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The effects of vibration frequencies on physical, perceptual and cognitive performance

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Defence R&D Canada
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Abstract

In the study of crewmember performance in land-driven vehicles, it is necessary to consider the effects of vibration on the human body. The Advanced Vehicle Architecture for a Net enabled Combat Environment Technology Demonstrator Project (ADVANCE TDP) aims to demonstrate improved crew performance using an integrated multi-layered vectorics network, supported by an active suspension system that stabilizes the vehicle platform. This review discusses the effects of different frequencies and magnitudes of vibration on specific aspects of performance: manual control, vision, perception and cognition. The results of the numerous studies that have been done on manual tracking and visual acuity during vibration exposure have been well-documented and summarized. It has been demonstrated that vibration does not significantly affect performance on simple perceptual tasks involving auditory or visual detection of signals. Vibration has been shown to have a negative effect on complex cognitive tasks; however, vibration frequency or magnitude dependencies have not been proven.

Résumé

Pour étudier le rendement des équipes circulant à bord de véhicules terrestres, il est essentiel de tenir compte des effets des vibrations sur le corps humain. Le projet relatif à l'architecture de véhicule avancée pour environnement de combat réseau-centrique (ADVANCE TD) vise à démontrer le rendement accru des équipes utilisant un réseau multicouches intégré de vétronique conjugué à un système de suspension active destiné à stabiliser la plateforme du véhicule. Ce document passe en revue les effets de différentes fréquences et amplitudes vibratoires sur divers aspects du rendement, comme la commande manuelle, la vision, la perception et la cognition. Les conclusions des nombreuses études réalisées sur la poursuite manuelle et l'acuité visuelle durant l'exposition à des vibrations ont été largement étayées et résumées. Il a ainsi été démontré que les vibrations affectent peu le rendement lors de tâches perceptuelles simples faisant appel à la détection de signaux auditifs ou visuels. En revanche, il a été établi que les vibrations nuisent aux tâches cognitives complexes; il reste toutefois à prouver qu'il en va de même de la fréquence ou de l'amplitude des vibrations.

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Executive summary

The effects of vibration frequencies on physical, perceptual and cognitive performance

Nakashima, Ann; Cheung, Bob; DRDC Toronto TR 2006-218; Defence R&D Canada – Toronto; October 2006.

The Advanced Vehicle Architecture for a Net enabled Combat Environment Technology Demonstrator Project (ADVANCE TDP) has been established by Defence R&D Canada to demonstrate improved crew performance in military combat and combat support vehicles. This is to be achieved through two objectives: 1) the integration of a multi-layered vecronics network, whereby all systems will be accessible through each of the crew workstations, and 2) the development and integration of an active suspension system to minimize the vehicle vibration, thereby allowing a stabilized environment for use of the vecronics network. An active suspension takes dynamic energy from the ground, analyzes it, and applies an appropriate energy signal to compensate for the ground roughness and enables a smoother ride. However, because real ground surfaces and the resulting vibration exposure are complex, it is not possible to eliminate the vibration completely. It is thus of interest to know which vibration frequencies have the largest effects on human performance, and what magnitudes are required to produce a performance decrement. This review of performance studies focuses on the effects of vibration on manual, visual, perceptual and cognitive tasks.

Numerous studies have investigated the effects of vibration on manual tracking tasks. The majority of the studies used vertical (z-axis) vibration rather than horizontal (x- and y-axis) vibration. The effects were best summarized by McLeod and Griffin (1986), who produced a design guide for manual tasks in vibration environments. Vibration frequencies in the region of whole-body resonance (2 to 10 Hz for vertical vibration; below 3 Hz for horizontal vibration) may have adverse effects on manual task performance. Precise manual tasks such as writing are affected the most by vibration of 4 to 6 Hz, and errors increase approximately linearly with vibration magnitude. Subjects described writing as being “very difficult” when the vertical vibration magnitude was 1.0 m/s^2 or higher.

Vibration exposure may cause relative movement between the viewed object and the retina, resulting in a blurred image. The vestibular system functions to stabilize gaze and ensure clear vision against both volitional and passive mechanical disturbance through the vestibulo-ocular reflex and vestibulo-spinal reflex. Pursuit eye movements tend to suppress the vestibulo-ocular reflex at vibration frequencies below 1 to 2 Hz, but at higher vibration frequencies, visual acuity is affected. Decreased visual performance is generally affected between 2 and 20 Hz, where the primary and secondary body resonances occur.

Physiological changes, reaction time and performance on cognitive tasks during vibration exposure have also been studied in the laboratory. No significant effects on skin temperature or heart rate have been shown. Performance of tasks involving simple reaction time was not significantly affected. Vibration has been shown to have a negative affect on more complex cognitive tasks, such as those involving short- and long-term memory. However, the relationships between vibration frequency and magnitude on performance are unclear.

Sommaire

The effects of vibration frequencies on physical, perceptual and cognitive performance

Nakashima, Ann; Cheung, Bob; DRDC Toronto TR 2006-218; R & D pour la défense Canada – Toronto; Octobre 2006.

Le projet d'architecture de véhicule avancée pour environnement de combat réseau-centrique (ADVANCE TD) a été mis sur pied par Recherche et développement pour la défense Canada afin de démontrer le rendement accru des équipes circulant à bord de véhicules de combat et de soutien au combat. L'amélioration du rendement passe par la réalisation de deux objectifs : 1) l'intégration d'un réseau multicouches de vétronique, dans lequel tous les systèmes pourront être accessibles sur chacun des postes de travail de l'équipe, ainsi que 2) la conception et l'intégration d'une plateforme de suspension active capable de réduire au minimum les vibrations du véhicule et de fournir ainsi un environnement de travail suffisamment stable pour utiliser le réseau de vétronique. Une suspension active absorbe l'énergie dynamique du sol, l'analyse, puis applique un signal d'énergie équivalent visant à compenser les aspérités du sol, ce qui permet d'amortir les vibrations lors du déplacement. Cependant, il est impossible d'éliminer entièrement les vibrations, étant donné la complexité des surfaces du sol et des vibrations elles-mêmes. Il est donc intéressant de connaître les fréquences vibratoires qui ont un impact majeur sur le rendement humain, ainsi que l'amplitude vibratoire à partir de laquelle le rendement commence à décroître. Notre examen des études de rendement s'intéresse principalement à l'incidence des vibrations sur les tâches manuelles, visuelles, perceptuelles et cognitives.

Nombre d'études ont analysé les effets des vibrations sur les activités de poursuite manuelle. La majorité de ces études se sont penchées sur les vibrations verticales (axe z) plutôt que sur les vibrations horizontales (axes x et y). Ces effets sont particulièrement bien résumés par McLeod et Griffin (1986), qui ont rédigé un guide de conception prenant en compte les tâches manuelles effectuées dans des environnements vibratoires. Les fréquences vibratoires proches de la zone de résonance du corps entier (vibrations verticales : de 2 à 10 Hz; vibrations horizontales : de moins de 3 Hz) peuvent nuire à l'exécution de ces tâches. Des tâches manuelles précises, comme écrire, sont des plus difficiles à exécuter lorsque la fréquence vibratoire se situe entre 4 et 6 Hz; la relation entre le nombre d'erreurs et l'amplitude des vibrations est alors pratiquement linéaire. Les sujets ont mentionné qu'il était « très difficile » d'écrire lorsque l'amplitude des vibrations verticales était égale ou supérieure à 1 m/s^2 .

L'exposition à des vibrations peut induire un mouvement relatif (décalage) entre l'objet fixé et la rétine, ce qui contribue à restituer une image floue. Le rôle du système vestibulaire consiste alors à stabiliser le regard et à assurer une vision claire, malgré les perturbations mécaniques tant volontaires que passives, par le biais du réflexe vestibulo-oculaire (ou phénomène des yeux de poupée) et du réflexe vestibulo-rachidien. Lorsque les fréquences vibratoires sont en deçà de 1 à 2 Hz, les mouvements oculaires de poursuite suppriment généralement le réflexe vestibulo-oculaire; on constate toutefois une baisse de l'acuité visuelle au-delà de ces valeurs. Ainsi, une diminution de l'acuité visuelle est habituellement observée entre 2 et 20 Hz, zone où se produisent les résonances primaire et secondaire.

Les changements physiologiques, le temps de réaction et le rendement lors de l'exécution de tâches cognitives en environnement vibratoire ont aussi fait l'objet d'études en laboratoire; aucun effet notable sur la température de la peau ou la fréquence cardiaque n'a été observé. L'exécution de tâches faisant appel à un temps de réaction simple n'était pas non plus très affectée. Il a été prouvé que les vibrations exercent un effet négatif sur les tâches cognitives complexes, comme celles nécessitant de recourir à la mémoire à court et à long terme. Cela dit, l'incidence de la fréquence et de l'amplitude vibratoires sur le rendement n'a pas encore été clairement établie.

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Introduction

In air, land and sea transport, military personnel often experience discomfort attributed to the motion of the vehicle. Whole-body vibration (WBV) occurs when the mechanical vibration from the vehicle is transmitted to vehicle occupants. The amount of vibration exposure depends on a number of factors, including the type and design of the vehicle, the speed at which the vehicle is travelling, the environmental conditions, and the body posture. Repeated and prolonged exposure to vibration has been linked to fatigue, pain and even injury over time. During exposure, vibration can also have negative effects on performance of the tasks at hand.

WBV generally occurs in three axes: fore-to-aft (x-axis), lateral (y-axis) and vertical (z-axis). Rotational vibration about the x-, y- and z-axes (called roll, pitch and yaw, respectively) may also occur, but is infrequently discussed in the literature in the context of WBV. The basic method for determining the magnitude of WBV is the root-mean-squared (rms) acceleration, in units of m/s^2 . Vibration may be sinusoidal (containing only a single frequency) or complex (containing multiple frequencies). In practice, vibration exposure is always complex, although there may be certain frequencies that are dominant. The vibration frequency range that is considered important for health, comfort and perception is 0.5 to 80 Hz (ISO, 1997); the discussion in this document will be limited to this frequency range.

The existing standards for the evaluation of WBV (ISO 2631, BS 6841 and the European Directive 2002/04/EC) give guidelines or limits for vibration exposure that may be uncomfortable or pose health risks. They do not discuss the effects of WBV on performance. Performance effects are of interest for military applications. Early studies of performance in vibration were prompted by the problems related to low-altitude, high-speed flight (Grether, 1971; Shoenberger, 1972). Problems arising from vibration exposure can also exist in land operations. For example, in a command and control vehicle, a soldier would have to see displayed text and graphics (perception), understand the display (cognition), communicate and collaborate (team performance) and use input or control devices (motor activities) (Hill and Tauson, 2005).

In the ADVANCE TDP (Advanced Vehicle Architecture for a Net-Enabled Combat Environment, Technology Demonstration Project), the requirements of an active suspension system are to be defined. The suspension should compensate for vibration that may affect soldier performance. In order to design such a system, knowledge of the effects of different frequencies and magnitudes of vibration on the human body is required. The purpose of this review is to summarize the effects that different types of vibration exposure have on the physical, perceptual and cognitive performance of individuals.

Manual Tasks and Tracking

Controlled movement of the limbs is required for flying aircraft, driving ground vehicles and operating construction machinery. For operators of these vehicles, for whom tracking is the primary task, the vibration of the vehicle could have a significant impact on performance. The extent to which tracking performance is affected could depend on a number of factors, including the frequency and amplitude of vibration, the type of vibration (single frequency or random) and the duration of exposure. The effects of vibration on tracking performance were studied by many investigators in 1960s. A number of different approaches were used. Hornick (1962) and Buckhout (1964) studied tracking errors while varying the frequency and amplitude of a sinusoidal vibration input. Harris et al. (1964) kept the vibration frequency constant at 5 Hz and studied tracking performance for different vibration amplitudes. The effect of the spectral content of random vibration signals on tracking was studied by Holland (1966). Harris and Shoenberger (1966) investigated tolerance thresholds by varying the minimum vibration amplitude required for performance decrement for several frequencies. Fatigue effects were studied by Hornick and Lefritz (1966), who studied tracking performance during a 6-hour exposure period in the interest of pilot performance. The numerous approaches that were used to study tracking and manual task performance in an environment where vibration is possible make it difficult to summarize the effects. A number of authors have written review papers on this topic.

In a review by Grether (1971), it was concluded that decrements in tracking performance have been found for vertical (z-axis) vibration frequencies between 2 and 12 Hz, with the greatest decrements occurring at the lower end of the frequency range. In horizontal (x- and y-axis) vibrations, tracking errors were the greatest between 1 and 3 Hz. Grether concluded that the magnitude of the vibration had a larger effect on tracking performance than did the frequency. Shoenberger (1972) noted that tracking error generally increased as the magnitude of vibration increased, and that performance was most sensitive to 5 Hz vertical vibration. Collins (1973) expanded on Grether's review by plotting the results of previous studies as percentage of errors on a vibration magnitude vs. frequency graph (for z-axis vibration). These graphs showed that 15-20% tracking error could be expected for vibration as low as about 0.14 m/s^2 rms at 0.75 and 5 Hz; however, there were few studies that used frequencies below 5 Hz and thus very little data exists to support the effects at low frequencies. It was suggested that below 3 Hz, no amplification of the input vibration occurred at the head and arms and that maximum amplification occurred between 3 and 6 Hz. Above 6 Hz, amplification of the input vibration decreased. These conclusions were all for z-axis vibration, as the few existing studies that used x- and y-axis vibrations did not produce consistent results. No significant differences were found between sinusoidal vibration and random vibration containing a sinusoid of the same frequency and comparable amplitude (Collins, 1973).

More complex studies were performed in the 1970s. Cohen et al. (1977) investigated performance on a four-limb tracking task (e.g., as in the operation of a construction vehicle such as a bulldozer) during exposure to vibration. Out of the four conditions (no vibration, 2.5 Hz vibration, 5.0 Hz vibration and 2.5 + 5.0 Hz mixed vibration at 0.7 rms m/s^2), the mixed vibration caused the greatest performance decrement by 24%. The 5 Hz sinusoidal

vibration and the mixed vibration containing the 5 Hz frequency were found to have similar transmissibility between the vibration surface and head/shoulders.

Lewis and Griffin (1976) studied the mechanism behind tracking errors during vibration exposure. Rather than analyze the overall performance of the operator system, the various components of the system and how they were affected by the vibration were analyzed. For example, the amount of vibration transmitted to the controlling limb depended on the seat characteristics and the postural position of the body, while the extent to which performance was affected depended on the amount of support given to the controlling limb, design of the controller (e.g., steering wheel or stick) and the efficiency of kinaesthetic feedback (e.g., how the muscle spindles tolerate and react to the vibration). The results indicated that a possible source of error with respect to tracking performance was the interference in the muscle spindle feedback caused by the vibration. Tracking error was reduced when the stiffness of the controller was increased.

McLeod et al. (1980) studied the effects of ship motion on three distinct manual motor skills and reported that tracking with an unsupported movement of the arm and tracking with a supported arm showed marked degradation under moving conditions. However, the motion did not appear to affect keyboard digit punching with unsupported hands. These results suggest that the degree to which the arms are supported, as well as the nature of the task itself, have a direct effect on performance (e.g., fine motor control skills versus ballistic punching with fingers). Similarly, Crossland and Lloyd (1993) and Wertheim et al. (1995) reported reduced motor control due to ship motion in visual motor computer tracking, and that ship motion also interferes with paper and pencil tasks. Using static and dynamic conditions in a ship motion simulator, statistically significant differences were found between the two conditions for hand steadiness, arm-hand steadiness, and the speed at which psychomotor tasks were completed (Holcombe and Holcombe, 1997). The results of these studies suggest that while ship movements are likely to affect motor control, performance will depend on the experience of the subjects in performing the tasks on a moving platform.

McLeod and Griffin (1986) wrote a design guide for manual tasks in vibration environments. Performance on manual tasks is more disrupted in the region of whole-body resonance. This region is normally between 2 and 10 Hz for vertical (z-axis) vibration and below 3 Hz for horizontal (x- and y-axis) vibrations. Using the results of a series of experiments performed over a 10-year period, the effects of different frequencies and amplitudes of vibration were observed for different manual tasks. For writing tasks, subjects had the most difficulty when exposed to vertical vibration frequencies between 4 and 6 Hz, and the tasks were described as being “very difficult” at vibration magnitudes of 1.0 m/s^2 rms and higher. Tracking error at a given vibration frequency was found to increase approximately linearly with increasing vibration magnitude, with 5 Hz vibration having the steepest slope. For multi-axis vibration when significant vibration occurs in more than one axis, greater disruption should be assumed than when motion is only in one axis.

Vision

Vibration that causes relative movement between the retina and the visual display may produce a blurred image, degrading visual performance. These movements may arise from vibration of the display, vibration of the observer, and vibration of both the display and the observer. The vestibular system (organ of balance) functions to stabilize gaze and ensure clear vision against both volitional and passive mechanical disturbances through the vestibulo-ocular reflex and vestibulo-spinal reflex. The frequency response of these two reflexes is below 1 Hz. Therefore, within the nauseogenic range of passive oscillatory motion, oculomotor pursuit (eye movements to follow objects of interest) and compensatory eye movement to body motion are generally well maintained. If the frequency of oscillation of the visual display or the observer increases above 1 Hz, the object-following eye movements lag behind and the image becomes less clear. In addition, the effects of translational (linear oscillation) vibration of the observer decreases with increasing viewing distance, but the effects of rotational oscillation of the observer are independent of the viewing distance. When both the display and the observer oscillate in phase at low frequencies (below 1-2 Hz), the pursuit eye movements tend to suppress the vestibulo-ocular reflex and visual performance is maintained. As the vibration frequency increases, there is an increased phase difference between the visual display and the observer's head; suppression of the vestibulo-ocular reflex is not possible and visual performance will decrease.

Among all visual tasks, the monitoring of visually presented information is important in all vehicles, particularly when it is necessary to read alpha-numeric characters (e.g., in a cockpit). Shoenberger (1972) reviewed some of the early studies of the effects of vibration on visual acuity. The studies generally agreed that visual performance decreased with increasing vibration magnitude, but there was poor agreement on which vibration frequencies caused the most problems. Some studies did not find any general frequency effects at all. It was concluded that there were three frequency-dependent factors that affect visual performance: 1) compensatory tracking movements of the eye, which preserve visual acuity for low-frequency vibration as indicated above (below about 1 to 2 Hz), 2) amplification or attenuation of vibration from the seat to the head, and 3) resonances within the eye at high frequencies (above 20 Hz). These conclusions were made only for vertical vibration.

In a review by Grether (1971), it was concluded that visual performance was affected by vibration frequencies between 10 and 25 Hz. Collins (1973) suggested that, from the results of laboratory studies comparing vibration of the subject only and vibration of the display only, subject vibration affected visual acuity over 10 Hz while display vibration affected acuity below 10 Hz. However, in the context of vehicle operation, it is likely that the operator and the visual display would both be vibrated, though not necessarily simultaneously.

Lewis and Griffin (1980a, 1980b) studied the effects of vibration exposure on the reading of numerical displays. Noting that the transmission of vibration from the seat to the head would have an impact on performance, an experiment was performed using two types of seats: 1) flat, hard wooden surface with no backrest and stationary footrest, and 2) hard wooden seat with backrest and foot rest that moved with the seat frame; the geometry of this seat was similar to that in a Westland Sea King helicopter. The visual display was fixed, and the subjects were required to read a matrix of 50 numbers. Using vibration frequencies at half-

octaves between 2.8 and 31.5 Hz, it was found that vertical vibration had a significant negative effect on tracking performance up to and including 31.5 Hz for the helicopter seat, but only up to 11.2 Hz for the flat seat. The number of reading errors showed linear trends with increasing vibration magnitude. Vibration in the x-axis did not have a significant effect for the flat seat, but a significant effect was seen for the helicopter seat between 4 and 16 Hz. Vibration in the y-axis did not significantly affect reading performance.

In another series of experiments by Lewis and Griffin (1980b), vertical vibration was found to affect reading time at frequencies up to 22.4 Hz, and maximum sensitivity for reading errors occurred for vertical vibration frequencies around 11 Hz. Reading errors of 10% occurred for levels as low as 0.2 m/s² rms. In testing the effect of reading distance on reading errors due to vibration, low frequency vibration (3.15 Hz) was found to cause reading errors only at close viewing distances. Higher frequencies (16 Hz) affected reading accuracy at all distances, with linear increases in error with vibration magnitude. In the third experiment, predictions of reading error for complex vibration exposures were made using the rms level, rmq level (root-mean-quad) and most severe component (the largest single-frequency spectral magnitude of the vibration signal). The rmq and most severe component methods gave the best predictions in most cases. In general, reading errors produced by most of the subjects under the complex frequency exposure were less than those produced by the largest spectral component alone. Griffin and Hayward (1994) reported that during fore-and-aft (x-axis) and lateral (y-axis) whole-body vibrations, reading speed in seated subjects was significantly reduced at frequencies between 1.25 Hz and 6.3 Hz, with greater impairment at higher magnitudes of vibration. Maximum interference with reading was reported at 4 Hz, and the effect was greater for x-axis vibration. Measurements of reading speed also revealed that subjects consistently overestimated their reduction in reading speed.

Visual search within a head-fixed display (helmet-mounted display) has also been studied and found to be degraded by whole-body angular oscillation at 0.02 Hz (at $\pm 155^\circ$ /s peak velocity) (Guedry et al., 1982). The subjects also exhibited motion sickness within 5 minutes of exposure. Exposure to 2.5 Hz (at $\pm 20^\circ$ /s peak velocity) produced equivalent performance degradation on the visual search task, but did not produce signs and symptoms of motion sickness within the same exposure time.

A design guide for visual displays in vibration environments was published by Moseley and Griffin (1986). As with manual tracking performance, the extent to which vibration affects visual acuity depends on how much vibration is transmitted from the seat. Below 2 Hz, the transmissibility is unity and there are no significant body resonances. The greatest transmission occurs at frequencies between 2 and 10 Hz, where the major resonance of the body occurs. Between 10 and 20 Hz, secondary body resonances may occur and above 20 Hz, the vibration is attenuated by the body structures and the transmission is less than unity. For the helicopter seat mentioned in the experiment above (Lewis and Griffin, 1980a), reading performance was most sensitive to vibration between 5 and 11 Hz. Vibration magnitudes at this frequency range (between 0.5 and 1.0 m/s² rms) were found to produce a 20% mean reading error. For vibration in the x-axis using the same seat, maximum sensitivity occurred at 5.6 Hz, with a magnitude of about 1.0 m/s² rms causing 20% mean reading error. Vibration in the y-axis has not been studied extensively, but is thought to have a less severe effect on visual acuity than x- and z-axis vibrations. When there is vibration in multiple axes, it is expected that performance would be more negatively affected than if the vibration occurred in

a single axis. The guide also gives recommendations for display character size, character separation and viewing distances (Moseley and Griffin, 1986).

Physiological Measures

In some studies of human performance during vibration exposure, physiological parameters were measured as secondary indicators of performance. Holland (1966) measured skin temperature and heart rate during a 6-hour exposure to vibration, during which the subjects performed tracking, and auditory and visual vigilance tasks. Subjects were exposed to mixed vibration of 1 to 6 Hz with a peak at either 2 Hz or 5 Hz, at magnitudes of 1.2 and 1.6 m/s² rms. Average heart rates were elevated at the beginning at the exposure period, declining until the 4th hour and then levelling off. The average heart rate was the highest for the 1.6 m/s² rms vibration magnitude and lowest for the control condition, although it was not stated if the differences were significant. Changes in skin temperature between the two groups and vibration magnitude conditions were not significant. Hornick and Lefritz (1966) also found that heart rate was elevated at the onset of vibration, but gradually returned to a normal resting state. Skin and rectal temperatures, body weight and heart rate were measured by Grether et al. (1971) while subjects performed various tasks under different stress conditions, including vibration. The vibration alone condition did not have any significant effects on the physiological measures. Other studies have examined the combined effects of stressors (noise, vibration, heat) on physiological measures (Manninen, 1984, 1985); however, since the interactions of combined stressors are not well understood, the effects on the body due to vibration alone could not be determined.

Perception and Cognition

Perceptual tasks require visual and auditory detection of various signals. Shoenberger (1967) investigated the effects of vibration on three different perceptual tasks: target identification, probability monitoring and warning-lights monitoring. In the monitoring tasks, the subjects had to identify and react when changes in the dial settings or light patterns occurred. In the target identification tasks, the subjects identified which of two images presented sequentially was identical to a reference image. The tasks were performed during exposure to 5, 7 or 11 Hz vibration at levels of about 2 to 3 m/s² rms. The only significant performance decrement between the vibration and the control conditions was the response time for the warning lights monitoring task during 7 Hz vibration. There was generally an increasing trend for response time with vibration intensity.

The results of experiments that investigated reaction time, pattern recognition and monitoring during vibration exposure were summarized by Grether (1971). In most cases, exposure to sinusoidal or random vibration did not produce any significant increases in simple reaction time, no matter what frequencies were used. Increases in reaction time over time were seen in experiments using long exposure durations (4 to 6 hours), but these results were thought to be decrements in vigilance that were not solely due to the vibration exposure. Similar conclusions were made in Shoenberger's review (1972). However, Poulton (1978) argued that vertical vibration at 5 Hz acts as an alerting mechanism and can increase vigilance. Malone (1981) reported that no motion-induced performance decrement was observed during long duration radar monitoring. It was also suggested that biomechanical effects might indirectly interfere with perceptual performance when perception itself is not affected. For example, in the absence of oculomotor factors (as described earlier) there is little evidence that ship movements affect perception.

Shoenberger (1972) also reviewed studies that investigated performance on simple mental tasks. Studies that involved only mental addition as the task and only vibration as the stressor did not show any performance decrement; however, performance decrements were shown in studies that used a combined task (e.g., mental addition and memory) or a combined stressor (e.g., vibration and noise). The effects of vibration on more complex cognitive processes were studied in subsequent years. Harris and Shoenberger (1980) studied the effects of noise and vibration on performance of a complex counting task, but they did not use a vibration-only condition. Sherwood and Griffin (1990) investigated the effects of 16 Hz vibration of magnitudes 1.0, 1.6 and 2.5 m/s² rms on the performance of a short-term memory task. The subjects were presented with sets of 2, 4 or 6 letters on a screen for 1, 2 and 3 seconds, respectively, and were asked if a probe letter presented 1 second later had been presented in the preceding set. Response time and accuracy were used as indicators of performance. The results for both measures clearly indicated that vibration impaired the memory scanning task, especially for the 1.0m/s² rms vibration. Significant increases in reaction time, but not errors, were seen for the 1.6 and 2.5 m/s² rms vibration.

Sherwood and Griffin (1992) studied the effects of the environment (vibratory versus static) on information processes of learning and recall. The subjects were required to learn 32 names and to which of two teams did they belong. Half of the subjects performed the task in the first session while static and the other half were exposed to 16 Hz, 2.0m/s² rms vibration; this was

the learning session. The vibration stimulus was chosen to approximate the conditions in rotary aircraft. The subjects returned one week later and long-term memory was tested as they performed the same task with the same list of names, in either a static or vibratory environment; this was the recall session. Thus, there were four groups of subjects exposed to different pairs of conditions across the two sessions: 1) static, then static, 2) static, then vibratory, 3) vibratory, then static and 4) vibratory, then vibratory. The groups who were exposed to vibration in the first session performed significantly worse than the groups who were not vibrated. The results for the second session did not show any significant effect of the recall environment on the memory recall process. It was concluded that exposure to vibration affected the learning of associations rather than their subsequent recall.

There have been numerous studies conducted in both ship motion simulators and at sea to determine the effects of motion on cognitive abilities (Wertheim and Kistemaker, 1997, Holcombe, 1997). However, contrary to sailors' self-reports of increased fatigue when working aboard ships, no decrements in cognitive performance were found. It should be noted that many of these experiments were conducted within a ship motion simulator or at a low sea state, which are extremely limited motion conditions.

Ljungberg et al. (2004) also used 16 Hz vibration combined with helicopter noise to study their effects on short-term memory. The subjects were assigned to one of three conditions: low (77 dBA noise and 1.0 m/s² rms vibration), medium (81 dBA noise and 1.6 m/s² rms vibration) and high intensity (86 dBA noise, 2.5 m/s² rms vibration). Short-term memory was measured using a letter recall task similar to that used by Sherwood and Griffin (1990) that was described earlier. Performance was measured by response time. There were no significant differences between the response times of the three groups, indicating that a combined increase in noise and vibration amplitude did not affect short-term memory.

Application to Command and Control Vehicles

Many of the earlier studies of cognition and perception in vibratory environments were done in the interest of aircrew performance. In more recent years, research on performance in land vehicles has grown in application to mobile command and control operations. Tauson et al. (1995) studied cognitive performance and stress levels of passengers in a prototype command and control (C2V) vehicle while the vehicle was stationary, driven straight on a dirt road, and driven cross-country in a figure-eight pattern on a sandy stream bed. The subjects performed a subset of the Expanded Complex Cognitive Assessment Battery (CCAB) administered by computer at four workstations in the back of the vehicle. The four tests in the CCAB were: logical relations, information purchase, route planning and missing items. The results were analyzed for effects of road condition, test presentation order, time of day, and seat position in the vehicle (one seat faced towards the front of the vehicle, while the other three seats faced sideways). The road condition (road march versus idling), and the interaction of road condition, test presentation order and seat position had a significantly negative effect on performance on the logical relations test. The interaction of time, test presentation order and seat position was significant for the information purchase task. Route planning was negatively affected by test presentation order. Performance on the missing items task was affected by time and the interaction of time, test presentation order and seat position. The subjects reported moderate levels of stress while the vehicle was mobile compared to the pre-test and post-test conditions (idling). The authors concluded that the vehicle movement did not directly affect performance of the CCAB.

Schipani et al. (1997) used tests from the CCAB and the Criterion Task Set (CTS) to study cognition during mobile operations in the M113 armoured personnel carrier (APC). The chosen psychometrics were continuous recall, mathematical processing, grammatical reasoning, Sternberg's memory search, route planning and missing items. The M113 APC was driven on off-road terrain at 0, 10 and 20 mph to produce different vibration levels. The approximate vertical vibration levels for the three vehicle speeds (quantified by the most dominant frequency) were 0.3 m/s^2 at 12.5 Hz, 6.4 m/s^2 at 4 Hz and 8.6 m/s^2 rms at 3 Hz, respectively. The tests were performed 8 times in contiguous 40-minute segments. The general finding of the study was that the combination of increased vibration levels and increased amount of time spent inside the vehicle (endurance) significantly impaired performance. Comparing the results among the CCAB and CTS tests (test difficulty), the subjects performed the route-planning test the slowest and with the least accuracy. The subjects achieved the highest percentage correct and fastest completion times on the continuous recall test. Comparing the results across sessions (endurance), performance on the time-sharing test suffered the greatest decrease in accuracy over time, and the missing items test was the worst in terms of increased completion time. Performance on Sternberg's memory task was affected the least for both percent correct and completion time. Performance on all of the tests decreased significantly from the baseline when the vehicle was driven at 20 mph (highest vibration exposure).

Cognitive ability, motor coordination and stress levels have also been studied in C2Vs by Cowings et al. (2001). However, the tests were only administered when the vehicles were parked. The focus of these studies was mainly to determine performance effects as a result of motion sickness in the C2V. Vibration frequencies of less than 0.5 Hz have been shown to

cause symptoms of motion sickness, which include drowsiness, headache, nausea and emesis. All of the subjects reported at least some symptoms of motion sickness, which appeared to have an effect on performance in both the cognitive and motor tests. Vibration measurements were not taken, so the characteristics of the vibration exposure remain unknown.

It appears that in a mobile command and control environment, the vehicle occupants may be exposed to vibration spectra that includes nauseogenic frequencies. Thus, the laboratory studies discussed in the previous sections may not be realistic as cognitive performance may be affected by mechanical vibration and sickness induced by the vehicle motion.

Conclusion

To summarize, previous authors have concluded that:

- Tracking performance and writing are most affected for vertical vibration around 5 Hz. Tracking error increases approximately linearly with vibration magnitude. The use of supports (e.g., armrests) can help to reduce the vibration effects. Relatively little is known about the effects of horizontal vibration, although it has been suggested that frequencies below 3 Hz have a negative effect on tracking.
- Visual acuity is affected between 2 and 20 Hz. The use of optimal viewing distances, font/image size and collimated displays can alleviate this problem.
- Vibration does not appear to have significant effects on skin temperature or heart rate.
- Vibration does not appear to affect performance on tasks that involve simple reaction time.
- Vibration may have a negative effect on more complex cognitive processes, although it is not clear if there is a relationship between frequency and amplitude on performance.

Relatively little is known about the effects of vibration in the horizontal (x and y) axes. Vibration in these axes may be a significant factor for passengers in command and control vehicles or armoured personnel carriers, as they are often seated sideways to the direction of motion.

During mobile operations, it is likely that the vibration exposure will include the nauseogenic frequencies (< 0.5 Hz). Thus, it is important to take measurements of the vibration exposure in vehicles to determine the range of frequencies as well as any dominant frequencies. It is also important to consider that mechanical vibration, as well as motion sickness, may impact performance. For example, in the presence of mechanical vibration, but in the absence of motion sickness symptoms, how well can the subjects perform the task, and vice versa.

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List of abbreviations/acronyms

ADVANCE TDP	Advanced Vehicle Architecture for a Net-Enabled Combat Environment, Technology Demonstration Project
APC	Armoured Personnel Carrier
C2V	Command and Control Vehicle
CCAB	Complex Cognitive Assessment Battery
CTS	Criterion Task Set
dBA	A-weighted sound pressure level
ISO	International Organization for Standardization
Rmq	Root-mean-quad (for vibration acceleration)
Rms	Root-mean-squared (for vibration acceleration)
WBV	Whole-Body Vibration

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(U) In the study of crewmember performance in land-driven vehicles, it is necessary to consider the effects of vibration on the human body. The Advanced Vehicle Architecture for a Net enabled Combat Environment Technology Demonstrator (ADVANCE TD) project aims to demonstrate improved crew performance using an integrated multi-layered vectronics network, supported by an active suspension system that stabilizes the vehicle platform. This review discusses the effects of different frequencies and magnitudes of vibration on specific aspects of performance: manual control, vision, perception and cognition. The results of the numerous studies that have been done on manual tracking and visual acuity during vibration exposure have been well-documented and summarized. It has been demonstrated that vibration does not significantly affect performance on simple perceptual tasks involving auditory or visual detection of signals. Vibration has been shown to have a negative effect on complex cognitive tasks; however, vibration frequency or magnitude dependencies have not been proven.

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(U) whole-body vibration, motion sickness, C2V

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