Field of view requirements for night vision devices

A review of empirical research

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Abstract

Night vision devices (NVDs) are widely employed by military and law enforcement to facilitate human vision when ambient light levels are low. One of the potential limitations to NVDs is that they present a relatively narrow field of view (FOV) compared to the user's natural field of view. A longstanding engineering problem surrounds the performance compromise that occurs when FOV is restricted in NVDs and of particular interest for designers of NVDs is the minimum FOV required for normal performance. However, FOV requirements for NVD devices are expected to differ depending on the task that is performed by the user. The present paper provides a review of empirical research to date investigating FOV requirements for viewing tasks that are relevant to dismounted soldiers and vehicle operators. Though the empirical literature on FOV requirements for NVD-related tasks was found to be sparse, we were able to obtain tentative lower bounds on FOV requirements for NVDs. An all-purpose NVD system based on these lower bounds would be binocular and have a FOV of at least 150˚ horizontal x 90˚ vertical. However, there are important caveats for these conclusions and the lower bound values reported here must be interpreted with caution. Accordingly, further research in this domain is recommended.

Significance to defence and security

Night vision devices enhance the operational performance of dismounted infantry and vehicle operators during night or low-light operations. The present review provides information that can inform the design and development of NVDs.

Résumé

Les dispositifs de vision nocturne (DVN) sont largement utilisés par les militaires et la police afin de faciliter la vision humaine lorsque les niveaux de luminosité ambiante sont faibles. Une des limites possibles des DVN est le fait qu'ils offrent un champ de vision étroit comparativement au champ de vision naturel de l'utilisateur. Depuis longtemps, un problème d'ingénierie qui compromet le rendement survient en raison du champ de vision restreint des DVN. Les concepteurs des DVN s'intéressent particulièrement au champ de vision minimal requis pour un rendement normal. Toutefois, les exigences relatives au champ de vision des DVN devraient être différentes selon la tâche que l'utilisateur exécute. Le présent document passe en revue les recherches empiriques menées jusqu'à maintenant sur les exigences relatives au champ de vision nécessaire aux tâches de visualisation propres aux soldats débarqués et aux conducteurs de véhicules. Même si nous avons constaté que la documentation empirique sur les exigences relatives au champ de vision requis pour effectuer les tâches liées à l'utilisation des DVN est plutôt rare, nous avons pu obtenir des limites inférieures provisoires. Un système DVN tout usage reposant sur ces limites serait binoculaire et aurait un champ de vision total de plus de 150o à l'horizontale sur 90o à la verticale. Toutefois, il faut apporter d'importantes mises en garde concernant ces conclusions, et les valeurs des limites inférieures indiquées doivent être interprétées avec prudence. Par conséquent, il est recommandé d'effectuer d'autres recherches dans ce domaine

Importance pour la défense et la sécurité

Les dispositifs de vision nocturne améliorent le rendement opérationnel des pelotons d'infanterie débarquée et des conducteurs de véhicules pendant la nuit ou lors des opérations à faible luminosité. Les travaux actuels fournissent des renseignements qui peuvent éclairer le processus de conception et de développement des DVN.

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1 Introduction

Night vision devices (NVDs) are widely employed by military and law enforcement to facilitate human vision when ambient light levels are low. One of the potential limitations of NVDs is that they present a relatively narrow field of view (FOV) compared to the user's natural field of view. The narrow FOV that is typical of NVDs is a consequence of the cost and practical difficulty associated with the production of image-intensifiers and electro-optic sensor arrays that sample space over a wide visual arc, and also in displaying that information to the viewer. In particular, increases in FOV for a given sensor and display resolution are accompanied by increases in weight, size, power, and cost, and consequently designers seek to provide the minimum FOV required to support operator performance. Therefore, a critical question for research and development of NVDs concerns the performance compromise that occurs when the natural human FOV is restricted in an NVD. While several papers have reviewed the visual human factors of NVDs (Capó-Aponte, Temme, Task, Pinkus, Kalich, Pantle, & Rash, 2009; Parush, Gauthier, Arseneau, & Tang, 2011; Patterson, Winterbottom, & Pierce, 2006; Rash & McLean, 1999; Salazar, Temme, & Antonio, 2003), the present paper focuses specifically on FOV requirements. To begin, we considered the characteristics of the human visual system that are relevant to this problem and identified the functional tasks that would be affected by reduction in the available FOV. Subsequently we review the body of research that has attempted to assess the impact of FOV reductions on operational performance across these tasks. Finally, the results are summarized and tentative recommendations are provided for conservative NVD FOV requirements for dismounted soldiers and vehicle operators.

1.1 The human visual field

The limits of the human visual field have traditionally been determined using the *perimetry method*, in which the subject fixates a central point and is required to detect a salient stimulus (e.g., a bright spot) that appears at various horizontal and vertical eccentricities from the point of fixation (for a historical review of perimetry, see Thompson & Wall, 2008). Using this method, estimates of the total binocular horizontal visual field for a normal human viewer have been reported ranging from 195˚ (Howard & Rogers, 2002) to 214˚ (Traquair, 1938, Roenne, 1915). The central 114˚ of this horizontal visual field is perceived by both eyes and thus supports stereoscopic vision (Howard & Rogers, 2002). In the vertical dimension the visual field extends approximately 60˚ above the horizontal meridian and 75˚ below, for a total of 135˚ vertical visual field (Spector, 1990). Under natural viewing conditions, eye movements can shift this field of view by up to 55˚ horizontally and 35˚ vertically (Guitton, 1992; Guitton & Volle, 1987) to produce an even larger *field of gaze*. In addition, the head as well as the eye participate in natural shifts of gaze to areas of the visual field. Head movements are initiated automatically and in co-ordination with movements of the eye, and may also be initiated voluntarily. Head movements can be observed for gaze shifts as small as 5˚, but are more typically observed for gaze shifts that are 18˚ or larger (Fang, et al., 2015; Stahl, 1999). Most of the gaze shifts that occur without head movements occur within the central 30˚ x 12˚ (horizontal x vertical) degrees of vision (Fang et al., 2015). For large gaze shifts (e.g., 60˚) a large proportion (> 80%) of the shift is achieved via movement of the head (Janson, Quam, & Calhoun, 1987). NVDs typically have a fixed *field of view* that can impose restrictions on the human visual field and field of gaze. In particular, NVDs can truncate the instantaneous visual field (e.g., when eyes are fixated straight ahead) and because NVDs are head-mounted, movements of the eye cannot reveal additional areas of the visual field. In addition, NVDs with a FOV that restrict the natural human visual field are also likely to impact upon the head movements that individuals make, as head movements that would naturally reveal a certain portion of the visual world might fail to do so given the FOV restriction imposed by the NVD.

While traditional perimetry methods were instrumental in determining the extreme limits of the human visual field, more recent research has attempted to measure the sensitivity to various stimuli as a function of their eccentricity within the visual field. Visual sensitivity across the visual field depends on the sensory characteristics of the retina. The human retina, upon which the visual scene is projected, can be divided into central and peripheral visual fields (Larson & Loschky, 2009; Remington, 2011). The central visual field includes the *fovea* (central 3˚ about the point of eye fixation), *parafovea* (central 9˚ excluding the fovea), and *perifovea* (central 18˚, excluding fovea and parafovea), and the remaining area outside of the perifovea is referred to as the *periphery*. The area of the retina receiving the central visual field (known as the *macula*) has high concentrations of cone photoreceptors and is sensitive to high spatial frequencies (i.e., high acuity) and chromatic information. In contrast, the peripheral visual field (i.e., non-central area of retina) has a low concentration of cone photoreceptors but a high concentration of rod photoreceptors. Under photopic conditions (i.e., daytime viewing, or nighttime viewing stimulated by a bright viewing source such as an NVD) this portion of the retina has low acuity and reduced sensitivity to chromatic information, but is nevertheless sensitive to stimuli with high luminance contrast, as well as luminance transients and motion (Banks, Sekuler, & Anderson, 1991; Findlay & Gilchrist, 2003; Hecht, 1937; for a review see Strasburger, Rentschler, & Jüttner, 2011). Under scotopic (dark night) viewing conditions, the central visual field is functionally blind and visual performance is supported by rod photoreceptors that provide low-acuity spatial information from the peripheral visual field. Visual performance under photopic and mesopic (dusk) conditions is most relevant to NVDs because NVD displays typically produce luminance in that range (CuQlock-Knopp, Sipes, Torgerson, Bender, & Merrit, 1996).

The central/peripheral anatomical distinction coincides with functional differences in the areas of the visual field during task performance. During scene viewing and visual search, areas of the visual field are selected for detailed processing in central (i.e., foveal) vision. Eye movements (known as *saccades*) align central vision to *fixate* those areas so that detailed visual processing can occur (Ghorashi, Enns, Klein, Di Lollo, 2010; Hooge & Erkelens, 1999; Tatler, Hayhoe, Land & Ballard, 2011; Losckhy, McConkie, Yang, & Miller, 2005; Shen, Reingold, Pomplun, & Williams, 2003; Zelinsky, 1996). Hence NVDs with a FOV that blocks or obscures areas of the visual field (typically peripheral vision) will prevent the viewer from detecting and subsequently fixating targets that they might otherwise detect in that area. Restricted peripheral vision might also impair visuomotor tasks including locomotion, reaching (Dichgans, 1977; Dolezal, 1982; Pelli, 1986), spatial orientation (Leibowitz, 1986), as well as postural stability (Jasko, 2003), and the perceived size and distance of objects in the visual field (Hagen, Jones, & Reed, 1978).

In addition to the central/peripheral distinction in visual processing, it has been suggested that certain visual information is processed more efficiently in the upper versus lower visual field. For example, there is evidence that contrast sensitivity, motion detection, processing of global information, and visual search among distractors are more effective in the lower visual field (Levine & McAnany, 2005). While the lower visual field has been found to be superior to the upper visual field in most tests, there is some evidence that the upper visual field is superior in in certain kinds of visual processing (e.g., "local processing", Christman, 1993). However, most of the research investigating vertical field asymmetry has tested performance at relatively small eccentricities (e.g., < 15˚), whereas for NVDs with a vertical FOV of 30˚ or greater the concern would be the effect of obscuring more eccentric portions of the vertical visual field.

1.2 Night vision devices past and present

Most off-the-shelf NVDs present the user with a circular FOV of 45 degrees or less (for reviews see Bayer, Nash, & Brindle, 2009; Parush, Gauthier, Arseneau, & Tang, 2011), and therefore impose a substantial reduction on the natural visual field. Because NVDs are typically head- or helmet-mounted, the available FOV depends on head position and cannot be extended by eye movements. For typical NVDs with a circular FOV of 40˚ or greater, the FOV restriction would encroach primarily upon the peripheral visual field. However, because the eyes are free to move during task performance, the users could presumably fixate areas near to the edge of the FOV presented through the NVDs, and consequently the NVDs' FOV reduction would effectively truncate perifoveal or parafoveal visual fields in those cases. A reduction in FOV requires the user to execute head movements in order to sample areas of the visual field that are obscured. Head-movement compensation for reduced FOV is not without drawbacks; pilots have found that rapid head movements with NVDs can cause disorientation (Seagull & Gopher, 1997), and a requirement for additional head movement might also contribute to neck strain that is associated with NVDs in certain operational contexts (Harrison, Coffey, Albert, & Fischer, 2015).

Accordingly, designers have sought to extend the FOV of NVDs. For example, a wide-FOV NVD providing image-intensified (I2) imagery has been developed ("Panoramic Night Vision Goggle", PNVG) for aircraft applications that features a 100˚ horizontal and 40˚ vertical FOV (Geiselman & Craig, 1999), with the central 40˚ receiving binocular imagery. For ground operations (e.g., dismounted infantry) a 70˚ horizontal x 40˚ vertical FOV I2 NVD has been developed (Isbell & Estrera, 2003). In another approach, a wide-FOV NVD image (82.5˚ horizontal x 55˚ vertical) was presented on a head-mounted display (HMD) (Browne & Foote, 2010; Browne, 2011) via digital image processing. This approach has the advantage of allowing for digital pre-processing of the sensor imagery, including contrast enhancement, sensor fusion, and symbology overlays.

However even these wide-FOV NVDs impose a restriction upon the natural visual field. In order to understand the potential hindrance caused by this restriction it is instructive to consider the contributions of the areas of the visual field to task performance. If the task requires visual information from the entire visual field then any obstruction would be expected to impair performance. For example, during visual search certain targets might be readily perceived in the periphery, such as moving targets or targets that have high luminance contrast, and in these cases the visual search deficit caused by a restricted FOV might be substantial. On the other hand, if the task requires information from a narrow part of the central visual field, performance might only be impaired with a severely restricted FOV. For example, reading is typically accomplished by processing information located within the central 40 degrees of visual angle, and hence a head-mounted device that restricts the FOV to ~40 degrees should not impair reading *per se*. This assumes, however, that the task does not entail other related, but necessary, tasks that require a larger FOV. For example, if the reader were to look away from the page momentarily and then return, the visual field outside the central 40˚ might be used to locate the page and then direct the appropriate head and eye movements to produce a gaze position that once again falls on the text. Hence to determine the FOV requirements for NVDs one must consider the range of possible tasks that one might undertake using an NVD.

2 Empirical research on the effects of restricted FOV

In general, the experimental paradigm that is used to derive task-specific FOV requirements involves measuring task performance while manipulating the available FOV. More specifically, performance is measured at successively smaller FOV settings. Presuming that a large FOV (e.g., the natural visual field) is required for normal performance on a particular task, a reduction of FOV will cause a performance deficit. If performance does not change across successively decreasing FOV settings, it can be inferred that the additional FOV was unnecessary for task performance. For example, if performance with FOV restricted to 120˚ was not different from an unrestricted FOV condition (e.g., natural viewing), then it can be inferred that the required FOV is 120˚ or less (an upper bound). If the next-smallest FOV setting tested was 100˚ and performance was impaired in this condition, then it can be inferred that the required FOV was greater than 100˚ (a lower bound), and thus the required FOV for the task can be bracketed. Note that if the experiment does not or cannot include an unrestricted FOV condition (i.e., natural visual field), then then it is not possible to estimate the upper bound of the FOV requirement. For example, if performance is found to increase across all FOVs tested but there is no unrestricted baseline condition to compare them against, then it can only be inferred that the required FOV for the task is greater than the penultimate FOV tested. This is because it is unclear whether the maximum FOV tested did indeed produce the true maximum performance value.

This general paradigm of manipulating available FOV in the context of NVDs has been implemented in several ways. The simplest method employs goggles that have a fixed FOV but otherwise do not impair viewing, and to observe changes in task performance under different FOV conditions. This method provides a straight-forward way to estimate the size of the FOV that is required for a task. However it does not speak directly to these requirements in the context of NVDs, due to the differences in imagery viewed by the subject. In order to determine NVD FOV requirements more directly, researchers have sought to compare operator performance using NVDs that differ in FOV, or by restricting the FOV for a relatively wide-FOV NVD. This approach is direct and intuitive, but experimental control is limited by the available NVD technology and it can be difficult to draw strong inferences about the role of FOV relative to other factors. For example, resolution and FOV tend to trade-off in NVDs (Donohue-Perry, Task, & Dixon, 1994; CuQlock-Knopp, Sipes, Torgerson, Bender, & Merritt, 1997), and hence changes in performance at larger FOVs might be partly related to other factors such as resolution. Furthermore, when comparing different NVDs it is difficult or impossible to obtain estimates of performance in an unrestricted condition, and thus the upper bound on performance and FOV might not be detected. A related approach is to simulate NVD imagery, and manipulate FOV using an FOV-restricting goggle or headwear. However, simulating NVD imagery is a non-trivial problem (Pleban & Beal, 2002).

A conceptually similar approach can be applied to determine the optimal FOV for completing tasks in a virtual environment using virtual-reality (VR) HMDs. The findings resulting from this approach might be applied to the NVD problem, though the extent to which they are applicable depends on the degree to which the HMD and VR environment simulate the task to be performed in the real world with NVDs. There are numerous additional engineering challenges for HMDs in VR environments that are not directly relevant to the NVD FOV problem. For example, VR environments might entail reduced visual quality compared to NVDs, and require accurate head tracking in order to update the HMD imagery upon movement of the head, but perhaps more importantly they are unlikely to convey the same kind of information as NVDs (i.e., nighttime viewing of scenery). In addition, HMDs for VR environments have temporal lag in display updating that might not be characteristic of NVDs, and HMDs in VR poorly accommodate user locomotion (e.g., the visual scene might move but the user does not), while user locomotion is involved in many real-life NVD tasks.

Nevertheless, it is instructive to consider all approaches to the FOV problem in order to estimate the minimum FOV required for viewing tasks in NVDs. In the following sections we review empirical studies that investigated FOV requirements across a variety of viewing tasks. A subset of these tasks is relevant to dismounted infantry operations: visual search, depth perception, manoeuvring and locomotion, while others are specific to vehicle operators: visuomotor tracking, rotary-wing aircraft operation, fixed-wing aircraft operation, and automobile operation.

2.1 Visual Search

Wells and Venturino (1990) investigated the effect of FOV on visual search of simulated wireframe imagery scenes viewed through an HMD. In particular, the subject viewed an array of 3, 6, or 9 target shapes superimposed over a virtual landscape, and periodically one of the target shapes (representing aircraft) would change into a "threat", and the subject was required to locate and "engage" the target. The horizontal FOV of the HMD was manipulated (20˚, 45˚, 60˚, 90˚, and 120˚), and the authors found that search times generally decreased as FOV increased, but for the 9 target condition there was little difference between the 90 degree and 120 degree conditions, suggesting that a horizontal FOV of 90 degrees constitutes an upper bound for the FOV requirement in this task. It should be noted that in the 3 target condition the authors found no significant effect of FOV size, indicating that as the visual search task becomes more demanding (i.e., with nine targets), a wider FOV is used in support of task performance. This underlines the role of task demands in determining the observed effect of FOV on performance, and in particular it raises a concern for all research in this domain, namely that FOV requirements for a particular task type (e.g., visual search) might be underestimated if task instance used in experimentation is not sufficiently demanding.

Piantanida, Boman, Larimer, Gille, and Reed (1992) manipulated FOV (circularly: 14˚, 28˚, 41˚, 53˚, or unrestricted) in an HMD display while subjects searched for shapes in a visual search display. Search time was found to decrease with increasing viewing area (FOV). While the authors did not conduct a statistical comparison to confirm it, there was a numerical decrease in search time in the unrestricted condition compared to the 53˚ condition, suggesting that the FOV utilized by subjects during visual search was greater than 53˚. Because of the circular FOV manipulation, it is not clear whether performance was affected by the horizontal FOV restriction, the vertical restriction, or both.

Ragan, Bowman, Kopper, Stinson, Scerbo, and McMahan (2015) investigated visual search behaviour in a virtual-reality world seen through an HMD. The authors manipulated the FOV visible through the HMD (horizontal x vertical = 30˚ x 18.8˚, 52˚ x 32.6˚, 102˚ x 64˚) while subjects searched for armed human forms among unarmed distractors in an urban street scene. The likelihood of detecting targets increased across each FOV setting, and given that there is no 'unrestricted' FOV condition to compare against, it can only be inferred that participants were able to process information from a wider area than that provided by the 52˚ x 32.6˚ FOV. Horizontal and vertical FOVs requirements were not distinguishable in this study.

Arthur (2000) had subjects search for three dimensional shapes embedded in a visual scene viewed through an HMD. The shapes could appear in the visual field from 90˚ to 130˚ and subjects were required to move their head position until the target was effectively at 0˚. Three horizontal FOV conditions were contrasted (48˚, 112˚, 176˚) with a constant vertical FOV (47˚). Search time was found to decrease significantly across FOV conditions. Because the 176˚ condition was the maximum FOV tested, it is not possible to determine from these data whether or not performance was asymptotic at that setting. Previous research (e.g., Wells & Venturino, 1990) would suggest that it might be, though this would have to be verified in further research. Nevertheless, from the Arthur (2000) data it is clear that search performance depended on information from a horizontal FOV greater than 112˚.

CuQlock-Knopp, Sipes, Torgerson, Bender, & Merritt (1997) investigated FOV and resolution using goggles with a green filter to simulate NVD (image intensified) viewing conditions. Subjects (US National Guardsmen) were required to detect targets (both real human targets and inanimate human silhouettes) while walking a forest path. While the primary interest for this study was the effect of FOV on human walking performance, the authors also reported the number of targets detected and it was found to increase monotonically over the three FOV settings (horizontally 40˚, 60˚, 80˚). This suggests that subjects required a horizontal FOV greater than 60˚ for visual search in this task.

Angel, Gaughan, Vilhena, & Boyne (2005) compared visual search performance with NVDs with three different horizontal fields of view (40˚, 70˚, 95˚) and a fixed 40˚ vertical FOV. Subjects were infantry soldiers and wore the NVDs while navigating an “MOUT” urban combat training course. As they moved through the course, subjects were required to detect pop-up targets. The authors observed that during day time target search (NVDs filtered for day use), search time tended to decrease as FOV increased, and for a subset of the target types the 95˚ FOV had significantly longer search times than the unrestricted condition, indicating that the required FOV for these targets was greater than 95˚. When tested during night time viewing there was no clear pattern of differences in the FOV conditions. This might be interpreted as resulting from differences in the search stimuli between day and night, but also the methodology used in this study might have lacked power to detect small differences.

To summarize across the studies that examined visual search using HMDs, there was evidence that the FOV requirement is greater than 112˚ horizontally and 53˚ vertically. For the studies that used real NVDs or simulated NVD imagery, there was evidence for a horizontal FOV requirement of greater than 95˚.

2.2 Manoeuvring and Locomotion

In an early study of the role of peripheral information in locomotion, Dolezal (1982) wore a FOV-restricted apparatus while carrying out routine daily activities. Among the aspects of performance that he observed to be impaired by the FOV restriction were locomotion, reaching and orienting. In subsequent years a substantial body of research has sought to determine the relationship between FOV and locomotor performance using FOV-restricting goggles. However, very few studies have directly addressed this question in the context of NVDs. Also, there has been very little research on the effect of FOV restriction on manoeuvring and locomotion in the context of HMDs, likely due to the fact that manoeuvring and locomotion are poorly captured in virtual environments presented on HMDs.

Alfano & Michel (1990) had subjects walk a winding path and perform eye-hand coordination tasks while their FOV was restricted (circularly) with goggles to 9°, 14°, 22°, or was unrestricted. The authors found that all of the FOV restrictions produced longer walking times and more errors, suggesting that the required FOV (either horizontally, vertically, or both) for locomotion exceeds 22°. Subjects in the restricted FOV conditions also took longer to complete the eye-hand coordination task, and within the restricted FOV conditions, smaller FOV produced longer completion times.

Toet, Jansen, & Delleman (2008) investigated the FOV requirement for locomotion and maneuvering in the real-world. FOV restriction was achieved by having subjects wear modified plastic safety goggles such that the available horizontal FOV was 30˚, 75˚ or 120˚ and with a fixed vertical FOV of 48˚. Subjects navigated an obstacle course that required them to turn, duck, and step over obstacles. The authors found that maneuvering time was slowest for the 30˚ condition and that the 75˚ and 120˚ conditions did not differ, suggesting that a 75˚ horizontal FOV might be sufficient for maneuvering. However, both the 75˚ and 120˚ conditions were significantly slower than the unrestricted FOV control condition. While the authors do not speculate on the reason for the performance plateau between 75˚ and 120˚, it is possible that the 48˚ vertical FOV that was present in all restricted-FOV conditions resulted in a performance decrement compared to the unrestricted viewing condition.

A subsequent study by Jansen, Toet, & Delleman (2010) investigated this possibility by manipulating the vertical FOV (25˚, 40˚, 60˚, 90˚, 135˚, unrestricted) in addition to the horizontal FOV (40˚, 80˚, 115˚, 200˚, unrestricted) while subjects navigated an obstacle course. Consistent with the prior study (Toet et al., 2008), time to complete the obstacle course was significantly slower for the 40˚ horizontal FOV than the other settings, while the other settings did not differ from one another, confirming that 80˚ horizontal FOV is sufficient for manoeuvring. Interestingly, the only vertical FOV that produced a significant performance decrement was the 25˚setting. Taken together, these data showed no statistically significant evidence for performance improvement beyond the 80˚ x 40˚ FOV setting, though there did appear to be a monotonic decrease in manoeuvring time as vertical FOV increased. It remains possible that a more difficult manoeuvring task and/or a higher power test would reveal a larger vertical FOV requirement. No performance plateau was observed as in Toet et al. (2008) and this discrepancy was not discussed.

A further investigation by Jansen, Toet, and Werkoven (2011) focused on the vertical FOV requirement for stepping over obstacles. Subjects stepped over obstacles while wearing FOV-restricting goggles that fixed the available vertical FOV to 25˚, 40˚, 90˚, or unrestricted, while the horizontal FOV was unrestricted in all cases. Motion capture allowed for precise measurement of subjects' step behaviour during the obstacle task. This revealed changes in step length and toe clearance as a function of vertical FOV; step length was longer and toe clearance was larger as FOV increased up to the maximum (unrestricted) FOV tested. These data suggest that the vertical FOV used in navigating obstacles is greater than 90˚. One aspect not considered in this study is the potential difference between the upper and lower visual field; presumably the lower visual field is more important for this kind of task. If so, a larger lower than upper FOV might be a suitable compromise for locomotor tasks.

De Jong (2011) investigated the effect of horizontal and vertical FOV restrictions on subjects' performance in moving through an aperture (e.g., a door or window), using a fully crossed-factor design. Subjects wore goggles with a horizontal FOV of 40˚, 80˚, 115˚, or unrestricted, and a vertical FOV of 25˚, 40˚, 60˚, or unrestricted. While the horizontal FOV restrictions did not affect the speed with which participants passed through the aperture, the 25˚ vertical FOV restriction produced significant performance decrements compared to all the other vertical FOV settings. Unfortunately, statistical tests were not presented comparing the unrestricted case to the smaller vertical FOV settings. Nevertheless, based on the pattern of average performance values it appears that a vertical FOV of 40˚ was sufficient for the aperture passage task.

Pretto, Ogier, Bülthoff, & Bresciani, (2009) investigated optic flow as a cue used to update body position and orientation in the environment. Subjects viewed a moving dot pattern projected on a wide-angle display and the available FOV was manipulated. The authors found that rotational flow could be accurately perceived with a relatively narrow horizontal FOV of 30˚ (vertical FOV was limited by screen height to 125˚). However, in a second experiment examining translational optic flow (e.g., moving forward) and where both horizontal and vertical FOV were restricted, it was found that translational movement speed was underestimated for FOVs smaller than 60˚ (horizontal and vertical). Unfortunately it cannot be surmised whether this decrement was due to the horizontal or vertical FOV restriction, or both.

Duh, Lin, Kenyon, Parker, and Furness (2002) examined factors affecting postural stability for users of HMDs in virtual environments. In particular, subject stood on a balance platform and viewed through an HMD a visual scene that underwent a roll motion. The FOV within the HMD was manipulated (circularly, 30˚, 60˚, 90˚, 120˚, or 180˚), and it was found that subjects had more difficulty maintaining balance as FOV increased, up to the highest FOV tested. While somewhat counterintuitive, this finding indicates that balance is influenced by information over a wide field (e.g., horizontal and vertical of 120˚ or greater). As for other studies that manipulate FOV circularly, it is unclear from these findings whether the FOV requirement as specific to the horizontal or vertical axes.

Gauthier, Parush, Macuda, Tang, Craig, & Jennings (2008) compared navigation performance using a binocular NVD system (adapted with a pinhole aperture for daytime operations) with a 30˚ FOV (100% binocular overlap) to a control condition where subjects wore no NVDs (e.g., free viewing). Subjects were required to locate objects in a "maze", which was a set of rooms resembling an indoor urban setting. Subjects in the NVD condition took longer to locate the target items and made more unnecessary turns while navigating the maze. Subjects were also worse at reproducing the locations of objects in the room in a later map-drawing task. However, because this study did not control for the differences other than FOV between the NVD and control condition it is unclear what role FOV played in the results.

In the study described in the previous section by CuQlock-Knopp et al. (1997), in which subjects wearing simulated NVGs were required to walk a forest path, the primary dependent measure of interest was the number of walking errors. The authors found that the number of locomotor errors that subjects' made decreased as the circular FOV increased (40˚, 60˚, or 80˚), suggesting that the horizontal and/or vertical FOV required for this task was greater than 60˚.

Taken together, the studies using FOV-restricting goggles suggest that the FOV required to complete the manoeuvring and locomotion tasks describe above would be no less than 80˚ horizontally (obstacle navigation; Jansen & Toet, 2010) and 90˚ or more vertically (stepping over obstacles; Jansen et al., 2011). There were only two studies that investigated these tasks using

NVDs (or simulated NVDs) and their results did not contradict the findings from the FOV-restricting goggle studies. One study investigating postural stability used HMDs in a virtual environment (Duh et al., 2002) and the results indicated a wider FOV requirement (>120˚ circularly). However, this might have been driven by factors related to the HMD and the virtual environment used, and research using FOV-restricting goggles would be required to replicate and validate the finding.

2.3 Depth Perception

Human perception of depth is based on multiple visual cues. Binocular vision provides a unique cue, binocular disparity, which is used to infer relative depth. Binocular disparity is the difference in the appearance of an object across the two eyes as a consequence of their slightly different views of the world. The use of binocular cues for depth perception is referred to as *stereopsis*, and the acuity with which a person can make depth discriminations based on binocular cues is referred to as *stereoacuity*. There are substantial individual differences in stereoacuity; some people are able to perceive very small relative differences in objects' depth based on binocular cues (high stereoacuity) whereas others are very poor at this (Bosten, Goodbourn, Lawrance-Owen, Bargary, Hogg, & Mollon, 2015), though the majority of people have functional stereopsis. Stereopsis has been shown to contribute to distance estimation (Palmisano, Gillam, Govan, Allison, & Harris, 2010), which is a task that is relevant to dismounted soldiers and vehicle operators. NVDs may impose restrictions on binocular visual processing: NVDs can be monocular, biocular (a single image presented to both eyes) or more recently binocular (different image to either eye). Binocular NVDs feature two image channels and therefore entail greater power consumption and weight. For this reason the design compromise for monocular and biocular NVDs is appealing, however it might have consequences for performance in tasks that demand depth perception and distance estimation based on stereopsis.

This question was investigated by CuQlock-Knopp and colleagues (CuQlock-Knopp, Torgerson, Sipes, Bender, & Merritt, 1995; CuQlock-Knopp, Sipes, Torgerson, Bender, & Merrit, 1996), who examined real-world locomotion, wayfinding, and visual search performance with monocular (one image intensifier tube, one eye display with 40˚ FOV), biocular (one tube, two eye displays with the same 40˚ FOV) and binocular (two tubes, two eye displays with different 40˚ views) in-service NVDs. Subjects navigated a nighttime forest path (either in ¾ moon condition or moonless condition) and were required to detect target figures standing on either side of the path. Subjects made substantially fewer locomotion/wayfinding errors in the binocular NVD condition compared to the biocular and monocular NVD conditions, which did not differ from one another. Target detection performance with the binocular NVDs was also superior to the other two NVDs under both lighting conditions. These findings suggest that binocular viewing is an important contributor to locomotion and wayfinding performance with NVDs.

Singer, Ehrlich, and Cing-Mars (1995) investigated the role of stereoscopic viewing on manoeuvring and distance estimation in a virtual environment viewed through an HMD. Subjects used a joystick to control their movement through the virtual environment, and were required to complete several tasks, including manoeuvring between rooms, tracking the position of objects that appeared in the environment, and estimating the distance to targets in the environment. Viewing was either stereoscopic or "monoscopic" (analogous to biocular as described above).

Compared to the monoscopic viewing condition, the stereoscopic viewing condition produced superior distance estimation; however, manoeuvring and target tracking were not significantly affected by the viewing condition.

Restricted FOV is a possible contributor to the performance deficit in both cases. However, Creem-Regehr, Willemsen, Gooch, and Thompson (2005) investigated distance estimation in the real-world with FOV restrictions and found that the FOV restrictions did not produce impairments. Loftus, Murphy, McKenna, and Mon-Williams (2004) examined reaching behaviour with restricted FOV, and concluded that FOV impaired aspects of the response, rather than distance estimation *per se*. Knapp and Loomis (2004) investigated the same question using HMDs, also finding that the field of view was not the cause of errors in distance estimation, and rather suggested that it was due to other aspects of display fidelity in the HMD/VR environment. Similarly, it might be the case that errors in distance estimation with NVDs are due to the reduction in visual quality rather than the restriction to the FOV. For example, it has been argued that the reduction in visual acuity that is imposed by NVDs compared to natural viewing is the prime contributor to the reduction in stereoacuity observed with NVDs (Harrington, McIntire, & Hopper, 2014; Knight, Aspey, Jackson, & Dennis, 1998).

To summarize, while there is some evidence that binocular viewing is important for some aspects of performance in NVDs (e.g., locomotion, manoeuvring), to date there is no evidence that FOV *per se* affects depth perception in NVDs. Further research might seek to verify this conclusion.

2.4 Operation of Vehicles

NVDs are widely used to enhance vehicle operation at night and hence the FOV question is particularly relevant in this domain. However, upon reviewing the research to-date, very few studies have empirically investigated the NVD FOV requirements for vehicle operation. In contrast, multiple studies have applied the technique of restricting FOV in order to estimate the FOV requirement for vehicle operation during natural day-time viewing. FOV requirements emerging from this research on visuomotor control and tracking, rotary-wing, fixed wing, and automobile performance are discussed in turn.

2.4.1 Visuomotor Control and Tracking

Sandor and Leger (1991) investigated the effect of a restricted FOV on a visuomotor tracking task. Subjects wore goggles that restricted the FOV (circularly 20˚, 70 ˚, or unrestricted) while viewing a projection screen. A moving target and a small (1 degree) ring were projected on the screen and subjects controlled a joystick in order to track the target with the ring. Tracking performance was worse for the 20˚ FOV condition compared to the unrestricted condition while the 70˚ and unrestricted conditions did not differ significantly. These data suggest a circular 70˚ as an upper bound on the FOV requirement for performance in this task.

Kenyon and Kneller (1993) investigated the FOV factor in the context of a visuomotor control task where the subject used a joystick to nullify a perceived roll. The perceived roll was induced by rotating a visual scene (e.g., ground, horizon, sky), and FOV was manipulated using a viewing device that obscured the scene outside a fixed radius (10˚, 20˚, 40˚, 80˚, or 120˚). The authors found that performance was nearly asymptotic for FOVs that were 40˚ or greater. Winterbottom, Patterson, Gaska, Amann, & Prost (2008) also investigated roll control in a simulator (10˚, 20˚, 40˚, or 226˚ circular) and found that performance in the 40˚ condition was not different from the 226˚ condition, suggesting that a circular 40˚ FOV was sufficient for performance in this task.

To summarize across these studies, a 40˚ circular FOV appears to be sufficient (i.e., an upper bound) for visuomotor control tracking. It is important to note, however, that these studies did not employ NVDs or simulated NVD imagery, and hence a question for future research concerns the generalizability of these findings to those contexts. In addition, within these studies horizontal and vertical FOV were not manipulated independently, and hence it is unclear the extent to which performance was limited by horizontal or vertical FOV.

2.4.2 Rotary-wing Aircraft

In an early study by Brickner and Foyle (1990), subjects flew a simulated helicopter flight course while viewing the simulated visual scene on a "heads-down" display (a computer screen) or a "heads-up" display (projection screen). FOV was manipulated (horizontal x vertical = 25˚ x 19˚, 40˚ x 30˚, or 55˚ x 41˚) and the authors observed that the number of errors (hitting virtual obstacles) decreased and the length of each turn (a measure of flying efficiency) increased for each successively increasing FOV setting. These data indicate that performance required a FOV larger than 40˚ x 30˚.

Jennings & Craig (2000) compared helicopter flight performance with two NVDs that differed in FOV (40˚ vs. 52˚, circular) and found that while performance did not differ between the two NVDs, both differed from a baseline unrestricted FOV condition. The factors influencing performance in this experiment were not tightly controlled, and hence based on these data it is difficult to draw strong conclusions about FOV requirements.

Haworth, Szoboszlay, Kasper, De Maio, and Halmos (1996) manipulated horizontal FOV (20˚, 40˚, 60˚, 80˚, or 100˚) for helicopter pilots with a FOV-restricting helment during real flight maneuvers (see also Kasper, Haworth, Szoboszlay, King, & Halmos, 1997). The vertical FOV was held constant at 40˚. Performance was observed to improve as FOV increased, and the authors concluded that the benefits to performance diminished for FOVs greater than 80˚.

In a similar study, Edwards, Buckle, Doherty, Lee, Pratty, and White (1997) investigated FOV requirements for helicopter flight. Pilots flew a helicopter with FOV-restricting goggles that provided 40˚, 60˚, 80˚, or 100˚ horizontally and 40˚ vertically. A variety of performance measures were analyzed, and significant performance decrements were observed for the 40˚ FOV for precision landing, turn-to-target, and acceleration/deceleration maneuvers. In addition, performance decrements were observed for the 60˚ and 40˚ for a bob-up maneuver. Taken together, these findings indicate that a horizontal FOV of 80˚ is sufficient for the helicopter flight tasks though the authors speculated, based on an assumption of linearly increasing performance with FOV, that performance would asymptote at a horizontal FOV of around 120˚.

Taken together, these studies suggest that helicopter operations require a horizontal FOV of at least 80˚. To our knowledge, the vertical FOV requirement for helicopter operations has not been investigated empirically, but based the above studies suggest at least 40˚.

2.4.3 Fixed-wing Aircraft

FOV requirements have been an important issue in the context of fixed-wing flight. Very few studies have used FOV-restricting goggles however, and instead most research on the topic has supported the question of simulator requirements. In particular, researchers have restricted FOV in simulators and investigated the effects on performance and training efficacy. FOV restriction in simulators can either use a fixed-field manipulation or a head-slaved field manipulation. In the fixed-field manipulation, subjects operate with a fixed sub-portion of the overall visual field provided by the simulator, but this sub-portion is fixed and centered. In the head-slaved manipulation, the sub-portion of the field is yoked to head movements such that by moving their head, subjects can reveal additional areas of the visual field. This latter method is analogous to the FOV-restricting goggle manipulation discussed earlier, and more closely matches the FOV restriction imposed by NVDs than the fixed-field manipulation.

An early study by Roscoe (1949) investigated the impact of a FOV on landing performance in a small civilian aircraft. Pilots landed either with unrestricted vision or using FOV-restricting goggles (10˚ horizontal x 10˚ vertical). Landing accuracy was impaired in the FOV-restricting goggle condition, leading the author to conclude that peripheral cues were important for landing maneuvers.

Subsequent work on FOV requirements for fixed-wing aircraft was conducted by the United States Air Force. Irish, Grunzke, Gray, and Waters (1977) manipulated FOV in a wide-FOV fixed-wing simulator (300˚ horizontal x 150˚ vertical) while subjects flew a simulated T-37 aircraft. In the restricted FOV setting, the display was limited to the central 48˚ x 36˚ in a fixed-field manipulation. The authors observed very few differences in basic flight maneuver performance between the limited FOV condition and the full FOV condition, however some maneuvers were impaired in the limited FOV condition, suggesting that the required FOV for basic flight maneuvers is greater than 48˚ x 36˚.

LeMaster and Longridge (1978) also examined fixed-wing FOV requirements in a flight simulator with a wide-screen display (300˚ horizontal x 150˚ vertical). The subject performed flight maneuvers (dive-bombing) and the simulator was configured with a head-slaved FOV manipulation. Using this method, FOV was restricted to one of five horizontal x vertical settings (52˚ x 38˚, 70˚ x 70˚, 90˚ x 70˚, 110˚ x 70˚, or 130˚ x 70˚). It should be noted that a white horizon line was visible in the area outside the available FOV, and therefore visual information was not entirely restricted outside of the FOV. Dive bombing accuracy was found to increase monotonically as FOV area increased, however there were only statistically significant differences in performance between the 52˚ x 38˚ and the 70˚ x 70˚ setting. There was, however, a substantial increase in performance between the 70˚ x 70˚and 90˚ x 70˚ condition, and the authors concluded that the 90˚ x 70˚ setting was a lower bound on the FOV requirement for the dive-bombing task.

A later study by Weikhorst and Vaccaro (1988) also examined the effect of FOV on pilot performance for fixed-wing dive-bombing in a wide-FOV flight simulator (300˚ horizontal x 150˚ vertical). FOV was limited by masking a portion of the display, resulting in a fixed-field restricted FOV of 150˚ x 50˚. Performance measures indicated that dive-bombing was impaired for the 150˚ x 50˚ condition compared to the 300˚ x 150˚ condition. This suggests that the required FOV for these maneuvers was larger than 150˚ x 50˚. However, it is important to note that for this study the FOV was not head-slaved as it was for LeMaster and Longridge (1978). For NVDs the available visual field can be shifted by head movements, and hence the earlier research using head-slaved FOV in simulators is likely to be more relevant to NVD FOV requirements.

The effect of reduced FOV on simulator training has also been investigated for fixed-wing flight maneuvers (Nataupsky, Waag, Weyer, McFadden and McDowell, 1979) and aircraft carrier landings (Collyer, Ricard, Anderson, Westra, and Perry, 1980). Both studies had subjects train in a wide-FOV simulator (300˚ horizontal x 150˚ vertical), and compared test performance for a group who trained with the full FOV with a group that trained with a narrow FOV (48˚ x 36˚, fixed-field). Both studies found no consistent effect of training FOV on test performance, and concluded that peripheral cues were not necessary for skill acquisition during training. However, a subsequent study on FOV requirements for training arrived at a very different conclusion. Dixon, Krueger, Rojas, and Hubbard (1989) investigated the effect of FOV on training in a combat flight simulator. Participants trained to conduct air-to-ground missions in a simulator with a very-wide maximum FOV (300˚ horizontal x 150˚ vertical). Using a head-slaved FOV manipulation, the FOV displayed to the pilot was limited (approximately) to one of four horizontal x vertical sizes: 127˚ x 67˚, 140˚ x 80˚, 160˚ x 80˚, 180˚ x 80˚, and these conditions were compared against the unrestricted 300˚ x 150˚ produced by the simulator. As a dependent measure the authors determined the number of training trials required for subjects to reach a performance criterion under each FOV condition. Significant increases in trials to criterion were observed for FOVs smaller than the 160˚ x 80˚ condition, suggesting that during the learning process a wide field of view (> 140˚, <=160˚ horizontal and 80˚ vertical) is beneficial to training.

Osgood and Wells (1991) investigated the role of FOV on flight performance in a simulated flight task. Military pilots flew a simulated fixed wing air-to-ground mission using an HMD that displayed a simulated forward-looking infrared (FLIR) scene, and the available FOV for the scene was manipulated in a head-slaved manner (circularly 20˚, 30˚, 40˚, 60˚, or 80˚). The authors found that in this condition the primary effect of FOV on performance was on the time required to locate the mission target within the simulated display. In particular, subjects took significantly longer to locate the targets in the 20˚ and 30˚ conditions compared to the larger FOVs. These data suggest that a circular 40˚ FOV is sufficient for performance in this flight task. The lack of evidence for a larger FOV requirement is surprising given the findings from prior research. This might be due to the use of FLIR scene information whereas for prior studies the pilots viewed either real or simulated visible imagery. Clearly, further research is required to reconcile these differences, and to determine whether the FOV requirements emerging from these studies will generalize to the context of NVDs.

To summarize, estimates of FOV requirements for fixed-wing aircraft operation vary considerably across studies. These differences are likely to be related to the particulars of the aircrew tasks employed in each study, and accordingly further research is required to better understand the role of FOV in fixed-wing pilot performance. Nevertheless, these studies allow for a conservative estimate of the lower bound on the FOV requirement. Based on studies that examined performance using a head-slaved restricted FOV in fixed-wing simulators, the FOV requirement is greater than 150˚ x 50˚. Based on studies that investigated the FOV required for training in fixed-wing simulators, the FOV requirement is greater than 140˚ x 80˚. Taken together, we suggest a lower bound of 150˚ x 80˚ on the FOV requirement for fixed-wing flight.

Finally, while outside of the scope of the present review, head-mounted or helmet-mounted display systems for aircraft introduce the possibility of projecting an overlay of aircraft state information onto the pilot's view (e.g., Joint Helmet Mounted Cueing System / JHMCS, F-35 Gen3 helmet-mounted display system). These displays typically involve presenting cues to the central field (e.g., central ~40˚). While the use of peripheral vision for the presentation of information about the aircraft state has also been investigated (Hennessy & Sharkey, 1997; Malcolm, 1984; Money, Malcolm, & Anderson, 1976; Sharkey, Hennessy, & Marlow, 2000), these techniques have not been adopted into in-service aircrew technology. Display technologies such as these will impose additional information processing requirements to certain areas of the visual field, and therefore might be expected to influence the FOV of requirements for aircrew tasks.

2.4.4 Automobiles

To our knowledge there are no studies that have tried to directly determine the FOV requirement for automobile operation with NVDs, though one study has applied the FOV restriction technique to estimate the FOV requirement during natural daytime viewing. Wood and Troutbeck (1991) manipulated available FOV using FOV-restricting goggles (20˚ binocular field, 40˚ binocular field, monocular viewing, or unrestricted) while subjects drove a fixed course. Significant performance decrements compared to the baseline unrestricted condition in terms of driving errors and time to complete the course were observed for the 20˚ condition but not for the 40˚ or monocular viewing conditions. This suggests that a 40˚ binocular FOV was sufficient to support driving performance in this task. However, to be clear, both the 40˚ FOV and monocular conditions showed performance decrements that were not statistically significant, and hence it remains possible that a more sensitive test might detect differences for these conditions. In a subsequent study with a similar methodology, Wood and Troutbeck (1994) compared a restricted FOV condition (90˚ horizontal and vertical) to a monocular condition and a baseline condition (150˚). The results showed that the restricted FOV condition produced longer driving time and more errors than the baseline condition as well as the monocular condition. This finding suggests that the FOV used by drivers is larger than 90˚, though due to the methodology used in this study it is unclear whether this is a horizontal or vertical FOV requirement or both.

3 Summary and Conclusions

In the present paper we reviewed empirical research on FOV requirements in order to derive an estimate of the required FOV for NVDs used during dismounted infantry tasks and the operation of vehicles. Accordingly, we considered research investigating FOV requirements during visual search, locomotion and manoeuvring, depth perception, visuomotor control, rotary-wing flight, fixed-wing flight, and automobile operation. Many of these studies were only able to provide a lower bound (i.e., FOV requirement is greater than a particular value). This is either because the study did not include an unrestricted field of view condition for comparison (e.g., in the case of some NVD field trials), or else a performance asymptote was not observed and instead performance was found to improve with increasing FOV size right up to the unrestricted FOV performance level, and consequently the only lower bound that can be inferred is the highest FOV setting that was tested. Also, few studies systematically distinguished between horizontal and vertical FOV, tending either to ignore vertical FOV or else hold it constant. In addition, as was discussed in Section 2, studies varied considerably in the method used to estimate FOV requirements. The most common technique was the use of FOV-restricted goggles during daytime performance, followed by FOV-restriction for HMDs while conducting task in a virtual environment or FOV-restriction for wide-angle simulators, and finally the use of actual NVDs or NVD imagery was rare. Because of the sparsity of available data for each task, we have elected to identify, for each task, the largest FOV requirement documented across all empirical methods used.

Accordingly, the following bounds were derived for each task and are summarized in Table 1. For visual search tasks, based on studies using actual NVDs, the horizontal FOV requirement is likely to be greater than 95˚ (i.e., a lower bound), and based on studies using HMDs in virtual environments the horizontal FOV requirement might exceed 112˚. The vertical field of view requirements for visual search in NVDs has not been systematically estimated, but based on the studies on visual search with HMDs, the vertical FOV requirement for visual search may be greater than 53˚. For manoeuvring and locomotion, subjects appear to use more than 80˚ horizontal and 90˚ vertical FOV. For depth perception and stereopsis, there is apparently no fundamental relationship to FOV, though research has shown that binocular NVDs are superior to monocular or biocular NVDs for manoeuvring and locomotion, and visual search. Visuomotor tracking and control tasks seem to require only central vision: 40˚ of vertical and horizontal FOV is apparently sufficient for performance. For rotary-wing aircraft operation, a horizontal FOV of 80˚ appears to be sufficient, though the vertical FOV requirements of this task have not been systematically investigated. Fixed-wing aircraft operation appears to require more than 150˚ of horizontal FOV. Vertical FOV has not been systematically investigated for fixed-wing flight, but the requirement might be 80˚ or greater. Finally, automobile operation is likely to require more than 90˚ of horizontal and/or vertical FOV.

Table 1: Summary of FOV requirements for each task. Values preceded by ">" indicate a lower bound; the real FOV requirement is likely to be greater than the value. Values preceded by "<=" indicate an upper bound; the real FOV requirement is likely to be less than that value. Values followed by "?" indicate that a) the value has not been established by a FOV-restricting technique or b) that it was not manipulated independently of the other FOV dimension, or c) it was determined using a circular FOV restriction.

Task	Horizontal FOV (˚)	Vertical FOV (˚)
Visual Search	> 112	> 53?
Manoeuvring and Locomotion	> 80	> 90
Depth Perception	Not dependent on HFOV, though binocular viewing important.	Not dependent on VFOV, though binocular viewing important.
Visuomotor Tracking	<= 40?	<= 40?
Rotary-wing	<= 80	> 40?
Fixed-wing	> 150, possibly <= 160	> 80?
Automobile	> 90?	> 90?

In order to design a general-purpose NVD with a suitable FOV for all these tasks, one must consider the most demanding horizontal and vertical FOV requirements across tasks. Within the tasks reviewed here, the largest FOV requirements were apparent for the operation of vehicles. A conservative estimate of the lower bound of the FOV requirement based on those data would suggest a system with at least 150˚ horizontal and 90˚ vertical FOV, which corresponds to 70% of the natural horizontal visual field and 67% of the natural vertical visual field. In contrast, when considering only the tasks carried out by a dismounted soldier (i.e., visual search, manoeuvring and locomotion, depth perception), the lower bound is slightly smaller (e.g., > 112˚ horizontal, 90˚ vertical). However, it must be noted that for the dismounted soldier tasks the estimates emerging from prior research are lower bounds (very few upper bounds were reported in prior research), and are limited to the subset of tasks that have been examined here. Therefore it is possible that the dismounted soldier FOV requirements are actually as large as the general overall requirements including those derived from vehicle operation tasks.

In addition, the general-purpose NVD system should be binocular and thereby provide stereo (e.g., overlapping) vision. The degree of binocular overlap (i.e., the size of the stereo FOV) is likely to be an important variable, though little research has directly investigated it. We speculate that the fields of view for either eye should overlap in the central 40˚ or greater, though empirical work is required to validate this estimate. We also speculate that the stereo FOV requirement might also differ as a function of task (e.g., dismounted soldier vs. vehicle operation tasks).

There are important caveats that accompany the present conclusions. First, the FOV requirements described above are based on experiments using very different methodologies: daytime viewing using FOV-restricting goggles, FOV restriction in HMDs while viewing VR imagery and comparisons of NVDs with different FOVs for both day and night task performance. Ideally, the FOV requirements for NVDs should be derived from experimentation that manipulates FOV while subjects perform tasks wearing NVDs, or viewing simulated NVD imagery (e.g., presented on an HMD). It is quite likely that the type of imagery viewed during task performance will influence the FOV requirement. For example, visual search within image-intensified (I2) imagery is likely very different than visual search of daytime imagery, due to differences in luminance, contrast, chromaticity, and the appearance of real world objects and scenery under different sensor imagers. Accordingly, different NVD sensor imaging solutions (e.g., short-wave infrared, long-wave infrared, I2, fused imagery) might entail different FOV requirements. Likewise, VR imagery presented over HMDs might also produce different FOV requirements than real-world imagery, for a given viewing task.

A second limitation for the present conclusions is that, as was mentioned earlier, very few of the studies reviewed were able to identify an upper bound on the FOV requirement. As such, while the present FOV requirements might be argued to be necessary for normal performance, the FOV that is sufficient for normal performance requires an estimate of the upper bound (i.e., how large is large enough). Therefore, the FOV requirements that are summarized and reported here should be interpreted with caution, and further experimentation is encouraged to further specify FOV requirements in these conditions.

Finally, the set of tasks considered in the present review is not exhaustive. For example, within the class of dismounted soldier activities one could further identify tasks that might have specific FOV requirements (e.g., moving while prone, mounting a vehicle, etc.). Similarly, for aircraft operation it is likely that the sub-tasks involved do not have equivalent FOV requirements, but instead the FOV requirement are likely to depend on the particulars of each sub-task. The sparsity of the literature on FOV requirements precluded the possibility of a more detailed task analysis for dismounted soldiers and vehicle operators. Accordingly we chose to divide the existing research into relatively broad task categories and then obtain conservative estimates of the lower bound on FOV requirements for those tasks. Therefore, this review provides an important starting point for estimating the lower bound on NVD FOV requirements and further empirical work is encouraged to further identify the task-specific FOV requirements for NVDs.

4 Future Work

This review identified several gaps in the literature on FOV requirements for NVDs that could be filled with further research. First, there are very few studies that have estimated the FOV requirements for tasks using actual NVDs or simulated NVD imagery. Instead, the vast majority of studies estimating FOV requirements for tasks use the method of day-time viewing with FOV-restricting goggles, or else FOV-restriction while viewing a VR environment within an HMD. It is very likely that empirically-derived FOV requirements depend strongly on the characteristics of the imagery viewed, and consequently research on FOV requirements for NVDs should be conducted using real NVDs or simulated NVD imagery. One drawback with the use of real NVDs is that it may be difficult to produce an "unrestricted" FOV condition, as all available NVDs will impose a restriction on the FOV. One solution would be to project simulated or real NVD imagery on a display surface that is wide enough to encompass the natural human visual field. The standard FOV-limiting experimental paradigm could then be used to infer the FOV requirement for a particular task. This approach would not be suitable, however, for tasks that require manoeuvring and locomotion.

The question of binocular FOV requirements for NVDs has received relatively little attention in research. Binocular FOV presents a considerable cost to engineers in designing NVDs because the binocular field (i.e., the visual field that is presented to both eyes) is effectively sampled twice, and this is accompanied by increases in weight, power consumption, and cost. Therefore, future research should seek to determine the minimum binocular FOV requirement for normal performance during NVD tasks. A further shortcoming in prior research is that vertical FOV is often ignored, and moreover horizontal and vertical FOV are rarely manipulated as independent factors. Instead, studies have tended to manipulate horizontal FOV while holding vertical FOV constant, or else both horizontal and vertical FOV are manipulated simultaneously (e.g., a circular FOV). Because performance could be limited by the restriction of the horizontal FOV or the vertical FOV, it is important that these factors are manipulated independently. It is also unclear to what extent horizontal and vertical FOV can compensate for one another when restricted.

An additional question for future research concerns the relative importance of the upper and lower visual field for task performance. For example, for dismounted soldiering tasks, it might be the case that an even split of the available FOV (e.g., 45˚ above and below horizontal meridian) might be less optimal than an system with a larger vertical FOV in the lower visual field (e.g., 60˚ below the horizontal meridian, 30˚ above) if visual information on the ground (i.e., obstacles, foot placement) is relatively important for dismounted operations. However, the suitability of such an arrangement might not hold for all tasks and accordingly further research would be required for its validation.

A related issue surrounding the estimation of FOV requirements with NVDs is learning and adaptation on the part of the user, as well as expertise. In particular, it is likely that users learn to accommodate FOV restrictions imposed by NVDs by developing conscious or unconscious strategies. Users might make additional head-movements in order to accommodate FOV restrictions, but they might also change their strategy in conducting the viewing task. For example, they might reduce their reliance on visual information in the periphery and rely more on information presented in the central visual field. Subjects might also adopt a more regimented scanning strategy when FOV is restricted. In the long term, users might develop expertise in using a particular NVD FOV configuration that mitigates performance deficits that were present during initial use. Therefore, one might distinguish between successively smaller FOV boundaries for a given task: the FOV at which performance becomes affected, the FOV for which performance is affected but normal performance can be achieved following learning, adaptation, and expertise on the part of the user, and the FOV for which performance is negatively affected and cannot be compensated through learning, strategies, etc.

Finally, one of the main assumptions incorporated into NVD technology is that the same information should be presented to the user across all areas of the visual field. For example, for current NVD technology, typically the image resolution is uniform across the entire visual field. However, the areas of the human visual field are not equal in terms of information processing: central vision is optimized for high acuity while the peripheral field is sensitive to lower spatial frequencies. Accordingly, for a uniform high resolution display, the high resolution information that is viewed with the peripheral visual field is filtered by retinal processing and information is lost. Therefore, a technological optimization could include presenting high resolution information to the central display area and lower resolution to the peripheral display area. The obvious difficulty with this approach is that the user can make eye movements and hence the user will be able to direct their high-resolution central vision to areas of the display that are lower-resolution (e.g., the peripheral part of the field of view). Nevertheless, because typical eye movements are less than 40˚, a simple scheme for central/peripheral resolution optimization could entail high resolution in the central 80˚ and lower resolution outside of that region. This optimization would reduce the requirement for sensor density outside of the central visual field and consequently reduce image data bandwidth and power consumption for the device.

In principle, further optimization of the information displayed to the user could be attained by employing a *gaze-contingent multi-resolutional display*. In such a system, the user's eye movements are monitored and the display is updated such that the area of the display within the user's central vision is rendered in high resolution and the area in the user's peripheral visual field is rendered in lower resolution (for a review see Reingold, Loschky, McConkie, & Stampe, 2003). Such a display system could be configured such that the resolution of the visual information in the display matches the spatial frequency sensitivity of the area of the user's visual field to which it is presented, and consequently resolution is not "wasted". Note that for this design the optimization is on the display side; there is no apparent savings in sensor density (i.e., the entire FOV must be sampled by sensors in high resolution). Furthermore, the gaze-contingent multi-resolutional display approach is technically challenging, relying on accurate eye tracking which may be difficult to achieve in a head-mounted NVD. While this idea has been discussed in the context of NVDs for over 25 years (Robinson & Wetzel, 1989; Rash et al., 1998; Seeman et al., 1992), it has yet to reach fruition in a marketed NVD system. Nevertheless, research is currently underway to achieve this outcome in the context of HMDs for training in a virtual environment (Eichenlaub, 2010).

In conclusion, there are numerous avenues for further research within the domain of FOV requirements for NVDs, and much of this research is required before strong conclusions can be made with regards to both general and task-specific FOV requirements for NVDs. However, based on the body of research to date we were able to provide evidence-based estimates of FOV requirements for various tasks that can serve as a starting point for future work in this domain.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
DRDC	Defence Research and Development Canada
FLIR	Forward Looking Infra-Red
FOV	Field Of View
HMD	Head-Mounted Display
JHMCS	Joint Helmet Mounted Cueing System
NVD	Night Vision Device
PNVG	Panoramic Night Vision Goggles
VR	Virtual Reality

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Night vision devices (NVDs) are widely employed by military and law enforcement to facilitate human vision when ambient light levels are low. One of the potential limitations to NVDs is that they present a relatively narrow field of view (FOV) compared to the user's natural field of view. A longstanding engineering problem surrounds the performance compromise that occurs when FOV is restricted in NVDs and of particular interest for designers of NVDs is the minimum FOV required for normal performance. However, FOV requirements for NVD devices are expected to differ depending on the task that is performed by the user. The present paper provides a review of empirical research to date investigating FOV requirements for viewing tasks that are relevant to dismounted soldiers and vehicle operators. Though the empirical literature on FOV requirements for NVD-related tasks was found to be sparse, we were able to obtain tentative lower bounds on FOV requirements for NVDs. An all-purpose NVD system based on these lower bounds would be binocular and have a FOV of at least 150˚ horizontal x 90˚ vertical. However, there are important caveats for these conclusions and the lower bound values reported here must be interpreted with caution. Accordingly, further research in this domain is recommended.

Les dispositifs de vision nocturne (DVN) sont largement utilisés par les militaires et la police afin de faciliter la vision humaine lorsque les niveaux de luminosité ambiante sont faibles. Une des limites possibles des DVN est le fait qu'ils offrent un champ de vision étroit comparativement au champ de vision naturel de l'utilisateur. Depuis longtemps, un problème d'ingénierie qui compromet le rendement survient en raison du champ de vision restreint des DVN. Les concepteurs des DVN s'intéressent particulièrement au champ de vision minimal requis pour un rendement normal. Toutefois, les exigences relatives au champ de vision des DVN devraient être différentes selon la tâche que l'utilisateur exécute. Le présent document passe en revue les recherches empiriques menées jusqu'à maintenant sur les exigences relatives au champ de vision nécessaire aux tâches de visualisation propres aux soldats débarqués et aux conducteurs de véhicules. Même si nous avons constaté que la documentation empirique sur les exigences relatives au champ de vision requis pour effectuer les tâches liées à l'utilisation des DVN est plutôt rare, nous avons pu obtenir des limites inférieures provisoires. Un système DVN tout usage reposant sur ces limites serait binoculaire et aurait un champ de vision total de plus de 150o à l'horizontale sur 90o à la verticale. Toutefois, il faut apporter d'importantes mises en garde concernant ces conclusions, et les valeurs des limites inférieures indiquées doivent être interprétées avec prudence. Par conséquent, il est recommandé d'effectuer d'autres recherches dans ce domaine.

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Night vision; NVGs; Field of view.