied in their perspective. There are two additional types of research projects that need to be performed to address important issues: basic research and field tests. Basic research will help predict outcomes and reduce the scope of empirical testing. Tijerina et al. (1995) list two of these needs: (1) identify the types of visual information used to control a vehicle (optical flow, looming, contrast, and object visual size) and how they are affected by a vision enhancement system, and (2) predict seeing distance based on a number of parameters using a visibility model based on Blackwell's threshold contrast research and PCDETECT model. On the other hand, field tests and validation experiments that utilize end products in real-life settings with experienced users will complement the current state of knowledge. Issues such as frequency of use, distraction when overused, misuse, system acceptance, and system reliability can be addressed best in a real-world setting. Some of these data may exist but are proprietary to the producers of the devices.

Following directly from the above summary of the literature, it is recommended that future studies address the identified gaps shown in Table 7. The open issues pertain both to military and civilian use of vision enhancement systems. However, as in all human factors studies, changing the typical characteristics of the task, the environment, and the driver will most likely change the results and affect the recommended design parameters.

Table 7. Open issues in the vision enhancement systems literature

	Open Issues (**X** = More research needed)	Target Detection	Distance / Gap	Driving Performance	Workload / Situation Awareness	Preference
Display	What are the optimal magnification and field of view for vision enhancement systems? Are they different from those recommended for remote driving?	**X**	**X**		**X**	**X**
Display	What are the advantages of enhanced imaging features (e.g., color, stereoscopic vision, and adjustable polarity)?				**X**	**X**
Display	How well do users perform when using head-mounted displays and wearable computers?	**X**	**X**	**X**	**X**	**X**
Sensor	How do different vision enhancement systems (e.g., thermal, NIR) compare?			**X**	**X**	**X**
Sensor	What is the optimal sensor position and how much does it matter given practical limitations?	**X**	**X**		**X**	
Sensor	What are the advantages of sensor fusion of various input types? Is sensor fusion ready for real-time use?			**X**	**X**	**X**
Environment	What are the effects of the type of road, amount and form of traffic, and the driver's task? How do drivers using vision enhancement systems fit into traffic?	**X**	**X**	**X**	**X**	**X**
Environment	What are the effects of driving speed on performance with vision enhancement systems?	**X**	**X**		**X**	**X**
Driver	How do the driver's age, driving experience, experience with vision enhancement, and risk averseness characteristics affect performance?			**X**	**X**	**X**
Field Studies	Does the use of vision enhancement systems reduce crashes?	Crash data, interviews				
Field Studies	What is the usage pattern (e.g., frequency, purpose) and system acceptance among various drivers?	observations, interviews				
Basic Research	Improve existing models of driving, detection of obstacles, pedestrians and other vehicles and apply them towards the use of vision enhancement systems.					
Military Specific	What design differences result from the difference in tasks between military and civilian?	Convoy driving, terrain, black-out, extreme fatigue				

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APPENDIX A - SUMMARY OF REVIEWED PAPERS

Each of the studies referenced in this report is summarized below. If the study was an experiment, the dependent and independent variables are listed and the author's conclusions are shown. The mixture of styles for these summaries (some outlines, some text summaries, and some combinations) was chosen for the authors' convenience and has been retained for cost effectiveness.

VES (PRODUCTS)

This section provides technical details about 6 products that have been described in the literature. Table 8 lists these products (in alphabetical order of the author's name).

Table 8. Vision enhancement products described in the literature

	Report	System	Vehicle	Sensor	Display
1	Barham et al. (1999)	NVS (night vision system)	Jaguar S-series	NIR	Contact HUD
2	Galaxy scientific (1998)	Driver's enhanced vision system NTV-2020	Airport rescue fire fighting vehicles	FIR	LCD in front of driver
3	Martinelli and Boulanger (2000)	Night vision system	GM Cadillac	FIR	Inset HUD
4	Pencikowski (1996)	Northrup Grumman Corp.	Unknown	NIR (laser gated)	Monochrome display
5	Schwalm and Brady (1996)	DVE (driver's vision enhancer)	Military HMMWV	FIR	LCD in front of driver
6	Shelley and McCaughran (2001)	DVAN (driver's vision at night) (similar to #1)	Military Bedford 8-ton truck	NIR	Contact HUD

Barham et al. (1999) - Jaguar car's near infrared night vision system - overview of human factors research to date

Barham, Oxley, Thompson, Fish, and Rio (1999) reported a set of three experiments conducted between 1994 and 1997 on an NIR night vision system with a contact analog HUD installed in a Jaguar. (The details of the experiment number 2 (Barham et al., 1998) are summarized separately.)

<u>Summary of requirements for VES based on three experiments</u>

- The images generated by the VES must be intuitive to inexperienced users. (Some FLIR images are not intuitive because heat is depicted by contrast differences in the image, which is different from a normal image.)
- Depth perception should not be compromised when the system is in use. The authors were very concerned that the planar image presented on the HUD would

hinder drivers' depth perception abilities by obstructing them. They found out in the second experiment that depth was overestimated less than without the system.

- The display should not be too bright so that dark adaptation would still occur and non-enhanced images will be visible to the driver. In addition, the visibility of objects just outside the borders of the enhanced image should not be hidden by a HUD image that is too bright.
- Drivers' scanning behavior is changed. In unaided night-time driving, drivers look at the road 43% of the driving time, compared to 93% of the time in daytime driving. Human factors research should establish the effects of VES on drivers' scanning behavior and whether this change benefits driving safety.
- Pragmatic considerations should not be ignored. For example, the driving task imposes requirements that are related to traffic and road signs. The VES has to allow recognition and readability of road signs, traffic signals, other vehicles' brake lights and indicator lights, etc. Signal processing might be useful in accomplishing these requirements.
- Industry-related considerations, though less safety-critical, are also important and play a crucial part in the development of the technology. Packaging requirements in the vehicle's cockpit are a good example.

<u>Image processing</u>

The near infrared image is processed by an on-board computer using real-time parallel processing before it is displayed on the HUD. This allows improvement in the sharpness and quality of the image. Additionally, it may allow artificial enhancement of line markers and even road signs and pedestrians. Human factors experts should identify the characteristics of the optimized image that is generated by the digital signal processors.

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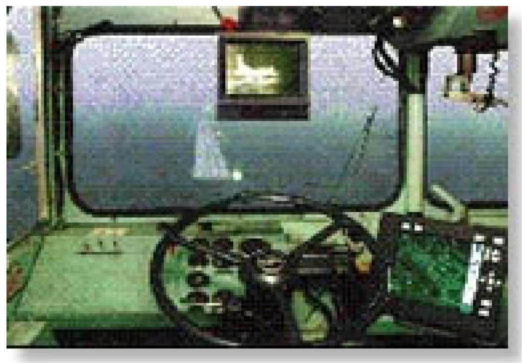
Galaxy Scientific (1998) - NTV-2020TM Driver's Enhanced Vision System (DEVS)

The NTV-2020™ Driver's Enhanced Vision System (DEVS) is an enhanced vision and navigation system for guiding Airport Rescue Fire Fighting (ARFF) and vehicles at night and during certain low-visibility conditions. The NTV-2020™ system combines advanced infrared sensing, moving-map display, wireless communication, and Differential Global Positioning System navigation technologies.

To enhance the driver's vision during inclement weather, the Galaxy system places a separate monitor directly in front of the driver. This monitor displays the driver's forward view of vision, provided by the sensing of the temperature gradient of objects and backgrounds with a sensitivity of 0.1° F. This image can assist rescue drivers in avoiding obstacles en route (e.g., signs, taxiways, edges) and, more importantly, in spotting victims at night, in water, in fog, etc., who might otherwise be overshadowed by the illumination of the accident scene.

FLIR specifications

Detection range:	Humans, 800 ft. Detection range of objects dependent on size and temperature
Pan, tilt:	360 degrees, +45 / -20
Controls:	Fully automatic gain and level controls
Field of View:	27 x 18 degrees
Display size:	5.25 x 4.75 x 6.5 in.



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Martinelli and Boulanger (2000) - Cadillac DeVille thermal imaging night vision system

Martinelli and Boulanger (2000) present the system requirements and parameters of the Cadillac DeVille thermal imaging night vision system.

System components

Camera:	12 cm cube. FIR. 320x240 pixels. BST detectors. Mounted on the center of the radiator grille
HUD:	Monochromatic LCD (active matrix), 16 shades of gray Focused at 2.5 m in front of the driver
Controls:	Off-on dimmer switch; vertical position switch
Requirements for system on:	Ignition switch in run and front headlamps or fog lamps are active and ambient light sensor indicates darkness.

System parameters

Magnification:	1x
FOV:	11.25 x 4 degrees (provides coverage of adjacent lanes at 68 m and above)
Camera optics:	Focal length 125 m. Depth of field - 25 m to infinity
Alignment:	Objects appear aligned horizontally. Horizon appears in the lower one-third of the HUD image.
Detection range:	The driver can detect a person (1.8 m tall x 0.5 m wide) from 300 m and a running vehicle from 500 m.

Polarity: White hot (objects of interest are typically warmer than the environment.

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Pencikowski (1996) - A low cost vehicle-mounted enhanced vision system comprised of a laser illuminator and range-gated camera

Pencikowski (1996) describes a laser illuminator and range-gated camera in development by Northrop Grumman Corporation. The system will deliver up to 3000 ft of penetration in dense fog, day or night. The image will appear on a display as a high-resolution monochromatic image.

Method of operation

A single pulse of laser light is directed toward a target of known distance. This distance is calculated from the transmit-receive time of either a reference pulse or the previous image-capture pulse. As the pulse moves away from the laser, unwanted light is reflected back to the camera from the weather/obscuration. It is this reflected light that is the “glare” seen when auto headlamps are turned on in fog. Since the camera shutter is closed until the determined time-of-arrival of a light pulse, unwanted noise is ignored and a clear-image picture is generated.

Open issues

- The laser must be absolutely eye-safe (work in wavelengths that are not dangerous to humans).
- The cost of current detectors is relatively high.

Implementation

The actual laser technology forecast for use is a commercially-available erbium laser at 1.54μm. The sensor will most likely be an intensifier tube (transferred electron photocathode). It is expected to have very good ambient light immunity and enhanced obscurant penetration due to the use of 1.54μm wavelength.

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Schwalm and Brady (1996) - Design solutions for thermal imaging devices in military vehicles

Schwalm and Brady (1996) discuss driver, operational, and technical considerations related to the use of the driver’s vision enhancer (DVE).

System parameters

Sensor

An 8-12 μm IR sensor (LWIR-long wave IR) built around a ferroelectric uncooled focal plane array which includes 328x245 pixels on a 48.5 μm pitch. LWIR exhibits better performance than MWIR (middle wave IR) in three categories: cold weather performance, hot target blooming, and smoke and obscurants.

Display
An active matrix LCD (AMLCD) with the following parameters is used: 10 inch diagonal, 640x480 resolution, 256 levels of brightness, and contrast ratio of at least 22.6:1. Specific technological solutions are provided for performance at low temperatures, sunlight readability, night vision band visibility (above 600 nm), and 40 degrees cutoff viewing angle.

Sensor field of view
The sensor provides a 40 x 30 degrees FOV (HxV). Field of view was maximized within the design constraints while maintaining a 1x magnification ratio. Wider FOVs provide earlier detection of objects in peripheral vision, more time to view objects that are moving towards the periphery, and better detection of vehicle speed and situation awareness. Since the display is positioned about 10 inches in front of the driver, it provides an actual field of view of 40 x 30 degrees, similar to that of the sensor.

Color vs. monochrome
A monochromatic display was chosen to allow for higher resolution and brightness.

<u>Vehicle parameters</u>

Sensor mounting position
The sensor is offset by as much as 20 inches from the driver's normal line of sight in the HMMWV. In the Bradley fighting vehicle, on the other hand, it is mounted directly in front of the driver. An offset of the sensor might cause parallax, which reduces vehicle guidance performance

Display viewing distance and angle
Discusses space constraints, but not what is desired.

Eye reference point/viewing position
The display has adjustable tilt but is otherwise fixed in height and distance.

Ambient illumination
The range of ambient illumination is from 5 fL inside a Bradley up to 300-500 fL in an exposed HMMWV.

<u>Driver parameters</u>

Magnification
The sensor magnification ratio is 1x. Display size and viewing distance contribute to the system magnification as perceived by the driver. The DVE display is designed such that its field of view in the operator's eyes is similar to the field of view of the sensor.

Perceptual cues
Perceptual cues are very limited, and in some cases false. While perspective cues are available, shading and shadows may represent thermal changes rather than useful

depth information. Other cues that are lessened include accommodation, binocular disparity, convergence, object overlap, and texture gradient.

Polarity
Performance advantages of either polarity have not been proven consistent and therefore are not considered significant factors in this system.
It is noted that some cues, such as the edge of an asphalt road, cannot be extracted from an IR image.

Training and experience
Learning what to expect, and how to recognize objects viewed in IR, is crucial.

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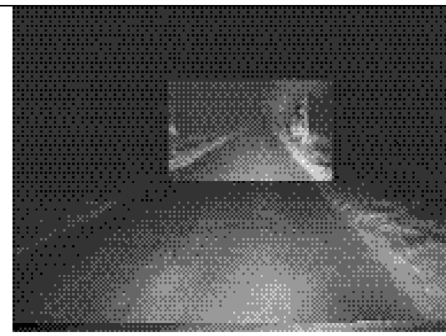
Shelley and McCaughran (2001) - A driver's night vision enhancement system to improve UK military logistics performance

Shelley and McCaughran (2001) report on an evaluation of a commercial night vision system (DVAN) installed on military vehicles. The DVAN, produced by Visteon and THALES and installed on a number of technology demonstrator vehicles based upon S-Type Jaguar sedans, uses active NIR sources to illuminate the road scene ahead. A compact NIR CCD sensor, mounted just above the driver's head, captures the NIR image. The image is processed and projected onto a combiner that is mounted on the line-of-sight of the driver. The image is focused at about 2 m in front of the driver's eyes.

DVAN installed in an S-type Jaguar

Projector and combiner

Military-installed DVAN



Sample image as viewed by the driver on a straight dark road

The operational context of using VES in the military is discussed. The military environment for combat support vehicles is diverse. Several scenarios should be considered when testing for military use. First, operating a single vehicle poses different requirements on the driver than operating a vehicle as part of a convoy. Second, the activities undertaken in peacetime are different than those under low intensity operations or war fighting.

Over a period of three consecutive nights, military drivers drove a Bedford TM 8-ton truck with DVAN installed. They concluded the following:

- The users reported that the use of the HUD was preferable to using NVGs. It was considered to cause less eye fatigue and provide more eye relief distance.
- The limited FOV was the main drawback of the system. The driver needs to see both edges of the road, the ground close to the vehicle, and the ground far in front of the vehicle to enable planning.
- Due to physical limitations in the prototype setting, soldiers of only specific heights could use the system. The required vertical range of eye height was estimated at 200 mm.
- Ambient illumination. The issue of illumination in the cabin resulting from luminance from the displays is a concern if stealthy operation using only convoy lighting is to be maintained. The current design of the DVAN allows control of the luminance reflected onto the driver's face. The projection system points down to the ground to the front off-side of the vehicle, minimizing luminance.

VES (GENERAL DISCUSSION)

Hahn (1994) - Vision enhancement: concepts for the future?

Hahn (1994) presents the state-of-the-art in vision enhancement technology and discusses experience from the European PROMOTHEUS program.

IRIMIS results suggest that IR imaging sensors are well suited for night driving but not very useful for rain or snowfall because of reflection from wet surfaces. In haze and fog conditions, only limited cases (heavy fog) provide a larger visible spectral range than unaided viewing. FIR is far better than MIR.

Contact-analog HUD limitations

1. Curvilinearity of the windshield might distort the view.
2. Possible mismatch of direct view and IR imaging can be distracting and cause misinterpretations.
3. Different vibration characteristics of the camera and the driver can increase mismatch.
4. A superimposed image can decrease the contrast of direct view by 10-20%.
5. IR images look different than direct view and might not be interpreted correctly. Training and driver knowledge should be studied.

Head-down display (HDD)

1. Requires looking away from the road.
2. Additional information has to be displayed on the HDD to improve spatial orientation.
3. Size considerations limit the available FOV or restrict the magnification of the image.

Risk compensation

Traffic with mixed technologies (some with and some without VES capabilities) is an important issue to be considered.

Kiefer (1995) - Human factors issues surrounding an automotive vision enhancement system

Kiefer (1995) provides a technological primer for automotive VES, reviews the relevant automotive and military human factors literature, highlights a few general human factors issues, and discusses accident data to show the need for VES. His literature review overlaps some of the references in this report.

Introduction

1. Properties of VES and choice of FIR over NIR are discussed.
2. Objects that appear during direct viewing might not appear with FIR (if there is no heat contrast between target and background).
3. Objects might appear on the display but look different with FIR (references given).

4. Contact analog (HUD) is the preferred option.
5. Need a minimal level of misalignment between the VES image and the objects at various distances.
6. Need to consider head movements.
7. Need an acceptable level of binocular disparity between the display and forward scene.
8. There is a technological limitation of HFOV (currently 15 degrees).
9. Inset display (HUD or HDD)
10. Location of HUD needs to be as close as possible to the line of sight to increase the speed and probability of detection of critical events.

Literature review

A comprehensive literature review is given. Among the cited papers: Foyle et al., 1990; Foyle and Kaiser, 1991; Ward et al., 1994; Ward et al. 1994b; Nilsson and Alm, 1994; Padmos and van Erp, 1994.

General HF issues

- The primary benefit of VES is to improve detection of critical, commonly-encountered real-world driving information such as pedestrians and curves ahead.
- Do the benefits of VES in dynamic driving outweigh the potential costs?
- A potential cost of VES is decreased attention to events outside the FOV of the VES.
- Other issues:
    - HUD-contact analog vs. inset HUD vs. HDD
    - Effect on driving while using the VES and effect while not using it

Crash data to support the need for VES

The ratio between night accidents and day accidents varies from 3.1 to 12.4.
Since rural roads are more poorly illuminated, they were analyzed further. Pedestrian accidents were affected by time of day much more than run-off-road accidents.

Table 9. Night - day ratios of crashes on rural roads

	Interstate	Arterial	Local roadway
Pedestrian crash types	10.3:1	11.8:1	7.5:1
Run-off-road	3.1:1	5.6:1	7.7:1

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Lunenfeld and Stephens (1991) - Human factors considerations in the development of an IVHS system: night vision enhancement

Lunenfeld and Stephens (1991) estimate the benefits of VES technologies in accident prevention.

Summary of VES technologies

Potential safety benefits of VES:

1. Reduce night crashes
2. Improve driving in low visibility (fog, snow, heavy rain)
3. Estimated 20% reduction in night fatalities and accident potential (estimated 5900 lives saved)
4. Estimated $1.8 billion in nighttime delay cost.

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Parkes et al. (1995) - The potential of vision enhancement systems to improve driver safety

Parkes et al. (1995) provide an analysis of the potential of VES to improve driver safety and discuss the human factors issues that should be addressed.

The role of vision in driving

The literature regarding driving and vision is reviewed. A synthesis by Stapleton (1993) of work by McKnight and Adams (1970) highlights the crucial role vision plays in driving. Specifically, the need to steer based on visual input from the road and the need to avoid obstacles is highlighted.

The need for vision enhancement

A comparison of vehicle crashes at night versus day suggests how impaired drivers are at night. Since lighting all the roads is too costly to be considered a viable universal solution, alternative solutions are suggested. A false sense of confidence is gained from being able to steer the vehicle well, while the focal vision is likely to fail in detecting unexpected objects such as pedestrians.

The need for human factors input

- A false sense of confidence might change driving behavior to become riskier.
- If other traffic participants do not have VES (including pedestrians), their behavior and expectations may conflict with those of the VES users.
- Older drivers might be drawn to change their driving habits and drive more at night.
- VES that work well in the military may not be as successful with a more diverse population.
- Peripheral vision, which is important for driving, will have to be compromised by VES.
- Potential differences in system capabilities and reliability may arise.

The technological solutions

Active systems are the most straightforward solution but they have to be controlled to prevent causing glare to drivers of oncoming vehicles or to the driver in fog and rain conditions. Other ranges of the spectrum may be explored. UV light has been proven to reflect well from animals and pretreated objects, but there is concern that it is a health hazard. Passive systems such as IR are promising in this respect.

Sensor technology
Discussion of NIR and FIR solutions based on military applications.

Head-up displays
For civilian application, the display is not likely to be mounted on the driver's head like in the military applications (NVG, HMD). A display on the dashboard is ruled out because of eye movement and accommodation times. A contact analog HUD is suggested.

Optics
HUDs require a collimator to control the focal distance and a combiner to display the HUD information with the real world-information. Refraction (lenses), reflection (mirrors), or diffraction (holograms) are suggested as possible technologies.

Human factors concerns with the technology

General problems with head-up displays
Unwanted reflections, limited visible envelope, difficulty in fitting a range of eye positions, inducing awkward positions for prolonged periods.

Problem with thermal images
Difficulty of interpretation may lead to increased mental workload; image change over time in an unpredictable manner may reduce interpretability; some unique thermal signatures differ from the regular representation of the original object; thermal images require a lot of training; image luminance may mask or reduce the luminance contrast of any visible light that may be spotted through the HUD; high luminance may decrease retinal sensitivity to lower contrast objects in the periphery; judgment of gaps and TTC under thermal imagery have been shown to differ from normal.

Attentional issues with head-up displays
Cognitive capture has been shown to occur when using VES.

The effects on peripheral vision
Fixation on the HUD accompanied with high workload that decreases the frequency of visual scanning of the outside scene; the functional or effective FOV shrinks depending on the perceptual load of the task; tunnel vision (or cognitive tunneling) are likely to occur.

The way forward

Size, shape, and position of display
A full FOV would have been preferable but is currently impossible to implement with a HUD. Within practical limitations, the optimal size shape and position need to be

researched, taking into account differences in preference and performance among different drivers.

Focal distance of the virtual image
Assuming a full 3D display is not available, a fixed focal distance has to be chosen. A trade-off then occurs between the accommodation comfort (focal distance should be close to optical infinity) and scene mismatch (focal distance should not exceed the actual distance to the object viewed).

Partial enhancement
There is a potential for the real-world scene to be completely masked by the virtual image. Partial enhancement is offered as an alternative to present only the enhanced edges to the driver and allow a normal see-through view of the actual object.

Reduction of cognitive tunneling
Reduction of cognitive tunneling by decreasing the perceptual workload may be achieved by reducing the qualitative disparity between the virtual image and the real scene (e.g. by improving the image quality, color, and resolution).

Behavioral adaptation
Should users receive special training? Would objective and perceived risk change?

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Tijerina et al. (1995) - Examination of reduced visibility crashes and potential IVHS countermeasures

Tijerina et al. (1995) examined reduced visibility crashes and potential IVHS countermeasures. The paper gives an overview to the problem of reduced visibility crashes, assesses detailed crash cases, presents the various crash avoidance concepts, and presents mechanisms of reduced visibility. Finally, it discusses future research needs.

<u>Imaging vision enhancement systems</u>

VES require sensors (e.g., infrared, active or passive millimeter-wave radar imaging, CCD, illuminator for active systems, processor, and driver display). Image VES do not provide overt warning of obstacles to the driver; instead, they provide optical information that the driver needs for vehicle control and object detection.

<u>Why VES HUD is possibly the best candidate</u>

- Reference to Hahn's comment that in haze or fog VES is not useful, and that FIR is the best candidate for night use.
- Active millimeter-wave radar imaging (reference to Hughes, 1993 and Kippola and Stando, 1994) investigated by Ford require treatment of pavement markings with reflective material and cannot provide the same level of image resolution as that available in the visible or infrared range.

- Direct view CCDs are unlikely to work because of proneness to streaking and blooming from bright sources and reliance on good contrast transmission through the atmosphere.

VES HUD

VES image presentation may be provided on a HDD or HUD. Since HDD may increase driver workload, HUD is preferred.

- Nilsson and Alm (1991) - Drivers in the simulator chose higher travel speeds with the VES HUD. This may negate visibility benefits and increase danger of crashes in mixed traffic if some of the vehicles are driving at high speeds that would be unexpected by others driving under poor visibility without vision enhancement.
- Ward et al. (1994) - Field study with contact-analog HUD. Drivers drove more slowly and reported higher subjective workload when using the HUD. But the display was quite difficult to drive with due to the time delay in superimposing the infrared image with the real object and in the ghostly appearance of the IR images.

The difference between the two above studies might be attributed to the quality of the system (ideal vs. poor). Results from Bossi, Ward, and Parkes in the simulator suggest that HUD for VES may capture driver visual attention to objects outside the eye box.

Reference to Hahn's comments about HF issues: mismatch, vibration, misinterpretation of visual info, reduction of contrast of direct view, images look different, training required.

Research Needs

- What are the types of visual information used to control a vehicle (optical flow, looming, contrast, and object visual size) and how are they affected by VES?
- Assess secondary consequences of using VES systems, such as the effects on other drivers.
- Workload and distraction (specifically with HDD) need further study.
- Interface design for driver performance, acceptance, and system reliability. Time delays, system failure analysis.
- Determine necessary and sufficient design parameters for in-vehicle imaging displays in terms of resolution, size, FOV, range, and on-screen target size.
- More about the effects of using a contact analog HUD on speed, peripheral detection, and workload.
- Related to crash analysis: More data, more analysis, more stratification.
- Related to visibility model: Based on Blackwell's threshold contrast research and PCDETECT model, enhance the model to assess the seeing distance based on light, weather, age, surprise, target shape, size, etc.

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VES (EXPERIMENTS)

Barham (2001) - The effect of an infrared vision support system on driver behaviour

Barham (2001) tested the effect of an FIR vision enhancement system on headway keeping.

Method

Twenty-four subjects (age unreported) drove a simulator with and without vision enhancement (a mockup of the DARWIN, an image projected above the dashboard). Their driving performance and subjective preference were recorded.

Independent variables

VES (2): with VES and without VES

Dependent variables

Mean headway
Number of collisions with lead vehicle
Number of lane departures
Subjective evaluation

Findings

- The mean headway was increased by 30% when the DARWIN system was used. Of five collisions recorded when the lead vehicle braked unexpectedly, four occurred when driving without vision enhancement.
- Most subjects used the brake less often when the DARWIN system was used. In a simulated emergency situation, the mean braking force was 77% with the DARWIN and 86% without it.
- Lane departures decreased from 143 without the system to 106 with the system.
- Subjects' views on system usefulness and safety were invariably positive.

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Barham et al. (1998) - Evaluation of the human factors implications of Jaguar's first prototype near infrared night vision system

Barham et al. (1998) tested the ability to perceive depth and estimate absolute distance on a prototype near IR night vision system taken from a military aircraft application and installed on a Jaguar.

Method

Forty-three subjects (four age groups, unspecified but assumed to include a wide range)
Airfield runway (tasks 1-4), suburban street (task 5), and perimeter track (task 6)
Military NIR VES installed on a Jaguar

Findings (by task)

Task 1: Perceiving which of three poles is closest (two poles at 44 m and one at 42 m)
More correct responses were made when the leftmost pole was the nearest. This observed predominance was much less marked when the VES was in use (possibly due to a flattening effect).

Task 2: Choosing a closest pole while driving (48 m, 50 m, 52 m)
There was no difference in subjects' performance on this test with and without the VES, implying that there were no significant difficulties with perceiving depth with the VES in this context.

Task 3: Estimating absolute distance without distance markers (30, 45, 50, 55 m)
At 30 m, estimates were fairly accurate (31 m). At all other distances, there was an overestimation of the distance but less so with the VES (50 m, 67.7 m, 54 m).

Task 4: Estimating absolute distance with distance markers (poles at: 30, 45, 50, 55 m; cones at 25, 50, 75 m)
At 30 m estimates were fairly accurate. At other distances there was a slight underestimate with the VES and a slight overestimate without it. The farthest distance was overestimated both with and without the VES, but more so without it.

Task 5: Detecting a pedestrian in a cluttered, dimly lit, environment
The use of VES substantially increased the distance over which the pedestrian was first detected from 61 to 95 m. Four subjects (three over 74 years old) detected the pedestrian without the system under 30 m and with the system over 100 m.

Task 6: Detecting road-side objects in an unlit environment on a 1100 m stretch of the perimeter track
The adult dummy detection increased from 24 to 63 m. The child dummy detection increased from 19 to 47 m. Road signs were not detected earlier with the system.

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Best et al. (1998) and Piccione et al. (1997) - Evaluating thermal and image intensification night vision devices for the ground environment: human factors and usability issues

Best et al. (1998) and Piccione et al. (1997) reported a set of five experiments that compared off-road performance using the DVE thermal imaging system to that with NVG. They specifically looked at the detection of drop-offs and the change in glance behavior when expecting drop-offs.

Introduction

A description of night vision goggles (AN/PVS-7B) and driver's vision enhancer (AN/VAS-5) is given. Reference to Army publications that stress the involvement of drop-offs and ditches in night vision related accidents. Fifty-seven percent of accidents involved drop-offs (sudden changes in elevation of 1 m or more) or ditches (sudden changes in elevation of less than 1 m), and 11% involved collisions with the rear of another vehicle.

Experiment 1 (Piccione, et al., 1997): Driving performance and object detection with NVG and DVE (Also reported in Piccione and Ferret, 1998)

Method

10 military police soldiers
Four driving courses

Independent variables

Sensor type (2): NVG and DVE

Dependent variables

Target detection
Elicited driving errors
Driving speed

Findings

- DVE had an advantage when smoke was present and when illumination was low.
- DVE was better for detecting vehicles, personnel, and obstacles.
- No difference was found in elicited driving errors.
- NVG had an advantage under high illumination conditions.
- NVG allowed for faster driving with greater confidence.

Experiment 2 (Collins et al., 1998a): Drop-off detection with NVG and DVE

Method

Nine soldiers driving at extremely slow speed (2-3 mph)
Three drop-off sites (subject familiar with the location)

Independent variables

Sensor type (2): NVG, DVE

Dependent variables

Detection time

Findings

- No difference was found between NVG and DVE in detecting a known drop-off.

Experiment 3 (Collins et al., 1998b): Driver visual behavior when searching for a drop-off with DVE

Method

Four drivers
Eye tracker
Task: Detect a drop-off using the DVE system while driving off-road

Independent variables

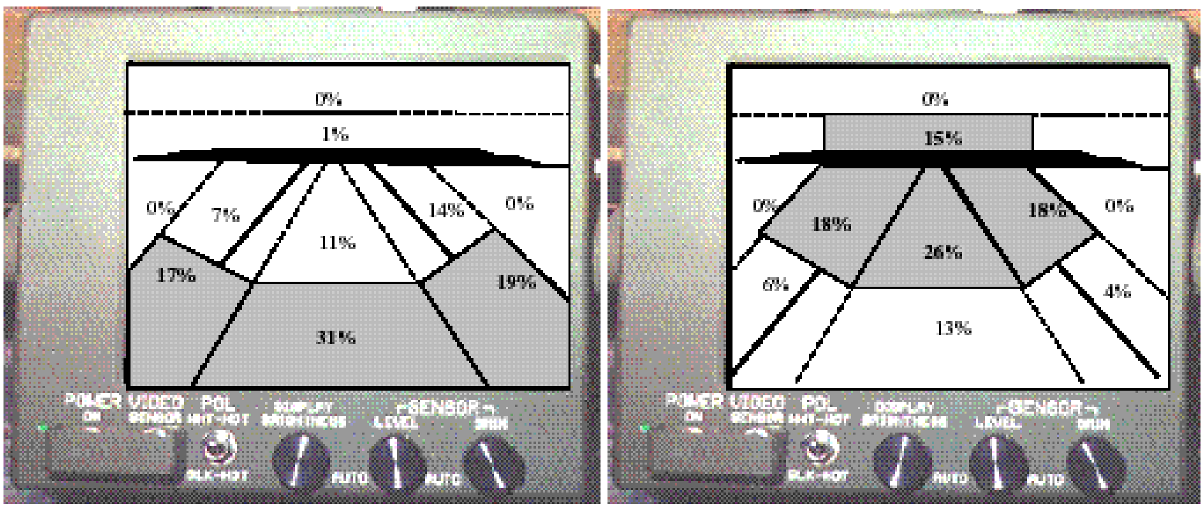
Drop-off (2): drop-off present and drop-off absent

Dependent variables

Distribution of view time of certain zones on the display
Detection distance

Findings

- Drivers spend the majority of their visual search time looking at the center two-thirds of the display. When searching for a drop-off, there is a shift towards the horizon, but when not searching, the fixations are at the near field (bottom third of the display).
- Implication for training: Scan the display and include the far field near the horizon.



. DVE field-of-view divided into areas showing percentage of time used during continuous driving on roads (left) versus driving in the vicinity of a drop-off (right).

The main cues used for detection of drop-offs were occlusion, shading, and motion parallax.

Experiment 4 (Ruffner et al., 1998): The effect of nonuniform and nonresponsive pixels in the DVE on target detection

The number of pixels in the sensor or in the display that are inactive or nonresponsive (NR) is limited by specifications. Similarly, nonuniformity of luminance that is caused by pixels in the sensor or the display (NU) may disqualify a device from use. The goal of this experiment was to determine if there might be a degradation in driver performance resulting from a relaxation of the specifications for nonresponsiveness and nonuniformity of DVEs.

Method

Four 20-minute courses were recorded with a real DVE installed on a Bradley and driven at 15 mph. They were played back to eight soldiers, who had to verbalize detection of objects on the screen.

Independent variables

Four display conditions were generated:
Baseline: NU of 5% small area and NU of 15% large area
Low NU: ±15% luminance distribution over the entire display
High NU: ±33% luminance distribution over the entire display
NR: 65 NR pixels for the 640x480 display

Dependent variables

Response time
Percent correct
Subjective preference

Findings

- No statistically significant differences were found in percent of objects identified or response times between the four DVE display conditions.
- The response times were slightly lower for the NU conditions than for the baseline or the NR conditions.
- Subjects did not show large preference differences between the devices although the NU cases were less preferred.

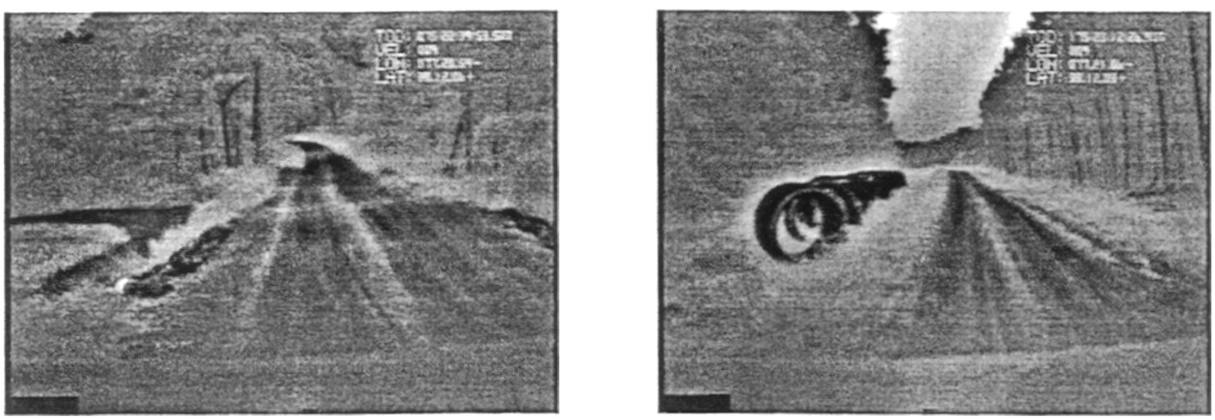
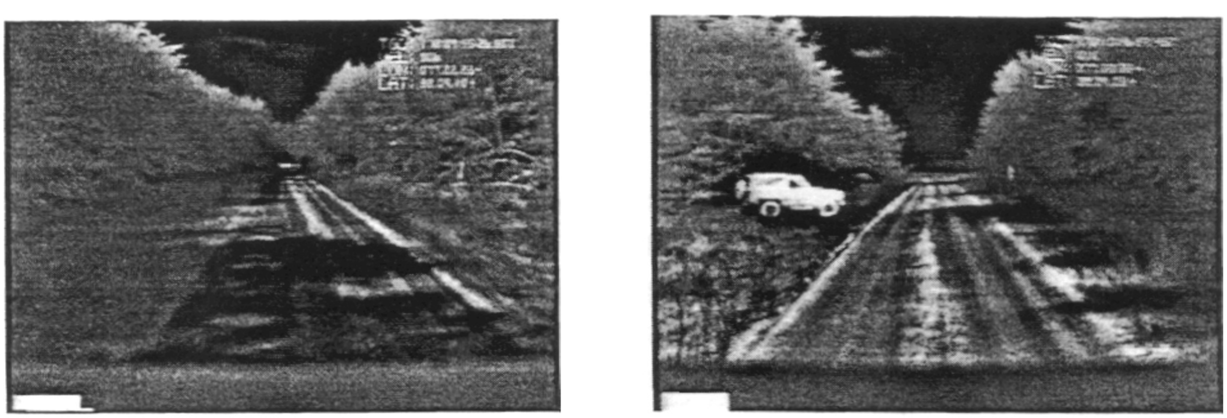


Figure 3. Example of DVE screen image from Scenario 1 (left panel) and Scenario 2 (right panel). Scenario 1 and Scenario 2 were filmed at night.



Note: Experiment 5 compared symbology options to be placed on the DVE and is not discussed here.

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Blanco et al. (2001a, 2001b) - Evaluating new technologies to enhance night vision by looking at detection and recognition distances of non-motorists and objects

Blanco et al. (2001, see also Blanco, Hankey, Binder, and Dingus, 2001) reported a two-part project in progress in which they performed a descriptive epidemiology study to demonstrate the higher fatality rate during nighttime, specifically for pedestrians. The empirical part tested 12 vision enhancement systems for detection distance, recognition distance, subjective rating and glare evaluation.

<u>Method</u>

Thirty subjects (10 ages18-25; 10 ages 40-50; 10 over 65) drove cars equipped with several different lights on a test track with obstacles at an instructed speed of 25 mph.

<u>Independent variables</u>

Age (three age groups)
Lighting settings (12 combinations):

(1) Halogen Low Beam [HLB]
(2) Hybrid UV-A together with Halogen Low Beam [Hybrid UV-A + HLB]
(3) Medium UV-A output together with Halogen Low Beam [Mid UV-A + HLB]
(4) Higher UV-A output together with Halogen Low Beam [High UV-A + HLB]
(5) Halogen Low Beam at a lower profile [HLB-LP]
(6) Halogen High Beam [HHB]
(7) High Intensity Discharge [HID]
(8) Hybrid UV-A together with High Intensity Discharge [Hybrid UV-A + HID]
(9) Medium UV-A output together with High Intensity Discharge [Mid UV-A + HID]
(10) Higher UV-A output together with High Intensity Discharge [High UV-A+ HID]
(11) High Output Halogen [HOH]
(12)Infrared Thermal Imaging System [IR-TIS]

Type of obstacle to be detected (nine combinations):

(1) White static pedestrian
(2) White perpendicular pedestrian
(3) White cyclist
(4) White parallel pedestrian
(5) Black cyclist
(6) Kid's bike
(7) Black perpendicular pedestrian
(8) Black parallel pedestrian
(9) Tire tread

Dependent variables

Detection distance
Recognition distance

Findings

- Young drivers detected and recognized objects 30 m before older drivers (185 vs. 155 m for detection; 155 vs. 130 m for recognition).
- The IR thermal imaging system allowed drivers to detect objects sooner than the other lamps (210 m). The recognition time, however, was not significantly better.
- Detection and recognition ranges varied a lot depending on which object was viewed. White colored clothing was detected around 250 m while black was detected around 100 m. A black tire thread was detected only 64 m in advance. Whether the object was moving did not affect the results significantly.
- With the IR TIS, detection of most objects was around 250 m. Interestingly, pedestrians with black clothing were detected later (200 m) than white objects. Tire treads and kids' bikes were detected later than with just normal headlamps.

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Bossi et al (1997) - The effect of vision enhancement systems on driver peripheral visual performance

Bossi et al. (1997) discuss VES technology in general, with many references to basic research done in this field. They describe an experiment that tested peripheral detection in a simulator.

Introduction

Comprehensive discussion of VES technology with many references to basic research.

Method

Thirteen subjects (ages 24-39)

Lab study using a simple part-task driving simulator 50 x 33 degrees
Simulated HUD on top of the screen 15 x 10 degrees
Landolt C's superimposed onto the video images at several eccentricities

Independent variables

Illumination (2): Night and dusk (edited from a daytime video)
VES (2): Unaided and aided
Eccentricity of target location (8)

Dependent variables

Detection rate

Findings

- At night, the presence of VES degraded peripheral target detection and identification performance. The difference was largest close to the HUD. There was no VES degradation at dusk.
- Target detection decreased with increasing target eccentricity regardless of VES or illumination.
- Target detection was better at dusk than at night.
- The difference between dusk and night was more evident in the outer positions.

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Hollnagel et al. (2001) - They drive at night - can visual enhancement systems keep the driver in control?

Hollnagel et al. (2001) reported a simulator study in which they tested the effect of a vision enhancement system with two levels of field of view and two levels of brightness-contrast on the quality of driving performance.

Method

43 drivers (age unreported) drove a wide view (115 degrees) simulator on rural roads with no traffic. A VES image with a new set of textures, adjusted to provide a monochromatic IR-like image, was superimposed on the road scene. Every 10-20 minutes there was an obstacle on the road (pedestrian, moose, car parked with person standing outside), to which subjects had to respond.

Independent variables

Variables were between subjects

Display (2):	With VES and without VES
HFOV (2):	12 degrees and 18 degrees
Brightness-contrast (2):	Low (the enhanced image includes humans, animals, and warm parts of vehicles but no surroundings) and high (the enhanced image includes everything from the original road scene, inverted to grayscale).

Dependent variables

Quality of driving performance (based on reaction time to perceived obstacles, changes in vehicle speed, variation in speed, steering wheel position, accelerator and brake pedal position, and lateral position of the vehicle)
Subjective evaluation

Findings

Findings have not yet been reported. The hypotheses were:

- Use of VES during night driving enhances the quality of driving.
- A wide angle display yields better driving performance than a narrow angle display.
- A high intensity display yields better driving performance than a low intensity display.

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Gish, Staplin, and Perel (1999) - Human factors issues related to use of vision enhancement systems

Gish, Staplin, and Perel (1999) describe a test track study comparing detection of different targets using a mock-up VES with NIR sensitivity.

Method

Eight subjects – four ages 26-36, four ages 56-70
A mock-up VES with a head-down display and HFOV of 6 degrees. The NIR camera provided monochrome images. Four targets w/NIR transmitting gelatin were used.

Independent variables

Age (2):	Young and old
Display (2):	Unaided and aided (also compared to predicted optimal performance)
Target (4):	Deer, pedestrian, gray square, and grating
Glare (2):	Present and absent
Location (2):	Left and right
Task (2):	Navigation and speed monitoring

Dependent variable

Detection distance

Findings

- Young subjects benefited from the VES. Detection increased from 300 to 400 ft for small targets and from 400 to 600 ft for large targets.
- Older subjects did not benefit from the VES. Most of the older drivers (55-70 yrs) did not take advantage of the target contrast presented on the mockup VES. They did not use the display, only used it to detect curves, or used it but were uncomfortable with it. The added workload and risks associated with scanning down to the in-vehicle display were unacceptable to the older drivers.
- On average, VES detection occurred 150 ft after the target appeared on the VES.
- Detection in the presence of glare was the same for aided and unaided vision.

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Meitzler et al. (2000) - Noise and contrast comparison of visual and infrared images of hazards as seen inside an automobile

Meitzler et al. (2000) examined detection of potential road hazards on a projected screen with VES at varying combinations of contrast and noise.

Method

Twenty subjects (10 per display type, age unspecified) viewed a display with simulated driving (viewing only, no steering) on two displays of 40 x 30 degrees.
Five target types: cinder block on the road, lane closed sign, pedestrian crossing, bicyclist, and tire

Independent variables

System (3): Aided black hot, aided white hot, and unaided video clips
Fog (2): With fog and without fog
Noise in image (2): With noise and without noise
Display (size, distance, and type but constant FOV) (2):
PC monitor and wrap-around screen - between subjects

Dependent variables

Response time from target detection to depressing the brake

Findings

- Black-hot was best, then white hot, and then normal B&W view.
- Display type did not affect response time suggesting that the task was foveal and therefore the wide screen did not help.
- Detection times in fog were worse than no fog.
- Detection times under a noisy image were worse than without noise.
- Moving objects were more likely to be detected than static ones.

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Nilsson and Alm (1996) - Effects of a vision enhancement system on drivers' ability to drive safely in fog

Nilsson and Alm (1996) studied the changes in driving performance when using a simulated VES in a driving simulator.

Method

Twenty-four subjects (ages 23-46)
Moving base simulator HFOV=120 degrees
Targets: Red square 400 m ahead, standing van 400 m ahead, oncoming traffic.
VES - clear video 17x12 cm 140 cm straight ahead

Independent variables

Visibility (3): Clear - 480 m, fog - 50 m, fog + VES - 50 m (between subjects)

Dependent variables

Driving performance: Speed (M, SD) and lateral position (M, SD)
Braking RT and distance; subjective load: NASA TLX

Findings

- Speed in fog was higher with VES than without VES but less than in normal driving.
- Use of VES when driving in fog resulted in greater lateral position variance and no difference in workload level.
- In all conditions, there was no difference in speed variance.
- In fog, subjects drove closer to the centerline.
- Variance in lateral position was highest in fog + VES and least in fog.
- NASA TLX ratings were higher for fog and lowest for the control.

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O'Kane (1996) - Driving with indirect viewing sensors: understanding the visual perception issues

O'Kane (1996) discusses limitations of visual perception at night and touches upon the costs and benefits of using thermal devices for night driving.
Distance visibility of daytime, standard headlights, and a thermal image were compared (see Figure 2 below). No quantitative findings were reported.

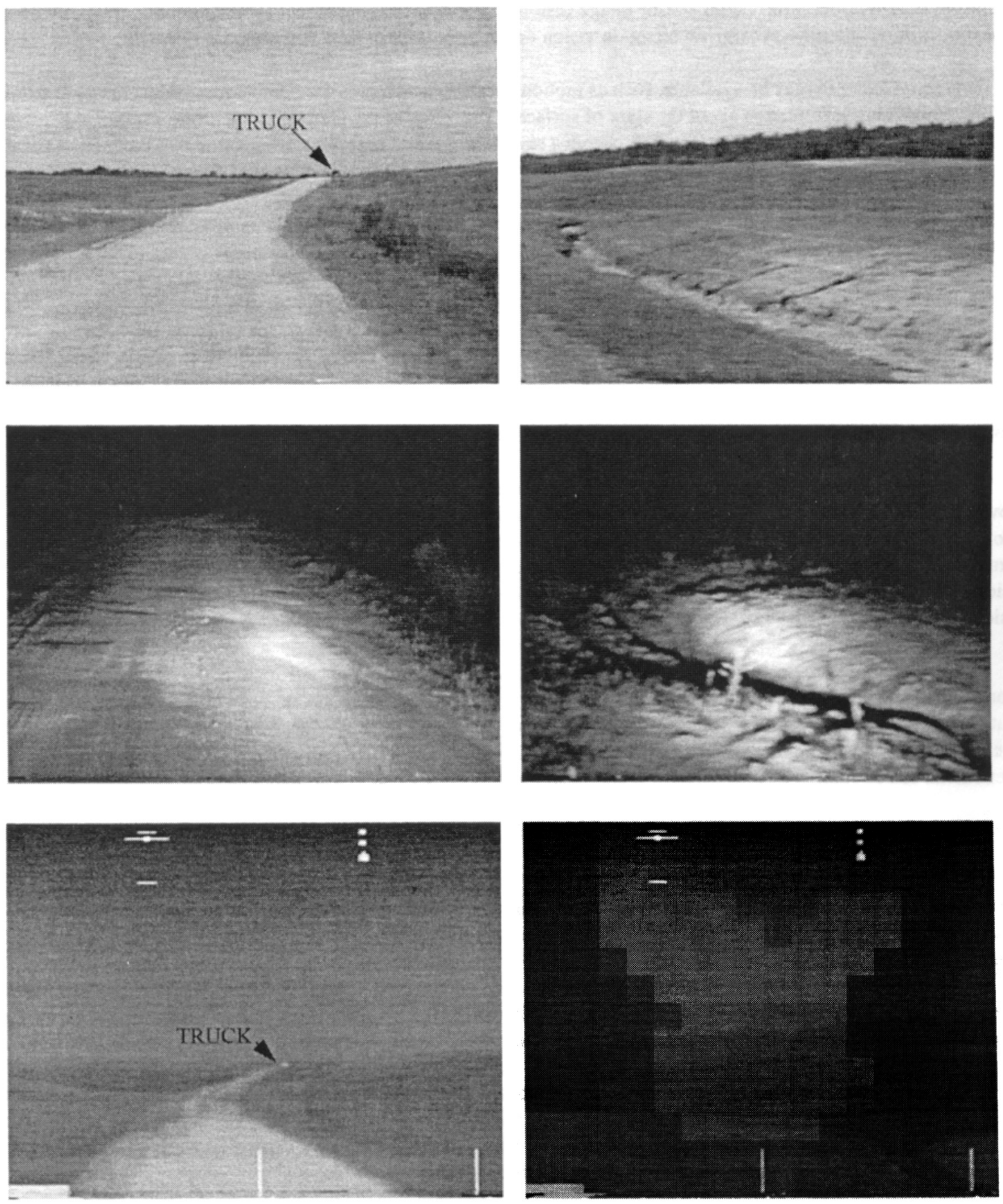

Figure 2. Distance visibility comparison for distance viewing (left) of "disabled" truck in the roadway and close viewing (right) of a ditch along the side of the road. Day (top), headlights (middle) and thermal (bottom) are shown for comparison.

Oxley et al. (1994) - The Jaguar night vision trials. A report on the use of an infrared based vision system by a sample of elderly drivers

Oxley et al. (1994) tested the first prototype of the Jaguar night vision system. (From abstract. For other studies in this series, see Staahl et al., 1995 and Barham et al., 1998 and 1999.)

Abstract

Fifteen volunteers aged between 65 to 80 participated. The purpose of the study was to gain early insights into key issues related to night-time imaging in an automotive context and to assess the extent to which such technology might help elderly drivers drive in conditions of reduced visibility.

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Staahl et al. (1995) - The use of vision enhancements to assist elderly drivers

Staahl et al. (1995) describe two vision enhancement experiments. The first experiment is an evaluation of the Volvo UV light system (since UV light solutions are out of the scope of this report this part is not summarized herein). The second experiment is the first part of the Jaguar NIR night vision system also reported by Oxley et al. (1994) and Barham et al. (1998 and 1999).

Method

Fifteen subjects (11 men and four women) aged 65-80 participated. They drove on a test track with the first prototype of the Jaguar NIR vision enhancement system. FOV was 12.8 x 17.6 degrees (horizontal x vertical) and could be extended to 22 x 17.6 degrees if the driver leaned forward. Their task was to call out an object by its name as soon as they saw it (detected and recognized what it was).

Independent variables

VES (2): With VES and without VES.
Detection object (6): Live pedestrian, adult dummy, child dummy, two road signs, a set of traffic cones

Dependent variables

Relative recognition distance (distance with VES minus distance without it)
Subjective evaluation

Findings

- All but two of the subjects registered increases in the distance at which they first saw the dummies, ranging from +12.5 to +112.5 m. Half of the subjects saw the cones earlier (by 12.5 to 87.5 m), but for five subjects there was no difference and two subjects saw the cones later.
- Detection distances of the road signs were not significantly different with and without VES. It is noted by the authors that the task was to recognize the road sign, not just detect it, which may explain why the NIR system did not help in some cases.

- Detection of a pedestrian at 100 m in front of the car (presumably while not driving) showed a modest improvement between the VES and the main headlamps. Without VES only 11 subjects saw the pedestrian, but with VES 13 subjects saw the pedestrian. When just using dipped lights, none of the subjects could see the pedestrian.
- The system was rated as very easy to drive with (8.2/10), very easy to interpret the enhanced view (7.8/10), and easy to adjust the brightness and contrast (8.4/10). Overall ease of use was rated 7.7/10 and comfort was rated 7.6/10, mainly due to two subjects who did not like the narrow field of view of the system.
- All 15 subjects said they felt safe with the system. Thirteen of them said they would use the system if it were installed in their vehicle.

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Stanton and Pinto (2000) - Behavioural compensation by drivers of a simulator when using a vision enhancement system

Stanton and Pinto (2000) describe a driving simulator study using simulated VES to measure the trade-off between visibility and speed.

Introduction

Levels of automation:
- Dichotomy of systems - Those that replace the driver and those that support the driver.
- Risk homeostasis theory - Behavioral adjustments to control risk

Method

Eleven subjects (21 years old) drove a simulator with a simulated on-screen VES

Independent variables

Driving conditions (6): day, night, night+VE, day+fog, day+fog+VE, day+fog+VE failure

Dependent variables

Speed
Number of overtakes

Findings

- VE allows higher speed.
- Speed behavior changed after a VE failure occurred. Before the failure. speed was similar to daytime driving, while after the failure it was more like day+fog.

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Ward, Stapleton, and Parkes (1994a) - Behavioural and cognitive impact of night-time driving with HUD contact analogue infra-red imaging

Ward, Stapleton, and Parkes (1994a) present a field evaluation of a prototype NIR VES using a contact analog HUD.

<u>Method</u>

Five subjects (mean age 26)
Field study on 1 km of a rural roadway (including straight and curve)
Prototype VES contact analog HUD; monochromatic green; HFOV 13 degrees; 5 m focal distance.
Three pedestrian silhouettes

<u>Independent Variables</u>

VES (2): Unaided and aided
System failure simulation

<u>Dependent variables</u>

NASA TLX-R
Target detection time
Overall speed (M, SD)

<u>Findings</u>

- No significant difference in target detection time with and without VES.
- Slower overall speed for VES (55.5 vs. 61.5 km/h).
- Speed increased by 6 km/h during trials in both VES and non-VES.
- Speed variation was higher with VES.

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Ward, Stapleton, and Parkes (1994b) - Night-time gap acceptance and time-to-coincidence judgements based on visible wavelength and infra-red imaging

Ward, Stapleton, and Parkes (1994b) examine night -time gap acceptance and time-to-coincidence judgements with a video recording of VES.

<u>Method</u>

Sixteen subjects (eight ages 20-25, eight ages 55-70)
Simulated scenarios (view video), 38 degrees HFOV
Far infrared thermal camera 8-13 micron and a visible light video camera

<u>Independent variables</u>

Scenario A.

Age (2):	Young and old
Camera image (2):	Visible light and FIR black hot
Speed (2):	20 and 40 mph
Gap size between obstacles (5):	+200, +100, 0, -100, and -200 mm

Scenario B.

Age (2):	Young and old
Camera image (4):	Visible light, FIR black hot, visible light (matched for white hot), and FIR white hot
Speed (3):	20, 30, 40 mph
Time occluded before impact (3):	1, 2, 3 s

Dependent variables

Scenario A. The number of correct gap acceptances and correct gap rejections, response time
Scenario B. Estimated TTC, accuracy

Findings

- Black-hot FIR promoted a greater number of correct rejections (gap is too narrow to pass) but fewer correct gap acceptances (gap is wide enough to pass through) than visible light camera image.
- Correct decisions on gap size were made sooner with the FIR camera (5.2 s before impact) than with the visible light camera (1.9 s).
- The superiority of the FIR was most predominant at the extreme gap sizes.
- TTC was typically underestimated (consistent with earlier findings).
- Subjects were comparably accurate in estimating TTC in the black-hot setting and the visible matched scenes but less accurate in the white-hot setting than the visible matched scenes.
- TTC judgements were more accurate at higher speeds.
- TTC judgements were more accurate for shorter occlusion periods.

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NVG

Biberman and Alluisi (1992) - Pilot errors involving head-up displays (HUDs), helmet-mounted displays (HMDs), and night vision goggles (NVGs)

Biberman and Alluisi (1992) conducted a review of the difficulties associated with night vision and display equipment in helicopters and fixed-wing aircraft.

Summary

The report begins with a review of research on HUD- and HMD-related problems including misaccommodation, field of view limitation, convergent versus divergent fields of view, divided attention, misperception, and spatial disorientation.

Operational problems associated with the use of NVG, HUD, and HMD are then described. A categorization of reasons for crew errors when using NVG may provide some insight to the context of driving with NVG. The seven categories of crew errors are shown below with the frequency of occurrence:

1. Improper scanning [36%]. Too much time looking inside the cockpit and scanning patterns of the outside scene that are not thorough.
2. Inaccurate estimation [8%]. Distance between objects and rate of closure with objects are likely to be estimated inaccurately.
3. Low detection rate [2%]. Not identifying obstacles and not recognizing other hazardous conditions.
4. Improper identification of an emergency situation [4%]
5. Failure in crew coordination [27%]
6. Failure to maintain or recover orientation [23%]
7. Failure to choose appropriate flight options for known conditions prior to the flight and during the flight [32%]

Additional issues discussed:

1. There is a wide variation in skills, even among the most highly experienced NVG pilots.
2. NVG maintenance and calibration are not trivial and it is almost impossible for users to assess the adequacy of a specific NVG set without very well controlled procedures. For example, in a comparison of a formal test-lane procedure with the "usual method of adjustment" performed by various users, the percent of devices with visual resolution of 20/45 or better was 60% with the formal test-lane versus 28% without it. Moreover, most subjects could not judge the adequacy of their visual acuity even when it was worse than 20/100.

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CuQlock-Knopp et al. (1995, 1996) - Human off-road mobility, preference, and target-detection performance with monocular, bi-ocular, and binocular night vision goggles

CuQlock-Knopp et al. (1995, 1996) compared performance of soldiers navigating on foot using monocular, bi-ocular, and binocular goggles. The 1996 study was a follow-up study that concentrated on scanning for targets while navigating.

<u>Method</u>

Thirty five national guardsmen (ages 19 to 54), and 36 national guardsmen (ages 24-54) in the second study, walked through three 1-km courses in the woods with a variety of terrain hazards to foot travel such as drop-offs, berms, and ditches.
Two human targets in each course, three silhouette figures

<u>Independent variables</u>

Type of goggles (3):	Binocular AN/PVS-6 ANVIS, bi-ocular AN/PVS-7B, and monocular ANVIS with one eye removed
Visibility (2):	No moon and three-quarter moon

Dependent variables

Eight types of errors: contact with hazard (at eye level, ground level, or a terrain contour), marked decrease in walking pace, request for assistance, stop, stumble, or other
Course traversal time
Ratings of seven items: warnings afforded by the NVG, ability to detect targets, confidence, comfort, and general feeling
Rankings in six dimensions: depth perception, comfort level, target detection, hazard detection, environmental awareness, and overall choice
Number of steps to complete the course
Number of detected targets in each course

Findings

- The binocular goggles yielded better performance (participants moved 10% faster and made 40% fewer errors) and were preferred to the other two types of goggles.
- The monocular goggle showed no consistent difference from the bi-ocular goggle for any of the measures.
- Moon illumination did not affect the ordering of the goggles on the dependent measures.
- In the second study (CuQlock-Knopp et al., 1996), it was thought that the addition of a target-detection task would give relative advantage to the monocular because the free eye could be used, thus changing the relative ordering of the monocular goggle versus the bi-ocular or binocular, but this did not happen.

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Gawron and Priest (2001) - Night vision goggles lessons learned

Gawron and Priest (2001) describe human factors topics related to the use of NVG in aviation and in general and provide some basic reference to related vision questions.

Basic vision

Peripheral target recognition and visual field are narrowed in high workload conditions.

Characteristics of two generations of NVG

	Generation II	Generation III
MTBF	2000 hours	7500 hours
System gain	800	2000
Signal to noise ratio	4.5	16.5
Resolution	25 linepairs/mm	36 linepairs/mm
Peak performance wavelength	<700 nm	>700 nm thus effectively exploiting the characteristics of typical night sky radiation
Interference from cockpit	Exists	Is minimized <625 nm is filtered out thus making green-blue cockpit light effectively invisible to the system

Perceptual problems:
- Narrow field of view (40 vs. 200 degrees of unaided vision)
- Reduced visual acuity (20/40 at best)
- Objects appear closer with NVG

Other Limitations
- Eye relief must be sufficient to allow the user to look under the tubes to view the cockpit and in some cases wear corrective glasses.
- Weight causes imbalance and fatigue.

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Hudson (1986) - Driving at night in armoured fighting vehicles

Hudson (1986) discusses design aspects for development of NVG for night driving.

Design considerations for NVG in night driving

1. Large range of temperatures (-40 °C to +55 °C)
2. No risk of facial injury when driving over rough terrain
3. Comfortable to use for periods of up to 12 hours
4. Minimize controls
5. Magnification has to be unity (based on "common sense")
6. Limited FOV requires special attention
7. Low resolution is problematic in detecting obstacles and reading signs
8. Focal distance is normally 20-30 m. Objects at 300 m are still in focus
9. Eye relief is large (about 100 mm) so that glasses or gas masks can be worn
10. Exit pupils are large (about 100 mm) so that the driver can move their head significantly without losing the image
11. Monochromatic image due to technical limitations
12. Optimal decay time of phosphor is a function of reducing the smudging of moving objects while maximizing the dynamic range of the image
13. Monocular goggles prevent stereoscopic vision

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Rabin (1996) - Image contrast and visual acuity through night vision goggles

Rabin (1996) examined the effects of display contrast and luminance on visual resolution when viewing through simulated NVG.

Method

Four young subjects viewed computer-generated letter charts in a laboratory setting simulating NVG. Visual acuity was measured across a wide range of luminance and contrast levels. Viewing distance was 2.7 m.

Independent variables

Luminance (14): From 0.006 to 46.2 fL in 0.3 log unit steps (about 2x steps)
Contrast level (6): (At a constant luminance level of 0.2 fL) ranging from 4.8 to 71.3% in about 1.8x steps.

Dependent variables

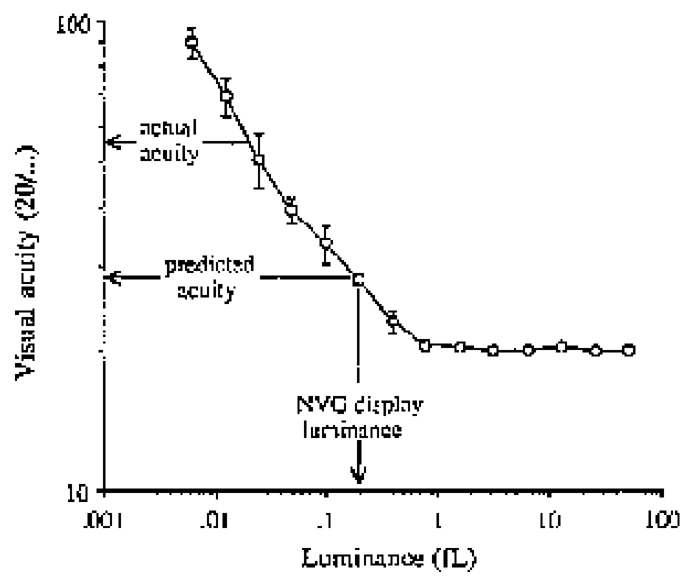
Visual acuity (visual resolution)

Findings

- Display luminance does not in itself account for the level of acuity achieved with NVG.
- An attenuation of contrast better explains the level of resolution obtained.

The adapted figure shows mean (±1SE) high contrast visual acuity from four subjects plotted as a function of display luminance. Visual acuity is maximum at moderate to high light levels, but decreases at values <0.6 fL. This reduction in visual acuity with luminance (<1fL) is best described by a power law function:

Snellen denominator = 17.4 x (luminance$^{-0.31}$ R^2=0.98



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U.S. Army (1998a) - Night vision goggle driving techniques and procedures and operations under blackout conditions

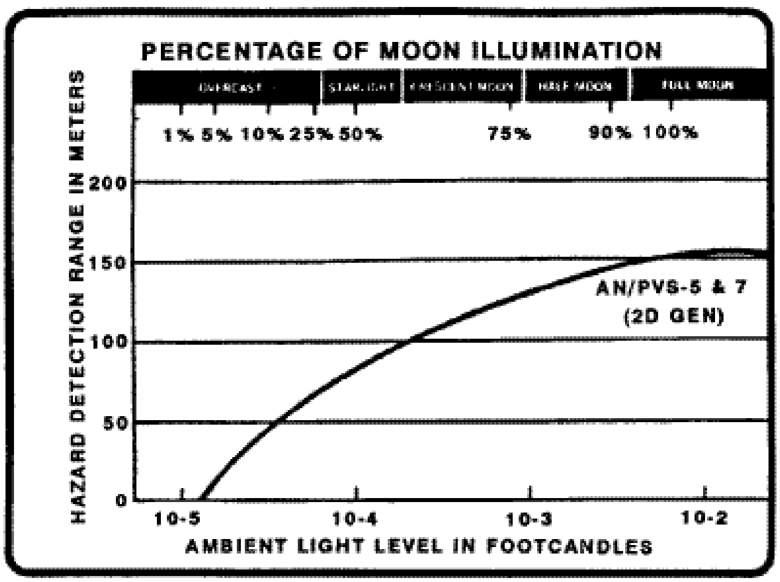
Chapter 21 of the U.S. Army manual for the wheeled vehicle driver (U.S. Army, 1998a) addresses night vision goggle driving techniques and procedures. It specifies considerations for using NVG for driving.

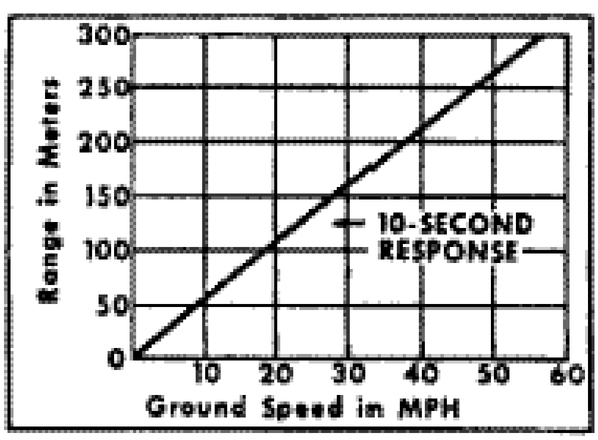
<u>Weather considerations</u>

Rain, haze, fog, snow, or smoke reduce NVG effectiveness. When visibility restrictions exist, a halo appears around artificial lights and there is an increase in image noise.

<u>Ground speed limitations</u>

There is a tendency to drive faster than one's true capabilities. Ground speed limitations can be extracted from the minimum hazard recognition range graph and the ground speed limitation inferred from it (shown below).





Convoy driving

The major concern in convoy driving under NVG is keeping a safe distance between the vehicles. Loss of visual contact with the lead vehicle is also dangerous. Additional problems may occur when driving over dirt or extremely dusty surfaces.

Illumination

When ambient light sources provide illumination, the task of driving with NVG is easier. It is suggested to schedule training when more than 25% moon illumination is available and the moon is visible more than 30 degrees above the horizon

Fatigue

Initially, some drivers experience sore neck muscles, headaches, and fatigue. Support personnel undergoing night training should not exceed 8 continuous hours and instructors are limited to 4 hours per day. The fatigue caused by using NVG for one hour is likened to 3 hours of not using them.

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Van Winsum and Kooi (1999) - The effects of monocular and binocular night vision devices on driving behavior and comfort

Van Winsum and Kooi (1999) conducted a field experiment to compare driving performance in rough terrain with monocular and binocular NVG. (The report is in Dutch, only the abstract was readily available in English.)

Findings

- Drivers were able to drive safely at night with binocular NVG, even when an alignment error was induced.
- While the study found no serious visual discomfort or discomfort problems while wearing the glasses, visual comfort was rated lower for the monocular NVG.
- Driving with a monocular NVG resulted in equally good driving performance. However, some of the drivers were not able to complete the two-hour session, implying that binocular devices are more suitable for prolonged driving.

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Wiley (1989) - Visual acuity and stereopsis with night vision goggles

Wiley (1989) measured stereopsis and visual resolution achieved using unaided monocular and binocular viewing with two types of NVGs.

Method

Binocular and monocular viewing with AN/PVS-5A and bi-ocular viewing with AN/PVS-7 second generation tubes in the goggles.

Independent variables

NVG type (3): monocular, binocular, and bi-ocular

Dependent variables

Stereopsis
Visual resolution

Findings

- Stereopsis through night vision goggles, regardless of the model or viewing condition, is essentially eliminated and equivalent to the threshold obtained with unaided monocular viewing.
- Spatial resolution capability with all of the goggle systems is superior to performance with unaided vision.
- Visual acuity with the goggles is approximately 20/50 but only for high contrast targets and simulated full moon ambient light levels.
- As light levels decrease to quarter moon conditions or target contrasts are reduced to more realistic values, visual spatial resolution with the goggles is much poorer.
- For infantry use, any differences in visual performance between monocular, bi-ocular, and binocular designs probably are not operationally meaningful.

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SENSOR FUSION

Aguilar et al. (1999) - Field evaluations of dual-band fusion for color night vision

Aguilar et al. (1999) studied the performance of the MIT fusion algorithm for detection and identification of targets.

Method

U.S. Army night vision experts were asked to judge three systems for performing several tasks.

Independent variables

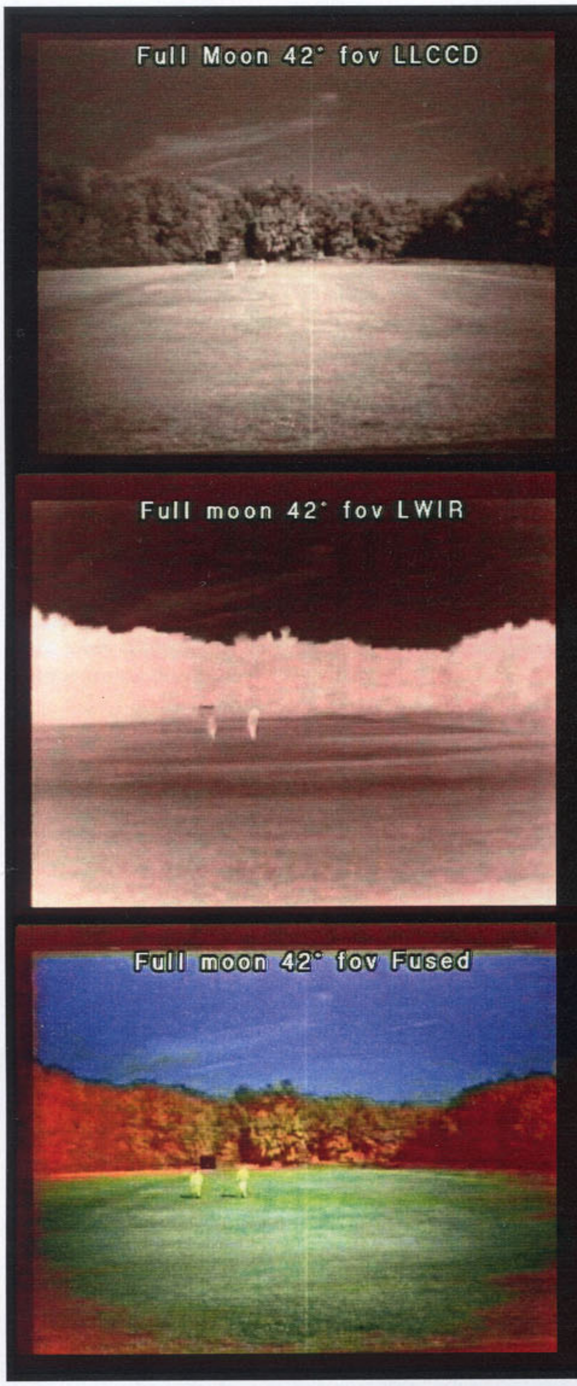
System (3):	Low-light visible camera, thermal IR, and color fused
FOV (2):	Wide (42 degrees), narrow (7 degrees)
Task:	Track, identify, and discriminate soldiers, vehicles, uniforms, weapons, camouflage, and obscurants

Dependent variables

Expert evaluation (easy, difficult, impossible)

Findings

Color-fused imagery was better than each separate system. (Report of quantitative results in this paper is extremely vague, no other publicly available papers are cited.)

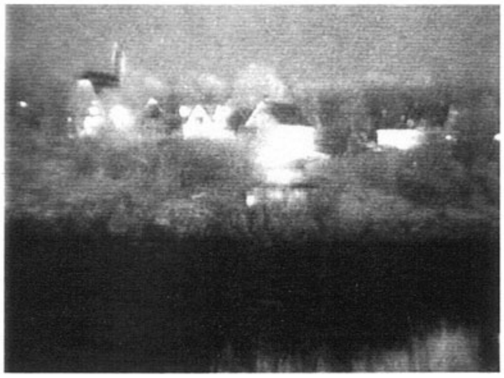


Color night vision by realtime fusion of low-light CCD visible and uncooled LWIR thermal imagery. Taken under full-moon (100mLux) conditions near Lincoln Laboratory using 42° field-of-view optics. Men are located at about 100m, background trees at over 200m from the sensor pod. (Top) low-light visible, (middle) LWIR, (bottom) fused imagery.

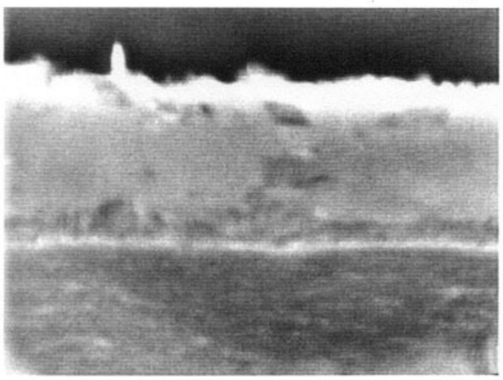
Figure 5. Color night vision by realtime fusion of low-light CCD visible and uncooled LWIR thermal imagery. Taken under starlight conditions at FT Campbell, KY, using 7° field-of-view optics. Men holding weapons are located at about 100m, background trees at over 400m from the sensor pod. (Top) low-light visible, (middle) LWIR, (bottom) fused imagery.

Aguilar et al. (1998) - Real-time fusion of low-light CCD and uncooled IR imagery for color night vision

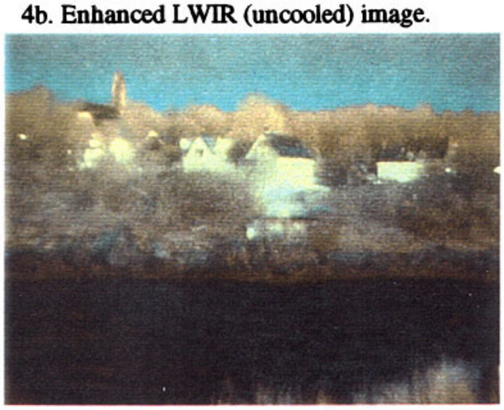
Aguilar et al. (1998) present technical information on real-time fusion of CCD images with IR for color night vision. Examples of sensor fusion capabilities can be seen in the figures. A few experiments regarding sensor fusion are described (e.g., Waxman, 1996; Toet, 1997) in support of an advantage for sensor fusion over no fusion.



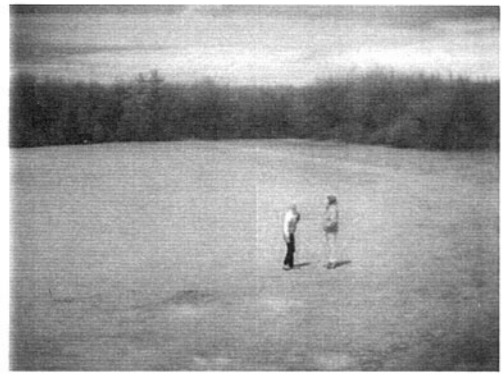
4a. Enhanced Intensified-CCD visible image.



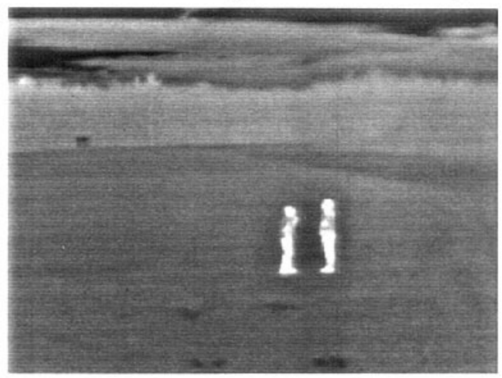
4b. Enhanced LWIR (uncooled) image.



4c. Fused results derived from 4a,b.



4d. Enhanced low-light CCD visible image.



4e. Enhanced LWIR (uncooled) image.

4f. Fused results derived from 4d,e.

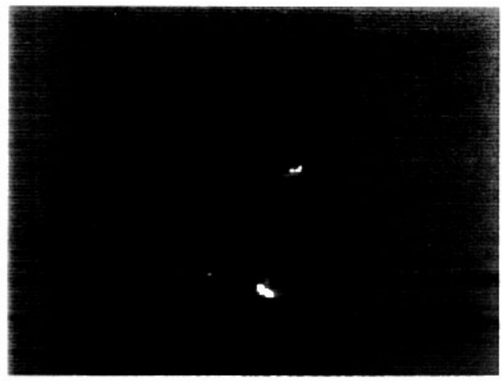
Color night vision by fusion of low-light visible and uncooled thermal IR imagery. (a-c) Lincoln Lab imagery (dusk conditions) using image intensified CCD and LWIR sensor pod. (d-f) Lincoln Lab imagery (starlight conditions) using new Lincoln low-light CCD and LWIR sensor pod.

5a. Original visible (intensified-CCD) image.

5b. Original thermal IR (FLIR) image.

5c. Fused result derived from 5a,b.

5d. Original visible (daylight-CCD) image.



5e. Original thermal IR (FLIR) image.

5f. Fused result derived from 5d,e.

Color fusion of CCD and FLIR imagery. (a-c) Army helicopter night flight at tree-top altitude. (Imagery provided by NVESD.) (d-f) Smokescreen (Canadian DREV imagery.)

Brickner and Zvuloni (1993) - The effect of polarity on object recognition in thermal images

Brickner and Zvuloni (1993) studied the effect of image polarity on target recognition.

<u>Method</u>

20 flight candidates viewed 60 images and touched the screen when they recognized a target they were requested to find.

<u>Independent variables</u>

Polarity (2): Black-hot and white-hot

<u>Dependent variables</u>

Response time
Correct responses

<u>Findings</u>

- Polarity effects were found in segments where the targets were vegetation, natural terrain, or square buildings. There were no polarity effects among other human-placed objects or among heat-emitting objects.
- The polarity effects, when found, were not in a single direction. Therefore, a recommendation cannot be given for either black-hot or white-hot.
- It is recommended that the operator be allowed to switch between polarity based on his/her specific needs.

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Das and Zhang (2000) - Color night vision for navigation and surveillance

Das and Zhang (2000) propose a new algorithm for sensor fusion and discuss its possible potential for application in the transportation domain.

In contrast to other existing methods, which are intrinsically color-processing schemes, the new method performs grayscale or monochrome fusion to obtain a gray image first and then separately colors that image for further enhancement.

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Krebs et al. (1999) - An evaluation of a sensor fusion system to improve drivers' nighttime detection of road hazards

Krebs et al. (1999) tested detection of a pedestrian in sensor-fused images with two levels of glare from an oncoming vehicle.

<u>Method</u>

Eleven military observers (age unspecified) viewed nighttime driving images collected by a visible light camera (400-700 nm) and an NIR camera (700-1250 nm). The images contained an opposing vehicle stationed at 45 m in front of the viewer and using its low or high beam lights. The task was to determine whether a pedestrian, crossing the road in front of the opposing vehicle, was present or absent.

Independent variables

Image format (6):	Visible, SWIR, sensor-fused dual band (two color and two achromatic)
Glare from opposing vehicle (2):	Low beam and high beam
Distance to target (pedestrian) (2):	30 m and 38 m

Dependent variables

Reaction time
Accuracy (sensitivity 'A')

Findings

- Reaction times with low glare were shorter than with high glare.
- Sensor-fused imagery produced sensitivity equal to or better than that produced by either single-band format under conditions of low beam and high beam, respectively.
- Color rendering of sensor-fused imagery did not improve performance relative to that obtained with achromatic rendering.
- Short-wave infrared was significantly worse than the other five formats, especially under the high-beam condition.

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McCarley and Krebs (2000) - Visibility of road hazards in thermal, visible, and sensor-fused night-time imagery

McCarley and Krebs (2000) tested two methods of sensor fusion for detection of pedestrians under different levels of illumination from an opposing vehicle.

Method

Nine naval officers (30-38 years old) observed images of an outdoor night-time scene arranged to simulate the forward view of a road seen through the windshield of a vehicle using a 34 x 26 degree FOV camera and viewed at 11 x 9 degrees. An opposing vehicle, parked 70 m in front of the sensors, varied the illumination level of its headlamps. A pedestrian was either absent from the scene or appeared at a distance of 23 m or 38 m.

Independent variables

Illumination by opposing vehicle (3):	Poor (parking lights), moderate (low beam), and excessive (high beam)
Format (6):	Visible, thermal (black-hot), color fused, gray fused, principal components-fused color, principle-components fused gray

Dependent variables

Reaction time
Accuracy (sensitivity 'A')

Findings

- Sensitivity with thermal imagery was relatively low across all levels of illumination.
- Sensitivity with visible and simple fused imagery was high except under high glare.
- Sensitivity with principal-components fused imagery was relatively high across all illumination levels.
- Performance with grayscale, simple fused imagery was as good as that with component imagery under low and excessive illumination and was better under moderate illumination.
- Performance with grayscale and chromatic principal-components fused imagery was equivalent to that with visible imagery under moderate illumination and dramatically superior under glare.
- Chromatic rendering of fused images modestly but reliably improved performance under poor illumination.
- Under low illumination, performance with grayscale principal-components imagery was worse than that with unfused visible images, indicating that spatial content of the visible input imagery was degraded by fusion.
- The benefits of sensor fusion may vary with environmental conditions and/or the quality of input imagery tested, and with the form of fused imagery under consideration.
- The authors recommend sensor fusion as a prospective method of enhancing imaging systems deployed as night-vision aids, but urge caution in the design and testing of any fusion system meant to function under a broad range of environmental conditions.

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Sampson (1996) - An assessment of the impact of fused monochrome and fused color night vision displays on reaction time and accuracy in target detection

Sampson (1996) compared reaction time and accuracy when viewing monochrome and color-fused night vision displays (from abstract).

Method

The output from an NVG and a FLIR were digitally fused into one image and then artificially colored. Six subjects viewed 24 fused images and indicated as fast as possible whether a target existed.

Independent variables

Image format (2): Sensor fusion present or absent

Dependent variables

Reaction time and accuracy

Findings

- Contrary to expectation, fusion decreased task performance. This was caused by a local impact on the target contrast when applying the fusion.

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Simard (2000) - Evaluation of algorithms for fusing infrared and synthetic imagery

Simard (2000) compared three image fusion algorithms as part of the development of an airborne enhanced synthetic vision system for helicopter search and rescue operations. The three algorithms compared were a simple pixel averaging algorithm, and two well know algorithms–one developed by TNO and one by MIT.

Application of all three fusion algorithms improved the raw infrared image, but the MIT-based algorithm generated some undesirable effects such as contrast reversals. This algorithm was also computationally intensive and relatively difficult to tune. The pixel-averaging algorithm was simplest in terms of per-pixel operations and provided good results. The TNO-based algorithm, while slightly more complex than pixel averaging, was more flexible and had the advantage of predictably preserving certain synthetic features that could be used to support obstacle detection.

The main issues that needed to be considered for the fusion of infrared and synthetic imagery were:

1. Performance under different sensor conditions (e.g., black-hot, white-hot)
2. Performance with varying quality of the sensor image
3. The effect of synthetic and enhanced sensor scene content mismatches arising from typical synthetic image inaccuracies on the usability of the fused image

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Sinai et al. (1999a) - Scene recognition with infrared, low-light, and sensor-fused imagery

Sinai et al. (1999a) evaluated the information conveyed by single- and dual-band sensor imagery by assessing performance on a scene recognition task.

Method

18 students (active duty military)
Stimuli were images collected using an uncooled LIMIRS long-wave IR sensor and a Fairchild image intensified low-light CCD. Fusion was performed by registering the images and combining both spectral bands into a two-dimensional color space.
A first image was shown for 100 ms, followed by 300 ms of a checker-board, and then a second image. The subject had to say whether the images were of the same scene.

Independent variables

Image format (6): Single-band IR (white-hot), single-band low-light, dual-band white-hot with low-light (either color or achromatic), and dual-band black-hot with low-light (either color or achromatic)

Dependent variables

Error rate

Findings

- Performance was best when the first and second images were presented in the same format.
- When format changed between the presentation of two images, performance deteriorated, but more so when the second image was of a single band format.
- The primary benefits of sensor fusion were in matching the content of the second image to a stored representation of the first, and not in processing the briefly viewed first image.

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Sinai et al. (1999b) - Psychophysical comparisons of single- and dual-band fused imagery

Sinai et al. (1999b) examined improvement in visual performance when using a dual-band sensor fused image compared to a single-band image. The observer's first task was to identify whether the object was a vehicle or a person. Their second task was to determine if an image was upright or upside down.

Method

60 active duty military personnel
Stimuli were images collected using an uncooled LIMIRS long-wave IR sensor and a Fairchild image intensified low-light CCD. Fusion was performed by registering the images and combining both spectral bands into a two-dimensional color space.
In the first task, the subject had to press a button to indicate whether a vehicle, a person, or neither was present in the image. In the second task, the subject had to decide whether the scene was upright or upside down.

Independent variables

Target type (3):	Person, vehicle, nothing
Image format (6):	Single-band IR (white-hot), single-band low-light, dual-band white-hot with low-light (either color or achromatic), and dual-band black-hot with low-light (either color or achromatic)

Dependent variables

Response time
Accuracy

Findings

Detection task

- Across all sensor formats, people were detected faster than vehicles, followed by a response for no object.
- There was no significant difference between formats in response time.
- Error rates were lowest for detecting people.
- The white-hot gray sensor fusion had the most errors while the white-hot color sensor fusion had the least.

Upright/upside down task

- The IR single band condition was significantly slower and contained more errors than the rest of the conditions. In addition, the white-hot grayscale had more errors than the other conditions.

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Toet et al. (1997) - Fusion of visible and thermal imagery improves situational awareness

Toet et al. (1997) tested two color image fusion techniques developed at TNO and MIT for detection and localization of a person in a displayed scene.

Method

Six young subjects (20 to 30 years old) assessed the position of a person in sensor-fused scenes relative to the reference features in the image. The scenes were projected for 1 s on a monitor at 0.60 m in front of the subject at an FOV of 25.5 x 19.5 degrees.

Independent variables

Image (6):	Gray level CCD, gray level IR, color fused image (MIT), color fused image (TNO), gray level fused image (MIT), and gray level fused image (TNO)
Color (2):	Color and gray level
Fusion (2):	Present and absent
Fusion algorithm (2):	MIT and TNO
Scenarios (3):	Guarding a UN camp, guarding a temporary base, and surveillance of a large area

Dependent variables

Fraction of slides in which the target (person) was missed (don't know reply)
Mean distance between the actual position and the reported position (using mouse to point)

Findings

- Color fused imagery lead to improved target detection over all other modalities. The lowest number of missed targets was obtained in the color-fused imagery (1.9% for

TNO and 1.5% for MIT). The gray-level images were next with 4.9% for TNO and 4.5% for MIT. The thermal image had 8% misses and the CCD had 20%.
- The MIT fused images had lower mean distance error than the TNO images (17 vs. 26 pixels, respectively). Non-fused images had higher mean distance errors than fused images (CCD 32 pixels and IR 37 pixels).
- Observers can indeed determine the relative location of a person in a scene with a significantly higher accuracy with fused images compared to the original image modalities.

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Waxman et al. (1996) - Progress on color night vision: visible/IR fusion, perception & search, and low-light CCD Imaging

Waxman et al. (1996) report on the development of a color night vision system that fuses low-light visible imagery with thermal imagery. Preliminary results of a human perceptual experiment are described.

System

Dual-band imager consists of a generation III intensified-CCD (imaging from 0.6-0.9 μm), an uncooled long-wave infrared thermal imager (imaging from 7.5-13 μm), and a dichroic beam splitter.

Method

Five subjects (age unspecified) searched for a square, artificial target on a 28° wide monitor with different imagery conditions.

Independent variables

Image (5):	Visible, IR, combined grayscale blue, combined grayscale red, combined full color
Low-contrast value of visible (7):	-15%, -10%, -5%, 0, +5%, +10%, and +15%
Low-contrast value of IR (7):	-15%, -10%, -5%, 0, +5%, +10%, and +15%

Dependent variables

Response time
Detection rate
False alarms

Findings

- Whereas one modality or the other become useless at low contrasts, the color-fused imagery supports consistent detection across all contrasts with acceptable response times.
- Whereas each of the grayscales shows two quadrants of short reaction times and two quadrants of long reaction times or missed targets, the color-fused results are consistent across all contrast levels.

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NIGHT DRIVING AND THE NEED FOR VES

Owens and Sivak (1993) - The role of reduced visibility in nighttime road fatalities

Owens and Sivak (1993) studied the role of reduced visibility in nighttime road fatalities.

In an analysis of 100,000 accidents during twilight hours, fatal accidents were found to be overrepresented during darker portions, but unrelated to time of day, day of week, or alcohol consumption. Reduced visibility was also indicated by higher overrepresentation of fatal accidents in low illumination under adverse atmospheric conditions and with pedestrians and pedalcyclists as opposed to all other accidents. Reduced visibility was more important than drivers' drinking as a contributor to fatal pedestrian and pedalcycle accidents. The reverse was true for all other fatal traffic accidents.

The study raises the need for intervention in night driving (which VES may solve).

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Ruffner et al. (1997) - Development of a night driving training aid concept

Ruffner et al. (1997) report on a development of night-driving training aid simulator software. In chapter 3, they analyzed 160 ground vehicle crashes (reported by the U.S. Army Safety Center) that involved night vision devices during the period of 1986-1996.

<u>Findings</u>

- Over two-thirds of the 160 crashes were attributable to three categories of terrain and roadway hazards/obstacles: drop-offs (34%), ditches (23%), and rear collisions with another vehicle (11%).
- One-third (34%) of the crashes involved an HMMWV, 18% involved the M1 Abrams Tank, and 14% involved the M2/M3 Bradley fighting vehicle.
- The most commonly occurring environmental conditions cited as contributing factors were dust (24%), blooming from light source (9%), and smoke (8%).
- Failure to detect a hazard or obstacle accounted for 43% of crashes, followed by misjudgment of size, depth, or location (19%).

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Sullivan and Flannagan (2002) - The role of ambient light level in fatal crashes: inferences from daylight saving time transitions

Sullivan and Flannagan (2002) estimated the size of the influence of ambient light level on fatal pedestrian and vehicle crashes based on crash data from 1987 to 1997.

Method

Analysis of crash data from the Fatality Analysis Reporting System (FARS) of the National Highway Traffic Safety Administration (NHTSA), for an 11-year period between 1987 and 1997.

The sensitivity to light level was evaluated by comparing the number of fatal crashes across changes to and from daylight saving time, within daily time periods in which an abrupt change in light level occurs relative to official clock time.
Three scenarios:

1. Pedestrian crashes at intersections
2. Pedestrian crashes on dark, straight, high-speed roads
3. Single-vehicle, run-off-road crashes

Independent variables

Lighting (2): Dark and daylight

Dependent variables

Number of crashes

Findings

- Scenarios involving pedestrians were most sensitive to light levels, showing between 3 to 6.75 times more risk when dark relative to daytime light (with time of day held constant).
- Single-vehicle run-off-road crashes on dark curved roads show little, if any, sensitivity to light level.

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U.S. Army Safety Center (1997) - NVDs peering into the darkness

A report in countermeasures from the U.S. Army Safety Center presents an operational accident in which a Bradley drove off a 14-foot cliff. The commander died. The crash occurred under poor visibility, using NVG (the commander was using AN/PVS7-B and the driver was using AN/VVS-2). Although the crew had been informed of the cliff by radio, the Bradley was driven over the cliff and landed on its turret.

The accident is analyzed and suggestions are given to prevent similar mishaps in the future.

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REMOTE DRIVING AND DRIVING WITH INDIRECT VIEW

Brown and McFaddon (1986) - Display parameters for driver control of vehicles using indirect viewing

Brown and McFaddon (1986) examined the effects of various display characteristics on judgments of coincidence with a target, in a lab simulation using fixed forward-facing optical systems.

Method

Two groups of eight subjects (average age 22.5 [19-30])
Video recordings made during a vehicle's straight approach to a target were presented to subjects in a lab. Their task was to signal coincidence between the target and their eye position after the target had disappeared from the displayed field of view.

Independent variables

Field of view (2):	14 and 26 degrees (between subjects)
Target preview time:	
Distance (2):	100, 200 ft
Speed (3):	5, 10, and 20 mph
System magnification (6):	0.75, 0.95, 1, 1.25, 1.5, 1.58 by combination of display size and distance
Display size (2):	11 and 14 in. diagonal display
Viewing distance:	From 15.5 to 76.1 in.

Dependent variables

Distance estimation error (collected as time between subjective to objective coincidence)

Findings

- Most subjects exhibited undershoot errors (around 6 ft).
- Mean undershoot was significantly greater for the 14 degrees field of view than for 26 degrees (8.5 vs. 4.6 ft, respectively).
- At the larger FOV of 26 degrees, mean undershoot was somewhat greater when the magnification was 1.25 versus 1.0.

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Conchillo et al. (1996) - Effects of retinal size and peripheral field restriction on speed perception of an automobile in a video scene

Conchillo et al. (1996) investigated the effect of retinal size and peripheral field restriction on the estimation of the speed of an automobile in a video scene.

<u>Method</u>

Sixteen subjects (ages 20-22) with no driving experience viewed video clips of driving on a test track with no traffic. They estimated speed relative to a baseline clip shown immediately before each test trial.

<u>Independent variables</u>

Partial design

Screen size (2):	Width: 40 cm, 200 cm
Distance to the screen (3):	1 m, 2 m, and 5 m
Peripheral visual information (2):	Full and 50% (25% on each side covered)

Four out of 12 possible combinations of the above factors were tested:

Three conditions of full screen:	Large screen at 5 m (22 degrees; 4x), small screen at 1 m (22 degrees; 4x) and at 2 m (11 degrees; 8x)
One condition of half screen:	Small screen at 2 m (11 degrees; 4x)Speed (11): From 40 to 140 km/hr in 10 km/hr steps

<u>Dependent variables</u>

Speed estimation after viewing an anchor speed or 70 or 100 km/hr

<u>Findings</u>

Neither retinal size nor peripheral field restriction showed an influence on speed estimation.

<u>Limitations</u>

This experiment may have tested the ability of subjects to compare visual flow to an anchor, rather than estimating speed based on visual cues. It found that inexperienced drivers were able to do this without effect of retinal size or far peripheral vision. The magnification was quite high at 87 degrees/23 degrees and 87 degrees/6 degrees.

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Drascic (1991) - Skill acquisition and task performance in teleoperation using monoscopic and stereoscopic video remote viewing

Drascic (1991) examined the potential benefits of stereoscopic video for teleoperation.

<u>Method</u>

Eight subjects (age unspecified) remotely drove a telerobot and lowered a simulated X ray photographic plate between two “bombs.“

Independent variables

Video system (2):	Stereoscopic video and monoscopic video
Target size (4):	8, 16, 32, and 64 cm

Dependent variables

Trial execution time
Trial success

Findings

- Stereoscopic video was easier to learn than monoscopic.
- When stereoscopic depth cues were relatively unimportant, the benefits of stereoscopic vision due to the quick learning were temporary.
- When stereoscopic depth cues were important, the benefits of stereoscopic vision lasted longer. (For difficult tasks, which depended on stereoscopic depth cues, the benefits of stereoscopic vision were still apparent, even after a great deal of practice.)

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Van Erp (1998) - Trade-offs between spatial and temporal resolution on driving an unmanned ground vehicle

Van Erp (1998) studied performance of military drivers in a driving simulator as a function of the spatial resolution of the display and its update rate. (Additional details appear in van Erp, 1996.)

Method

Eight military driving instructors drove a fixed-based simulator with a monitor mounted above the steering wheel and displaying images taken by a camera mounted 1.7 m behind the driver and 2.8 m above the ground. The field of view was 80 degrees and the magnification was 1.0x. The image was processed to simulate lower transfer rates and reduction in spatial resolution.

Independent variables

Update rate (3):	10, 5, and 3 Hz
Spatial resolution (3):	64x60, 128x121, and 256x242 pixels

Dependent variables

On a curve:	Course instability (SD of lateral speed) and steering activity (mean absolute steering wheel turning speed)
Lane changing task:	Standard error from midlane, course instability, and steering activity
Speed estimation:	Estimation error
Distance estimation:	Estimation error
Braking:	TTC at break, TTC min, and number of collisions

Findings

- Performance at 10 Hz and 256x242 pixels was similar to the baseline.
- Requirements on spatial and temporal resolution were task dependent. On sharp curves and lane changes, a minimum update rate of 5-10 Hz was required. On braking, speed estimation, and distance estimation, 3 Hz was sufficient.
- The lane change and distance estimation task required a resolution of at least 256x242 pixels, while for turning sharp curves, estimating speed, and braking, the 64x60 resolution was sufficient.
- No interaction was found between spatial and temporal resolution, suggesting that a higher level on one factor cannot compensate for a lower level on the other factor.
- In this battery of tasks, a minimum of 5 Hz and 256x242 is recommended.

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Van Erp and Kappé (1997) – Head-slaved images for low-cost driving simulators and unmanned ground vehicles

Van Erp and Kappé (1997) simulated driving a UGV when viewing the world through a camera-monitor system. (Additional details appear in van Erp, 1995.)

Method

Twelve young men (ages 20-26) steered a simulated vehicle with a joystick on a triangular circuit consisting of three curves at a fixed speed of 20 km/hr.

Independent variables

Viewing condition (4):

1. Fixed viewing direction/fixed display (40x40 degrees),
2. Variable viewing direction/fixed display (same FOV, analogous to a head slaved camera presented on a fixed display),
3. Variable viewing direction/moving display (same instantaneous FOV, the viewing window moves relative to the viewer), and
4. Unrestricted field of view (156x42 degrees).

Vehicle references (2): Present and absent
Driving direction (2): Left curves and right curves

Dependent variables

Standard deviation of lateral position, lateral speed, and heading change (rotation speed)
Viewing direction (the mean of the absolute value of the subjects viewing direction compared to the momentary orientation of the road axis)

Findings

- Driving performance in the condition simulating a head-slaved camera image on a fixed display was worse than the other three conditions. It was even worse than a fixed camera image with the same visible field of view.

- A fixed field of view of 40x40 degrees may be too small to allow good curve negotiation.
- Vehicle references did not improve driving performance. This is probably due to the confounded occlusion of the vertical field of view, which hides part of the vehicle close to the driver and makes curve negotiation more difficult.
- Head and camera movement analysis shows that subjects moved their heads in the variable viewing direction/moving display condition in similar magnitudes as in the unrestricted view. In contrast, when the display was fixed, they did not move the camera as much.

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Van Erp and Padmos (1998) - Simulated driving with camera view

Van Erp and Padmos (1998) simulated driving a UGV when viewing the world through a camera-monitor system. (Additional details appear in van Erp, 1995.)

<u>Method</u>

Eight military driving instructors
Driving simulator, simulation of figure-eight-shaped test track

<u>Independent variables</u>

Camera position (2): Low (1.4 m above driver) and high (2.8 m, 1.7 m behind driver)
Field of view (2): 40 degrees and 80 degrees
Magnification (2): 1.0x and 0.5x

<u>Dependent variables</u>

Percentage of distance driven with right wheel on or beyond the lane marking
Lateral distance from right lane marking
SD of lateral speed
Standard error for mid lane
Steering wheel turning speed
Percentage error of target speed and longitudinal distance

<u>Findings</u>

- Best overall performance and least difficulty rating were found in 80 degrees FOV and 1.0 magnification.
- It is important to show indicators for vehicle width and lateral position in the image.
- On sharp curves, camera (vs. direct view) degraded lateral stability and steering by about 20%. Wide field of view gave better performance. Magnification 0.5 caused worse performance, probably through underestimation of lateral speed and distance. The high camera position led to underestimation of lateral position and more so with the normal field because of the restricted lateral view and the lack of points of reference in the image.

- In the lane change maneuver, the camera view led to better overall performance, probably because the camera was positioned over the midline of the car. Magnification 0.5 caused considerably worse performance.
- Speed was underestimated with camera view. Field of view had no effect on speed estimation but magnification 0.5 caused a relative speed overestimation.
- In direct view, distance was overestimated by 25%. In camera view, distances were lower (relative overestimation over direct view). Magnification 0.5 showed large distance overestimation.

Comparison to field study

- Lane change in camera view was worse than direct view in the field study, and better in this simulator study.
- For sharp curves, wide field of view resulted in better performance in the field experiment, but worse performance in the simulator. In the simulator at wide field, the negative effect of minification on lateral speed was more important than the better lateral view.
- Only the lane change task was judged more difficult in the simulator experiment than in the field experiment (due to lack of mechanical feedback).

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Van Erp and van Winsum (1999) - The role of stereo vision in driving armoured vehicles in rough terrain

Van Erp and van Winsum (1999) studied the effect of binocular vs. monocular vision on driving an armored vehicle with unrestricted field of view, restricted field of view, and with a HMD.

<u>Method</u>

Eight military drivers drove a standard YPR-765 armored vehicle in a training field on a route with ditches.

<u>Independent variables</u>

Type of view (3): Direct view, restricted field of view (25x19 degrees), and HMD (25x19 degrees)
Stereo/mono (2): Both eyes and dominant eye only

<u>Dependent variables</u>

Time to complete track
Driving assessment by professional instructor (number of hard bumps and comments)
Subjective rating

<u>Findings</u>

- With the HMD, participants drove significantly slower but had less hard bumps. The difficulty rating was higher.

- Stereovision (binocular vision) reduced task time from 2.9 to 2.6 min. Similarly, difficulty rating decreased from 2.9 to 1.9.
- Stereovision had no effect on task completion time with direct view and restricted view, only with HMD.

	Direct view	Restricted view	HMD
Course completion time	2.5^{a}	2.4^{a}	**3.2^{b}**
Number of hard bumps	**6.4^{a}**	4.9^{a}	2.4^{b}
Difficulty rating (1-easy, 5-difficult)	1.3^{a}	2.3^{b}	**3.5^{c}**

Note: Similar letters ($^{a\ a}$) denote nonsignificant differences; different letters ($^{a\ b}$) denote statistically significant differences.

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Glumm (1992) - A study of the effects of lens focal length on remote driver performance

Glumm (1992) studied the effects of lens focal length on remote driver performance (speed and accuracy).

Method

Eighteen subjects (nine military, nine civilians; ages 18-35) drove a four-wheel teleoperated golf cart (max. speed 14 mph) in an indoor test course with different segments (straightaways, curves, serpentine, figure eight, obstacle avoidance)

Independent variables

Focal length (3): 12 mm (29 x 22 degrees), 6 mm (55 x 43 degrees), and 3.5 mm (94 x 75 degrees)
Note: with a 13 in. diagonal monitor at 30 in. (horizontal viewing angle of 19 degrees) viewing distance, the above correspond to magnification levels of 0.65x, 0.35x, and 0.20x, respectively.

Dependent variables

Deviation from the centerline of the road
Number of obstacles hit
Subjective preference

Findings

- For the first five segments of the course, speed and accuracy were significantly greater with the 6-mm lens than with either the 12- or the 3.5-mm lens.
- In obstacle avoidance, speed and accuracy were lower with the 12-mm lens than with either the 6 or the 3.5, but differences between the latter were not significant.
- Lower speeds occurred in remote driving than actual driving.

- The 6-mm lens offers a more acceptable trade-off among FOV, resolution, and image distortion than either the 12 or the 3.5 mm. There is evidence to suggest that FOV and visual distortions were the major contributors to degradation in remote driving performance.
- Subjects preferred the 6 mm and perhaps the 3.5 mm.

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Glumm et al. (1997) - An assessment of camera position options and their effect on remote driver performance

Glumm et al. (1997) assessed remote driving performance for an HMMWV using three camera positions.

<u>Method</u>

Using a remote camera and display, 18 subjects (nine military, nine civilian; 16 male, two female; ages 21-35) drove an HMMWV on an outdoor test course (at the Aberdeen proving grounds) with cones as fast as possible without hitting the cones.
The camera focal length was fixed at 6 mm (HFOV: 55 degrees; magnification: 2.75x)

<u>Independent variables</u>

Camera position (3): (Number 8, 9, and 10) back-low, back-high, forward-high

Camera position	Horizontal distance from front of hood	Vertical from front of hood	Depression angle under the horizon	View of ground in near front	View of ground near side
8 back low	3.76	1.40	10	Worst	Best
9 back high	3.76	1.73	10		
10 forward high	3.15	1.73	15	Best	Worst

Course segment (4): Straightaway, serpentine, slalom, parking

<u>Dependent variables</u>

Time to complete driving task
Number of driving errors (cones hit or turns missed)
Subjective evaluation of the adequacy of view and the ease of performance

<u>Findings</u>

- No significant difference in course completion time (73 s, 61 s, and 60 s for 8, 9, and 10 respectively).
- Significantly fewer errors with camera 8 (54 errors) than camera 9 and 10 (79 and 96 errors, respectively).
- No statistical difference between cameras in the assessment of ease of performance or adequacy of view.
- Most subjects were of the opinion that less of a view was needed above the horizon and of the hood, and more of a view was needed of the ground close to the front of the vehicle and the edges of the front fenders.

- Nine of 18 subjects preferred camera 10 because it provided a more desirable perspective of the HMMWV's hood and the ground close to the front of the vehicle. Eight of 18 subjects preferred camera 8 because of the improvement in vision to the sides of the front fenders. Only one subject preferred camera 9.
- A computer program was written to calculate optimal camera positioning as a function of the height of the vehicle's hood, vehicle width, vehicle length, and the FOV of the camera lens system.

Study limitations

Very low speed maneuvers (mean of straightaway < 10 mph)

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Holzhausen et al. (1993) - Human engineering experiments using a telerobotic vehicle

Holzhausen et al. (1993) studied the effects of mono and stereoscopic viewing on driving performance of a remotely operated vehicle.

Method

Six to eight subjects performed two tasks in a teleoperated vehicle (EROS): driving on a curved road and parking before an obstacle. Video images from two cameras 65 mm apart were displayed simultaneously to a viewer who wore LCD glasses. By flickering the LCD at 100 Hz, a stereoscopic image was obtained.

Independent variables

View (2): Monoscopic and stereoscopic

Dependent variables

S curve
    Task completion time
Parking
    Distance from front obstacle

Findings

- Driving time when using the stereoscopic view was shorter than with mono (35 vs. 41 s).
- The stopping distance from the obstacle, without hitting it, was shorter with the stereoscopic view (13 vs. 29 cm).

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Miller (1988a, 1988b) - Distance and clearance perception using forward-looking, vehicular television systems

Miller (1988a, 1988b) studied distance and gap estimation using camera view with a monochrome and color monitor.

Method

Thirty-eight subjects estimated the size, distance, and separation of two white vertical columns (8 inch diameter and 54 inches high) using video imagery produced by a forward-looking, vehicle-mounted camera. Subjects sat 4 ft from the monitor, with the targets subtending between 3 to 1 degrees vertically.
The camera (42 degrees FOV) was installed on a vehicle roof, 6.5 ft above ground level with 10 degrees negative pitch aiming 26 ft in front of the driver.

Independent variables

Separation of targets (4):	3, 5, 7, and 9 ft apart
Distance (4):	2, 4, 6, and 8 vehicle lengths (15 ft units)
Color (2):	Color and monochrome (between subjects)

Dependent variables

Width estimation: Can a 6-ft wide vehicle pass through the columns?
Distance estimation in vehicle length
Target size

Findings

- Subjects typically overestimated distances and gaps between objects, which was expected due to the minification effect of the camera lens.
- The overestimation increased with distance.
- The overestimation was larger for the subjects using color rather than monochrome imagery.
- Mean target height estimations in the color condition (6.3 ft) were larger than in the monochromatic condition (5.0 ft).
- It may be concluded that under remote driving conditions, drivers will tend to get close to obstacles and attempt to drive through gaps that are too narrow for passage. This problem is likely to be enhanced in color displays.

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Miller and McGovern (1988) - Laboratory-simulation approach to the evaluation of vision systems for teleoperated vehicles

Miller and McGovern (1988) compared real-time remote driving of a Jeep to watching a prerecorded video of the driving task under three camera conditions. (Also reported in McGovern, 1988.)

Method

Thirty-six subjects (age unspecified, six subjects per condition) drove a Jeep Cherokee equipped with a panning remote camera of 42 degrees HFOV.

Independent variables

Remote driving (2): Real driving and watching video
Camera (3): Steering-slaved panning color camera, fixed color camera, and fixed monochrome
(Both variables were between subjects)

Dependent variables

Object detection distance
Secondary task (detect an instrument out of range)
Subjective preference

Findings

- Due to the nature of the video-watching task, the subjects who did not really drive the Jeep preferred a narrower field of view than did the teleoperation subjects.
- Detection range had very large variance. For certain objects there was an advantage to the teleoperation over video (231 ft for a large cactus vs. 161 ft for a large cable spool), while for other objects there was an advantage to the video viewers (a large tire: 110 vs. 66 ft). Overall, the difference in detection distance was not significant.
- Detection range as a function of camera type and remote driving showed an interaction. In the video-viewing condition, steering-slaved was the best, followed by the color camera and then the black and white camera. In the teleoperation condition, steering slaved was only as good as the black and white camera, possibly because of jitter in the camera due to mounting hardware issues.
- In the video condition, 20 responses to the secondary task per session were made. In the teleoperation, however, only 0.3 per session were made. This suggests that the teleoperators had much higher workload and therefore devoted much less attention (and priority) to the secondary task.

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Oving and van Erp (2001a) - Driving with a head-slaved camera system

Oving and van Erp (2001a) tested the effectiveness of a head-slaved camera system for driving an armored vehicle using a head-mounted display. (Additional details appear in Oving and van Erp, 2001b.)

Method

Seven men (25-37 years old) drove an armored vehicle (YPR-765) on a paved track and off the road. The paved track driving task consisted of 7 subtasks: (1) positioning (parking over a straight line), (2) driving through a funnel of pylons, (3) driving at 30 km/hr by speed estimation, (4) driving a slalom course, (5) estimating the vehicle width, (6) estimating the turn angle, and (7) estimating longitudinal distance.

Independent variables

View type (4): direct view, periscope view, HMD-normal (40 degrees FOV; 0.96x), and HMD-wide (88 degrees FOV; 0.44x)

Dependent variables

Driving performance (for each task, different measures were taken)

Findings

- When the HMD system was used, better performance was achieved than with the periscope. Drivers were able to position the vehicle more accurately and hit fewer pylons with the right side of the vehicle. (However, more pylons were hit with the left side, which reflects unfamiliarity with the central position of the camera relative to the over-learned position of the periscope.)
- The wide FOV did not improve performance in the assigned tasks.
- When positioning (parking) the vehicle, the longitudinal error with HMD normal (0.32 m) was lower than HMD wide (0.41 m) and significantly better than periscope view (1.28 m).
- When driving through a funnel, the best performance was achieved under direct view and with HMD wide. With the periscope, pylons on the right were hit while with HMD –normal, pylons on the left were hit.
- On the slalom course, the number of pylon hits with the right side was lower in the HMD conditions than in the periscope and direct view. With the left side, the opposite pattern was found (i.e., more hits in the HMD conditions).
- Estimated distance in the HMD-wide condition (17.3 m) was shorter than in the other conditions (about 27 m).
- Track completion times off the road were shorter in the HMD-normal condition (120 s) than with periscope (140 s) and HMD wide (145 s), but direct view was shortest (100 s).
- More comments were made by the observer in the periscope condition as to the number times the vehicle was too close to the right edge.
- Three of seven subjects reported motion sickness.

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Padmos (1995) – Ambient view for operators of unmanned ground vehicles; a literature survey

Padmos (1995) reviewed the literature of remote driving to assess what is known about image properties required to provide the operator of an unmanned vehicle sufficient information for remote driving.

Table 10. Recommended image characteristics for remote driving

Characteristics (reported studies)	Conclusions
Camera position (2)	Mount the camera over the lateral center of line of the UGV to promote correct lateral positioning of the vehicle. Mount the camera high in the rear of the vehicle to give a better view of the vehicle's front and the ground immediately ahead to enhance spatial orientation.
Camera motion (11)	A joystick-controlled camera is inconvenient. A head-slaved camera combined with an HMD has the potential advantage of a large field of view while maintaining high resolution and correct spatial orientation.
Field size (7)	For a fixed camera, a horizontal field of view of 70-90 degrees is sufficient for most sharp curves. The vertical field must be such that part of the vehicle front is visible up to 5 degrees above the horizon. For a head-slaved camera combined with an HMD, an instantaneous field of view of 40-50 degrees is probably sufficient.
Resolution (5)	An effective acuity of 0.1-0.25 1/arcmin (20/200-20/80) is sufficient for road following. For other driving tasks, 0.5 1/armin (20/40) may be required.
Area of interest (3)	The desire for high resolution while maintaining a wide instantaneous field of view can be satisfied by an area of interest construction in which the central image is magnified and the rest of the image is left unchanged.
Magnification (7)	An image magnification of about 1 is adequate. Distance and speed overestimation may occur if the image is minified.
Color (4)	Application of color images is primarily useful for off-road driving.
Stereovision (14)	Stereovision is advantageous with off-road teleoperation, where it helps in detecting obstacles, potholes, and ditches.
Image compression (5)	Effects of image compression on driving performance are not known.
Update rate (2)	It appears that update rates of 8 Hz and above are acceptable.

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Padmos and van Erp (1996) - Driving with camera view

Padmos and van Erp (1996) examined driving performance when driving with camera view on a closed course track. (Additional details appear in van Erp and Padmos, 1994.)

Method

Eight military driving instructors (ages 23 to 38)
Black-and-white camera mounted on the vehicle's roof and viewed on a monitor positioned 25 cm in front of the driver's eyes providing 40° horizontal FOV.
Subjects performed seven driving tasks on a test track:

- Drive on a figure-eight circuit at a fixed speed of 40 km/hr
- Drive sharp curves at 20 km/h
- Perform a lane change maneuver at 20 km/hr and 40 km/hr
- Drive backwards
- Without the speedometer, speed up to an estimated speed of 25 or 50 km/hr
- Align the car's front bumper or rear wheels with a transverse line on the road
- Stop just in front of a transverse line (approach speeds: 30 and 60 km/hr)

Independent variables

Direct view (2): Direct view and camera
Camera position (2): Front (low) and rear (high)
Camera FOV and magnification (2): Normal (1x, 37 degrees), wide (0.5x, 80 degrees)
Monitor markings (2): Present and absent

Dependent variables

Lateral control measures:

- Percentage of distance driven on or over the road marking
- Mean lateral distance of right wheel from the road marking,
- Standard deviation of the lateral speed
- Mean absolute steering wheel speed

Longitudinal control measures:

- For speed estimation: percentage error from target speed
- For positioning: distance from bumper to transverse line
- For braking: time to coincidence (TTC)

Subjective evaluation of difficulty

Findings

Camera view vs. direct view
Differences between camera view and direct view were found for several performance measures and tasks:

- Control of lateral position is moderately worse with camera view. Lateral distance to road marking and course instability increased by up to 50%.
- Performance of braking tasks suggests a relative overestimation of distance for camera driving.
- Subjects rated driving with camera somewhat more difficult than direct view.

Camera position and field of view

- The effect of field of view, combined with the camera position, was significant but were not quite consistent for different tasks and different performance measures.
- On straight sections and moderate curves, for example, the wide view resulted in greater course instability.
- In contrast, on sharp curves it improved lateral control.
- Overall, wide field of view with 0.5x magnification at a high position was most preferred and most likely to produce better driving performance. Normal field of view with 1x magnification at the high position was the worst.

Monitor markings

- The monitor markings, which were designed to provide visual cues to improve driving performance, did not prove useful for most tasks.

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Smith et al. (1970) - Human factors analysis of driver behavior by experimental systems methods

Smith et al. (1970) studied the effect of the lateral position of a camera on driving performance when driving with camera view only.

<u>Method</u>

Twelve subjects (age and experience unspecified) drove a short curved road (255 ft) with camera view marked with traffic cones 10 ft apart at 15 mph.

<u>Independent variables</u>

Lateral displacement of camera (3): Left, center of the car hood, right

<u>Dependent variables</u>

The standard deviation of lateral position

<u>Findings</u>

- The right camera position produced the largest steering variance. The center and left camera positions were not statistically different, but the center position was slightly better.

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Smyth (2001) and Smyth, Gombash, and Burcham (2001) - Indirect vision driving with fixed flat panel displays for near-unity, wide, and extended fields of camera view

Smyth (2001) and Smyth, Gombash, and Burcham (2001) conducted a daytime field experiment to study the effect of FOV on the ability of soldiers to drive an HMMWV with an external vehicle-mounted camera array and panel-mounted video displays. They measured task performance and a battery of workload measures.

Method

Eight young males drove an HMMWV by viewing a 110 degree wide screen (consisting of three displays mounted next to each other).

Independent variables

Magnification level and HFOV (4): Direct view (1x, 110 degrees), indirect view (0.73x, 150 degrees), 0.54x, 205 degrees, and 0.43x, 257 degrees.

Dependent variables

Time to transverse the road course
Number of course barrels struck
Heart rate, rms head movement
Battery of subjective rating (some from ARL):
- Workload: Attention allocation loading, NASA TLX, motion sickness, SART
- Affective state: Subjective stress scale, MAACL-R today form
- Cognitive effects: Short-term memory, logical reasoning, addition, spatial rotation
- Map planning task: Select the shortest path

Findings

- Driving speed was greatest for direct viewing and decreased with increasing camera FOV. (Indirect: 14.2 mph, near unity: 11.8 mph, wide FOV: 11.3, and extended FOV: 10.1 mph). Speed = 22.3*compression^-0.332.
- The number of barrels struck increased with the levels of viewing, but the effect was not statistically significant.
- Subjective ratings of workload in direct view were different than indirect view, but not within the levels of indirect view.

Table 11. Summary of results

Configuration	Driving speed (km/hr)	Accuracy percent strikes	Metabolic workload	Motion sickness	TLX workload (percent)	SART SA-D[a] (percent)	Subject stress
Direct driving	22.84	3.19	1.00	1.02% 0/10	44.85	50.28	12.70
Flat panel display Near unity FOV-150°	18.92	5.53	1.04	21.67% 2/10	59.17	65.52	27.19
Flat panel display Wide FOV-205°	18.15	7.23	1.10	21.67% 2/10	59.17	65.52	27.19
Flat panel display Extended FOV-257°	17.08	8.27	1.16	21.67% 2/10	59.17	65.52	27.19
Helmet-Mounted Display	15.41	10.51	-	- 1/8	-	-	-

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Sudarsan et al. (1997) - Influence of frame rate and image delay on virtual driving performance

Sudarsan et al. (1997) studied the effect of frame rate and image delay (lag) on remote driving performance.

Method

Five subjects drove a simulated vehicle on a simulated track.

Independent variables

Frame rate (4): 30 Hz, 15 Hz, 7 Hz, and 3 Hz
Frame lag (4): 0 frames, 2 frames, 4 frames, and 6 frames
Only 11 combinations of the 16 possible were examined.
Field of view (2): Wide and narrow (unspecified)
Road section (4): Straight, curve, loop, and slalom

Dependent variables

Duration to complete the course

Findings

Time to complete the course increased exponentially as a function of frame rate and frame lag, and increased when the FOV was limited.

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HEAD MOUNTED DISPLAYS (HMD)

Bakker, van Erp, and van Winsum (2000) – Driving with head-slaved camera systems: a literature survey

Bakker, van Erp, and van Winsum (2000) reviewed the literature on the effects of indirect viewing on driving behavior and the use of head-slaved systems in vehicles.

The effects of restricted field of view and image quality on driving behavior

A distinction is made between foveal vision and peripheral vision. Some aspects of driving are more dependent on foveal vision and are affected by image quality (contrast and resolution); other aspects depend on peripheral vision and are affected by limitation of the field of view. Table 12 summarizes the roles of peripheral vision and foveal vision in driving as presented by Bakker et al. (2000).

Table 12. The roles of peripheral vision and foveal vision in driving

Peripheral vision	**Foveal vision**
Lane keeping and lateral control	Lateral control
Speed estimation and longitudinal control	Recognition of road signs
Detection of objects that are eccentric to the present path of the vehicle (including curve tangent points)	Identification of obstacles

Based on research on the roles of vision in driving, limited field of view is expected to affect lane keeping, speed estimation, estimation of time to collision, and detection of objects in the peripheral field. On the other hand, reduced image quality is expected to affect lane keeping, object detection, and identification of objects in the foveal field. Table 13 lists the effects of degraded visual function on driving performance as summarized by Bakker et al.

Table 13. The effects of degraded visual function on driving performance

Degraded function	Outcome
Field of view	Situational awareness is reduced, search performance is poor, and more disorientation is observed.
	Steering and tracking performance deteriorate.
	Steering into sharp curves is problematic.
	Awareness of vehicles approaching an intersection is reduced.
	Workload may increase because of the need to make more eye and head movement, thus deteriorating other aspects that are not specifically related to the limited peripheral vision.
Visual acuity and contrast	Poor detection of objects such as traffic signs, pedestrians, and bicyclists
Stereopsis	Hardly any effects on driving performance have been found.
	Some reported benefits of stereopsis may be reduced (e.g., in terrain driving, under limited visibility, when the maneuvering requirements are very precise with respect to close range objects, etc.).

General issues relevant to the use of head-slaved systems in vehicles

The following topics were discussed in detail in the report:

Vehicle control
Delays in the head-slaved loop
Spatial awareness
Changes in head and eye movement due to HMD weight, field of view, delay, and limited degrees of freedom
Visual comfort due to accommodation and vergence, interpupillary distance, partial binocular overlap, and distortions
Image blur due to camera vibration, vibration of the head and HMD, and vibration of the HMD relative to the head

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Davis (1997) - Visual requirements in HMDs: what can we see and what do we need to see?

Davis (1997) summarizes the visual requirements and considerations for an HMD.

Visual characteristics and their relation to HMDs

Brightness and contrast

In see-through HMDs, the real-world scene effectively provides a background against which the synthesized images and symbology are observed. At nighttime and under dim illumination, the effective background luminance provided by the real environment can be quite low, increasing the contrast and visibility of light symbols but decreasing those of dark symbols. To offset this problem, the gain of the overall luminance from the real-world scene can be changed to match some constant value and perhaps change the gain in the synthetic imagery. Another approach is to use light sensitive filters, which would become uniformly denser at higher luminance levels. This approach, however, does not deal well with local brightness peaks (such as an oncoming vehicle).

Visual acuity and spatial resolution

The ability to resolve a critical visual feature that subtends 1 min of arc corresponds to a visual acuity of 20/20. At any given distance, an optimal display should provide spatial resolution that is better than the critical visual acuity. There are several exceptions to the 1 min of arc design criteria:

- Under low luminance levels, the maximum spatial resolution is much lower than 1 min.
- Visual acuity becomes worse as the target is viewed farther away from the central 2 degrees of the visual field.
- Visual acuity and the sensitivity to intermediate and high spatial frequencies decreases with age, especially under low luminance levels. Presbyopia, the loss in accommodation due to aging, needs to be considered as well.
- Conversely, hyper-acuity, the ability of the foveal cones to detect an offset of two high-contrast lines that differ by only 2 sec of arc, allows detection of jaggy lines in the visual display at spatial resolution much higher than 1 min.

Critical flicker fusion, temporal resolution, and motion

Critical flicker fusion (CFF) is the lowest rate at which the displayed image appears to flicker on and off. CFF is dependent upon the overall mean luminance, the levels of the observer's light or dark adaptation, spatial frequency content of the image, location within the user's visual field, and properties of the display.

Motion perception might deteriorate if the update rate is not fast enough. The maximum displacement per frame that gives an impression of smooth, continuous motion is about 15 min of arc. The minimum frame rate is therefore the virtual object's angular speed in arcmin/sec divided by 15.

Field of view

The trade-off between field of view and spatial resolution is a crucial issue in the design of HMDs. When FOV is widened by means of magnification of the image, the spatial resolution is reduced because the number of available pixels is constant. Current HMDs have horizontal FOVs ranging from 22.5 to 155 degrees. Table 14 lists a few techniques for increasing the field of view in HMDs. The different approaches need to be considered while taking into account their technological feasibility, complexity, cost, and weight.

Table 14. Techniques for increasing field of view in HMDs

Technique	Comments
Magnification of pixels	Decreases spatial resolution. Very problematic in color images.
Tile multiple displays	Multiplies the cost. Seams between displays must be aligned properly.
Mixed resolution to provide a higher spatial resolution within the central 2 to 5 degrees of vision and a lower resolution outside this region	
Binocular HMDs with only partial overlap	No stereoscopic view available where overlap does not exist.
Design of a different and better display element	

The minimum acceptable FOV depends on the task and on the field size available in the real environmental situation. A distinction is made between immersive HMDs and HUDs or see-through HMDs because the latter allow viewing of the periphery with the naked eye. For most tasks, immersive HMDs require a FOV of at least 60 degrees, although 50 degrees has also been reported as acceptable. See-through HMDs with symbology overlaid on the real-world scene require a FOV of at least 15 to 30 degrees assuming that the user can "see around" the display.

Binocular, monocular, and bi-ocular

Monocular HMDs are not recommended. Binocular are preferred over bi-ocular in the following scenarios:

- The visual scene is presented in a perspective view rather than bird's eye view.
- Monocular cues may provide ambiguous or less effective information than binocular.
- Static displays, rather than dynamic displays, are used.
- Ambiguous objects or complex scenes are presented.
- Complex 3D manipulation tasks require ballistic movements or very accurate placement.

Color versus monochrome

There is conflicting evidence on whether color or monochrome HMDs should be used. Table 15 provides a summary of the arguments for and against color HMDs.

Table 15. Arguments for and against color HMDs

Arguments in favor of color HMDs	Arguments against color HMDs
• Users often prefer color. • Color adds realism. • Color coding can reduce clutter when the amount of information or its rate of change is high. • Memory for color is better than for shape. • Color is processed earlier and faster.	• Color displays usually have worse spatial resolution than their monochrome or grayscale counterparts. • Color displays have less contrast, and are heavier and more expensive. • 8% of the male population has color deficiency and will not benefit from color displays.

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Geri et al. (1999) - Head and eye movements in free visual search: effects of restricted field of view and night vision goggle imagery

Geri et al. (1999) measured combined head and eye movements of observers wearing a head-mounted display with limited fields of view.

<u>Method</u>

Ten subjects (age unspecified) viewed simple grating targets through an HMD under different levels of instantaneous fields of view.

<u>Independent variables</u>

Size of simple grating targets (2): 2 degrees and 6 degrees
Instantaneous fields of view (3): 10 degrees, 20 degrees, and 40 degrees (seven subjects) and NVG (five subjects)

<u>Dependent variables</u>

Eye movement
Head movement

<u>Findings</u>

- Increasing the FOV resulted in a decrease in the magnitude of head movements and a concomitant increase in the magnitude of eye movements. This suggests that only about 10 degrees of the visual periphery were effectively used in the visual search.
- Head scans and gaze magnitudes were independent of either the size of the test target or the level of background detail.
- Fixation duration was dependent on target size only at the smallest FOV.
- Comparison between the 40 degrees condition and the real NVG condition validates the findings in the other conditions.

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Glumm et al. (1998) - A comparison of soldier performance using current land navigation equipment on a helmet-mounted display

Glumm et al. (1998) studied soldier performance of land navigation and other daytime mission tasks using current navigational equipment integrated on a helmet-mounted display (HMD). The results indicated that the soldiers traveled less distance between waypoints and experienced lower levels of mental workload using information presented on the HMD than they did using current navigational equipment.

Although not directly related to vision enhancement systems, HMD navigation assistants such as the one tested in this experiment might find their way into vehicles, with either the driver navigating directly or a passenger assisting in navigation.

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Padmos (1999) – Head slaved displays in a driving simulator

Padmos (1999) studied how various head slaved displays influence driving performance and subjective difficulty in a simulator.

<u>Method</u>

Twelve young men (ages 20-27) drove a simulator with seven different displays on rural roads with traffic. The simulator display was 3.75 m in front of the driver and spanned 160 degrees. The HMD used was N-Vision Datavisor HighRes. Horizontal head motion was sensed with a Polhemus Fastrac head tracker.

<u>Independent variables</u>

Display conditions (7):

1. full screen (160x30 degrees)
2. head-mounted mask (38x30 degrees)
3. head-slaved windows discrete (one of four displays 39x30 degrees, spanning 160 degrees)
4. head slaved windows continuous (same as previous but 39x30 degrees instantaneous field of view can move freely within the 160 degrees screen)
5. HMD with see-through reference
6. HMD without reference
7. HMD with virtual computer-generated references

<u>Dependent variables</u>

Driving performance (mean and standard deviation of lane error, SD of heading, stopping error, path error during turn, RMS error during turn, lateral position error after turn, heading error after turn, conflicts with traffic, missed traffic gap, steering effort on straight sections, and steering effort on curves)

Head position (SD of head direction, speed of head rotation)

Subjective rating of task difficulty

Findings

- HMD has negative effects on driving performance.
- HMD has negative effects on comfort (3.7/5 with HMD versus 2.0/5 without it).
- The limited field of view is not the cause of the worst HMD performance. The weight of the headpiece and considerable image delays are more probable causes.
- A continuously head-slaved window of 40 degrees on the screen is a good alternative for projection on a large 160 degrees screen. (In this method, a limited field of view is seen in front of where the viewer looks based on their head orientation. When they turn their head, the window moves accordingly.)
- If an HMD is used, it is recommended to apply vehicle references in the generated out-world image.

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Venturino and Wells (1990) - Head movements as a function of field-of-view size on a helmet-mounted display

Venturino and Wells (1990) studied head movements made by subjects as they found and memorized the position of targets located around them. When slow search was performed, small FOVs produced more head displacement and lower head velocities than did the large FOVs. In the fast search trials, head velocity increased with increasing FOV.

Method

Twenty young men (ages 18-30) viewed targets using a head-mounted display with 120 x 60 degrees FOV, and a binocular overlap of 40 degrees. The targets were positioned in a computer-generated world of 4-pi steradians projected at optical infinity and updated at 20 Hz.

Independent variables

Instantaneous FOV (5):	20x20, 45x42.5, 60x60, 90x60, and 120x60 (degrees horizontal x degrees vertical)
Number of targets (3):	3, 6, and 9
Instructed search speed (2):	Slow (within 3 minutes) and fast (as quickly as possible)
Type of background (2):	Terrain scene with a horizon and landmark present or absent

Dependent variables

Head displacement in azimuth and elevation
Also measured but not reported:

Search time
Replacement error
The number of guessed target replacements

Findings

- Search time decreased significantly with increasing FOV size.
- Subjects moved their heads less using a 120 degree FOV than when using a 60 degree FOV.
- The magnitude of head movements was smaller with smaller FOVs.
- With large FOVs, subjects not only required less time to locate and rehearse target positions than with small FOVs, but they also moved their heads less in doing so.
- The faster search times associated with larger FOVs was due to subjects moving their heads less, but at higher velocities. With a large FOV, subjects could point their heads and use their eyes to scan within a large area to obtain the location of targets relative to one another and relative to their head position.

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OTHER RELATED STUDIES

Brickner and Foyle (1990) - Field of view effects on a simulated flight task with head-down and head-up sensor imagery displays

Brickner and Foyle (1990) studied the effect of FOV on simulated flight performance.

Method

Eight men (age not reported) flew a simulated helicopter through a slalom course.

Independent variables

Position of display (2):	HDD 15 degrees below horizon, HUD at eye level (1.5 m focal distance)
FOV (3):	25 x 19 degrees, 40 x 30 degrees, and 55 x 41 degrees
Speed (2):	82 and 109 knots
Ground texture (2):	Texture present or absent

Dependent variables

Number of hit pylons
Number of missed intervals between pylons
Average turn distance around the pylons

Findings

- Decreased FOV resulted in more hit pylons and smaller turn distances from the pylons.
- Overall performance with the HUD was superior to that with the HDD.
- The results are interpreted as an indication that subjects perceived the display as the entire world rather than as a window into the world. This effect was somewhat smaller with the HUD than with the HDD, possibly because the HUD better represented a window into the world.

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Meehan and Triggs (1988) - Magnification effects with imaging displays depend on scene content and viewing condition

Meehan and Triggs (1988) tested the effects of magnification on distance estimation for different levels of scene content.

Method

Twenty-four subjects (age specified only as "adults") viewed different scenes using a parfocal zoom lens (with which the point of focus does not vary with changes in focal length). They were asked to match the size of the image in the viewfinder with their natural view of the same scene by adjusting the zooming ring on the lens.

Independent variables

Viewing type (2): Monocular and binocular
Scene type (4): Four scenes differing in the amount of depth cues

Dependent variables

Magnification level perceived as similar to natural

Findings

- Converted optical images must be magnified (1.03 to 1.11x) for them to appear to be the correct or natural size (in contrast to findings by Roscoe (1984), which supported a magnification level above 1.2).
- The magnification values are highest in scenes with little visual cues and decrease as the amount of information increases.
- The magnification values are higher in binocular view than in monocular view.

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Radio Technical Commission for Aeronautics (RTCA) (1999) - Operational concept and operational requirements for NVG implementation into the national airspace system (NAS)

The FAA (Federal Aviation Administration) sponsored an RTCA (Radio Technical Commission for Aeronautics) subcommittee for night vision goggles (SC-196) to describe the concept of operations supporting the implementation of an aviation night-vision imaging system technology in to the civilian national airspace system (RTCA, 1999).

Available systems: Night vision goggles, night vision goggle HUD, and FLIR are described.

Prerequisites for use

1. Internal lighting of the cockpit must be changed to accommodate NVG use.
2. NVG can only be used if the environmental conditions are acceptable.
3. NVG must be properly aligned and focused.

Advantages of using NVG

1. Improved situational awareness ("Operator situational awareness (SA) comprises detecting information in the environment, processing the information with relevant knowledge to create a mental picture of the current situation, and acting on this picture to make a decision or explore further.")
2. Safety
3. Maneuverability
4. Navigation
5. Terrain and obstacle avoidance
6. Visual navigation
7. Target/area detection and identification
8. Traffic detection and identification
9. Emergency situations

Operational conditions

1. Illumination level
2. Weather
3. Airborne obscurants
4. Terrain contrast
5. Moon azimuth and elevation
6. Cockpit design constraints (lighting, windscreens)
7. Cultural lights (city and vehicle lights)
8. Skyglow
9. Physiological and other conditions
10. Crew coordination
11. Fatigue
12. Overconfidence
13. Spatial disorientation
14. Depth perception
15. Distance estimation
16. Complacency
17. Task saturation
18. Lack of proficiency
19. Lack of experience

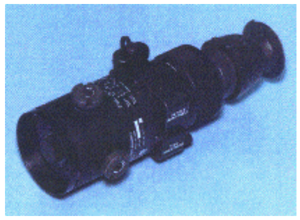
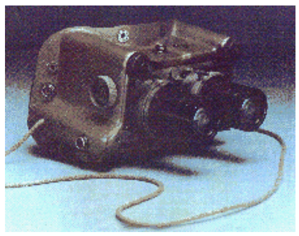
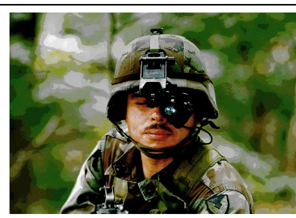
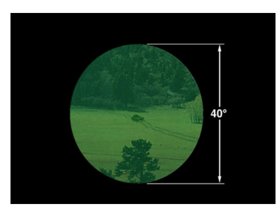
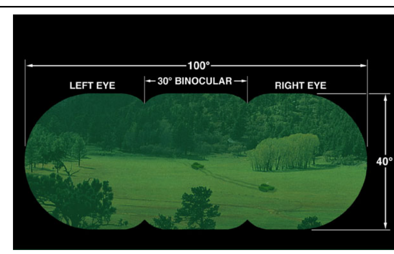
Limitations

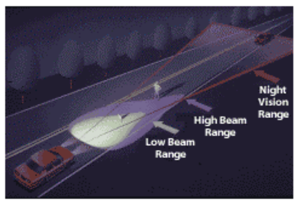
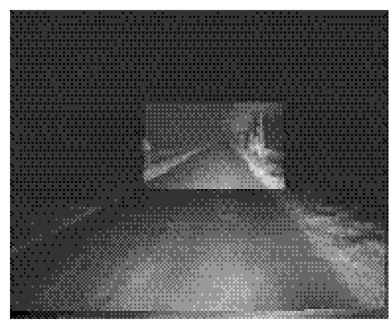
1. Reduced visual acuity
2. Reduced field of view
3. System weight and center of gravity
4. Monochromatic image

Winter operations

1. Snow - reflection
2. Ice fog - reflection
3. Icing - easy to overlook bad visibility
4. Low ambient temperatures - fogging of the goggles

APPENDIX B - IMAGES OF NIGHT VISION SYSTEMS

Product name	Image of product	Comments	Enhanced view
Gen I Stralight scope First used in the Vietnam War		Monocular	
Gen II AN/PVS-5 Late 1960s			
Gen III AN/PVS-7		Bi-ocular (one image source split to both eyes) HFOV - 40°	
Gen III AN/PVS-14		Monocular	
Gen III ANVIS AN/AVS-6		Binocular (an image source for each eye)	
PNVG (Panoramic NVG)		Binocular Extended HFOV -100°	

FLIR Driver's Vision Enhancer (DVE) AN/VAS-5			
GM Cadillac FLIR		The only product currently in civilian use	 
S-TYPE Jaguar/ Visteon/ Thales DVAN (drivers vision at night)	 	Product available	
DARWIN project (CEDIP IR systems, Fiat, Bosch, Vertex, Ind. & Materials Tech, Cranfield U.)	FIR camera 	In research	 

APPENDIX C - LITERATURE SEARCH

Keywords:

- Vision enhancement systems
- Night vision goggles
- Night vision
- Sensor fusion
- Night driving
- Remote driving
- Driving with indirect view
- Head mounted display

General search engines

First search	http://firstsearch.oclc.org
PsycINFO	http://mirlyn.web.lib.umich.edu
Ergonomics abstracts	http://www.tandf.co.uk/ergo-abs
DTIC	http://stinet.dtic.mil
HSIAC ordered search (performed by Mr. Craig Wilson)	http://iac.dtic.mil/hsiac
TNO database	http://www.tm.tno.nl/research/index.html
General Web search	http://www.google.com
National Transportation Library (U.S. DOT)	http://search.bts.gov/ntlsearch/query.html

Proceedings and books searched separately

- Proceedings of SPIE
- Proceedings of HFES
- Vision in Vehicles books and table of contents for last two conferences

What was not covered in this review

- A few papers that could not be located
- Unpublished material: Products (especially military) research and experience of the U.S. and other military organizations (e.g., Russian, German, French, British, and Israeli), though some work conducted by the Dutch for TNO was examined
- Unpublished material: Research by private corporations in the U.S. and in other countries with large car industries (e.g., France, Germany, U.K., Italy, Sweden)

APPENDIX D - VIEWING PARAMETERS

When watching the scene with indirect view, the following parameters are defined (Figure 3):

- Camera FOV (A): The angular size of the portion of the entire world that is viewed by the camera.
- Retinal FOV (B or C): The angular size of the displayed image in the viewer's eye (retina)
- Magnification: The ratio between the retinal size of an object on the display and the retinal size of the same object if it were viewed directly. (Can also be calculated as the ratio between the retinal FOV and the camera FOV.)

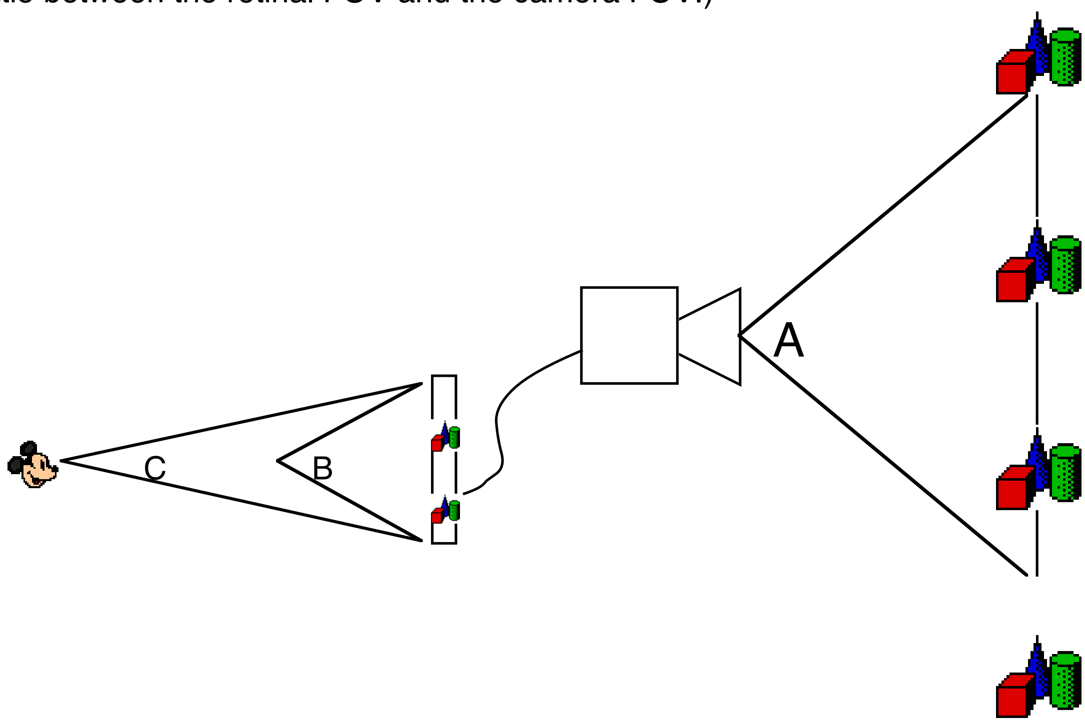


Figure 3. Fields of view for indirect-view:
A. Camera FOV, B. Retinal FOV close to display, and C. Retinal FOV far from display.

Table 16. Example FOV and magnification values

	Camera FOV (degrees)	Retinal FOV (degrees)	Magnification
Baseline	40	40	1x
Baseline + zoom lens	20	40	2x
Baseline + close view	40	80	2x
Baseline + zoom lens + close view	20	80	4x