WHOLE-BODY VIBRATION IN MILITARY VEHICLES: A LITERATURE REVIEW

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ABSTRACT

Military personnel are exposed to high levels of whole-body vibration in armoured vehicles. Since command and control operations are likely to become more mobile in the future, it is of interest to understand the effects of whole-body vibration exposure on human performance and communication. This paper is a review of the effects of whole-body vibration on hearing and cognitive performance. Exposure to vibration has been shown to exacerbate noise-induced hearing loss, which may have implications for radio communication and speech understanding. Vibration does not appear to affect performance for simple cognitive tasks, but it may degrade performance on more complex cognitive tasks, particularly if the exposure is of long duration. This could be of key importance in a command and control situation, in which operators are under high cognitive load. The severity of vibration that is experienced in armoured vehicles makes it difficult to perform realistic experiments in the laboratory, meaning that future studies of its effects on cognitive performance and communication will likely have to be performed in the field.

SOMMAIRE

Le personnel militaire est exposé à des niveaux élevés de vibrations globales du corps dans les véhicules blindés. Étant donné que les opérations de commandement et de contrôle seront de plus en plus mobiles dans l'avenir, il est important de comprendre les effets de l'exposition aux vibrations globales du corps sur la communication et le rendement humains. Le présent document est une étude des effets des vibrations globales du corps sur l'ouïe et le rendement cognitif. Il a été démontré que l'exposition aux vibrations exacerbe la perte auditive induite par le bruit, ce qui peut avoir des répercussions sur la communication radio et la compréhension de la parole. L'exposition aux vibrations ne semble pas altérer le rendement dans les tâches cognitives simples contrairement aux tâches plus complexes, en particulier si l'exposition est d'une longue durée. Ce facteur pourrait être d'une importance capitale dans le cadre des opérations de commandement et de contrôle, qui comportent une lourde charge cognitive pour les opérateurs. Compte tenu de l'intensité des vibrations auxquelles les conducteurs sont exposés dans les véhicules blindés, il est difficile de mener des expériences réalistes en laboratoire, ce qui signifie que les futures études des effets de l'exposition aux vibrations sur le rendement cognitif et la communication devront être menées sur le terrain.

1. INTRODUCTION

Exposure to vibration is inevitable in many occupational settings. Whole-body vibration occurs when the body is supported by a vibrating surface. 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 posture of the operator. Military personnel experience high levels of vibration in armoured vehicles. Command and control operations will likely become more mobile in the future, which will increase the cognitive and sensory demands on personnel while inside the vehicles (23). Clear communications and sharp situational awareness are essential for effective performance and, ultimately, survival during missions. It is thus of interest to understand the effects of vibration on hearing and cognitive function.

Guidelines for the measurement and evaluation of human exposure to whole-body vibration are defined by the International Organization for Standardization (ISO) in ISO 2631-1 (14). The frequency range that is most often associated with whole-body vibration is approximately 0.5 to 100 Hz (8). Vibration magnitude is generally measured in units of acceleration rather than the velocity or displacement between peak-to-peak movements. The preferred International System (S.I.) unit for vibration magnitude is meters-per-second-per-second (m/s^2), and measurements are often expressed as root-mean-squared (rms) values rather than peak values. The rms values are frequency-weighted according to weighting curves defined in ISO 2631-1, and averaged over time and frequency; this is the basic method for evaluation of whole-body vibration (14). Vibration signals that are measured in vehicles are usually complex in nature, containing occasional or repeated shocks (sudden, high acceleration vibration events). The basic evaluation method may underestimate the severity of vibration exposures that contain multiple shocks; other methods for assessing vibration of this type are given in ISO 2631-1 and ISO 2631-5 (14,15).

Translation vibration, or linear vibration, is generally measured in the fore-to-aft (x-axis), lateral (right to left side, y-axis) and vertical (z-axis) directions. The defined positions of the axes relative to the human body depend on whether the person is seated, standing or recumbent, and may differ slightly among published standards. In most cases, vibration is more significant in the z-axis than the horizontal axes. Maximum transmission of vertical vibration to the body typically occurs around 5 Hz. Human performance has thus been found to be affected the most when there is significant z-axis vibration at 5 Hz, and most laboratory investigations have studied the effects at this frequency. ISO 2631 states that vertical vibration levels of less than 0.315 m/s^2 rms are perceived as "not uncomfortable," while levels of greater than 2.0 m/s^2 rms are thought to be "extremely uncomfortable" (14). Vibration levels that are encountered in practice are often much higher than 2.0 m/s^2 rms (see for example, 23), which suggests that there are implications for adverse effects on human performance.

There are numerous review papers that discuss experiments on human performance in vibration, but to the author's knowledge, none have focussed on the effects on hearing and cognition. This review focuses on hearing and cognitive performance during exposure to whole-body vibration in the interest of communication and performance issues in armoured vehicles.

2. HUMAN PERFORMANCE IN VIBRATION

Experiments on human performance in vibration have historically sought to study the effects on physical, cognitive and sensory functions. The major themes of research in the 1960's and 1970's were tracking performance (manual control) and visual acuity in vibration. The results of such studies have been well-documented and summarized by a number of authors (4, 5, 7, 27), and will only be mentioned briefly in this paper. In the 1980's and 1990's, the attention turned towards the effects of combined stimuli (e.g. vibration in combination with noise and/or heat) on hearing and cognitive function. However, the effects of vibration on communication and complex cognitive task performance are still unclear. It is important to understand the effects of vibration on hearing and communication for the design and use of communication systems. Emphasis in this section will be placed on studies of hearing and cognition in vibration.

2.1 Visual Acuity and Manual Tracking Performance

In the past, the emphasis of human performance studies in vibration has been on visual acuity and manual tracking performance. Following a series of experiments that were performed from 1976 to 1985 (7), design guides for visual displays and manual tasks in vibration environments were written by Moseley and Griffin (21) and McLeod and Griffin (20).

When vibration is transmitted to the eye or the visual display, the result is usually a blurred image. In terms of reading performance, humans have been found to be sensitive to z-axis vibration between 5 and 11 Hz, and maximally sensitive to x-axis vibration at 5.6 Hz. Vibration in the y-axis does not have a significant effect on reading performance compared to the other two axes. Visual acuity is especially affected at viewing distances of less than 1.5 m. The use of collimated displays significantly improves visual resolution during vibration exposure (21).

For the purpose of discussing the effects of vibration on manual task performance, McLeod and Griffin described three types of tasks:

Type A: continuous, in which the subject controls their hand(s) freely in space;
Type B: continuous, in which the subject uses their hand(s) to operate a fixed controller;
Type C: discrete, in which a single operation is performed (such as pressing a button).

For simple Type A and B tasks, tracking error increases with vibration magnitude. In the case of Type B tasks, the use of arm supports may help to reduce the adverse effects of vibration. Little is known about the effects of vibration on Type C tasks. For z-axis vibration, disruption in task performance occurs for frequencies that are in the range of the body resonances, which occur between about 2 and 10 Hz. The greatest amount of manual task disruption has been found to occur between 4 and 6 Hz (3, 10, 11, 12, 28, 29). Body resonances in the x- and y-axes have been found to typically occur below 3 Hz (20).

2.2 Hearing

Since vibration is often accompanied by other stressors such as noise, heat or heavy physical activity, the effects of vibration on hearing are difficult to isolate. Studies on the effects of combined noise and vibration on hearing have been reviewed by Hamernik *et al*. (9). It has been suggested that whole-body and segmental (hand-arm) vibration tends to exacerbate low-frequency hearing loss in mining, forestry and lumber industry workers. However, the working environments that were studied are among the noisiest and most stressful of all industries. It is thus difficult to isolate the effects of vibration on hearing.

The effect of vibration on temporary hearing loss, or temporary threshold shift (TTS), was investigated in an experimental study performed by Okada *et al*. (22). Five male test subjects were seated on a vibrating table and exposed to 0.7 m/s^2 rms (2, 5 and 10 Hz), 3.5 m/s^2 rms (5, 10 and 20 Hz) and 7.1 m/s^2 rms (10 and 20 Hz) vertical vibration for a total of 60 min. The noise stimulus was recorded factory noise at 101 dB, and the subjects wore earplugs and earmuffs throughout the experiment. Hearing thresholds at 1 and 4 kHz were measured before the vibration exposure, after 20 min of exposure and at the conclusion of the experiment. When exposed to vibration alone, the greatest amount of TTS occurred for the 5 Hz vibration at 3.5 m/s^2, although it was considerably less than the TTS caused by noise exposure alone. When the 5 Hz vibration and noise were combined, the TTS was greater than with either stressor alone. The authors concluded that noise-induced hearing loss was aggravated by exposure to vibration.

Manninen studied TTS in men who were exposed to multiple stressors. The effects of both sinusoidal (5 Hz) and stochastic (bandwidth 2.8 to 11.2 Hz) vertical vibration on hearing were investigated in combination with noise and dynamic muscle work (18), and noise, heat and competition-type psychic load (19). The magnitude of vibration was 2.12 m/s^2 rms, and the noise stimulus was broadband noise of 90 dBA. Ninety subjects in the first study and 108 subjects in the second study were exposed to the stressors for 60 min. In both studies, the combination of noise and vibration was found to have an effect on TTS at 4 and 6 kHz. There were no clear differences in TTS when the subjects were exposed to sinusoidal versus stochastic vibration in the absence of other stressors. Seidel *et al.* (29) investigated mid- and high-frequency TTS (4, 6, 10 and 12 kHz) on subjects who were exposed to broadband noise of 92 dBA and 1.0 m/s^2 rms vertical vibration of 4 Hz. Six male test subjects were exposed to the stressors for a total of 90 min. The combined noise and vibration induced higher TTS at 4, 6 and 10 kHz compared to noise alone. The results of these studies support the conclusion made by Okada *et al.* (22) that vibration exacerbates noise-induced TTS at 4 kHz.

Voice communication was one of several performance measures studied by Grether *et al.* (6) during exposure to heat, noise and vibration. Ten test subjects were instructed to repeat a five-word phrase that was presented over a communication headset. The vibration test conditions were: 1) 5 Hz, 2.1 m/s^2 rms vertical vibration, 22°C ambient temperature, 80 dB broadband noise and 2) 5 Hz, 2.1 m/s^2 rms vertical vibration, 48.9°C ambient temperature, 105 dB broadband noise, for a duration of 35 min. Neither of the conditions had a significant effect on the percentage of words that were correctly repeated. However, since all of the hearing studies mentioned above found that vibration exacerbated noise-induced TTS at 4 kHz, which is known to be crucial to speech understanding (1), it is possible that prolonged exposure to vibration could impair communication. To the author's knowledge, there have been no long-duration studies of communication in vibration.

2.3 Cognitive Performance

In a 1971 review, Grether noted that little attention had been paid to the effects of vibration on intellectual functions (5). The studies that had been performed prior to Grether's review did not find any performance deterioration for reaction time, auditory and visual vigilance and pattern recognition during vibration exposure. Buckhout, for example, found that pattern recognition and reaction time were not affected by exposure to 5, 7 and 11 Hz vibration (2). In an experiment reported by Grether *et al.*, subjects did not show any performance decrement on a mental arithmetic test while being exposed vertical vibration of 5 Hz (6).

Experiments that have been performed since Grether's 1971 review have used more complex cognitive tasks. Harris and Shoenberger studied the effects of combined noise and vibration on cognitive performance using a complex counting task (10). The task involved keeping a simultaneous count of the flashes of three lights that flashed at different frequencies. Twelve subjects were exposed to 65 or 100 dBA broadband noise and 3.5 m/s^2 rms vibration composed of 2.6, 4.1, 6.3, 10 and 16 Hz sinusoids. When exposed to noise alone, the subjects performed better in 65 dBA noise than 100 dBA; however, when exposed to both noise and vibration, the subjects performed better in 100 dBA noise. Overall, the subjects performed the best when exposed to 65 dBA noise alone, and the worst when exposed to combined 65 dBA noise and vibration. The results suggested that the effects of noise and vibration on cognitive performance are interactive, but not necessarily additive.

Sherwood and Griffin investigated the effects of exposure to 1.0, 1.6 and 2.5 m/s^2 vertical vibration of frequency 16 Hz on a short-term memory task (25). Measurements were made of reaction time, number of attention lapses and number of errors using 16 test subjects. Impairment of short-term memory resulting from vibration exposure was indicated by all of the evaluation parameters, especially for the 1.0 m/s^2 vibration. In a subsequent experiment, the same authors studied learning and recall for 16 Hz vibration at 2.0 m/s^2 (26). In the first session, the 40 test subjects were asked to learn the names of members of an imaginary team. A week later, the subjects performed the same task with the same names, to assess long-term memory and re-learning ability. The results of the first session showed that the static subjects performed consistently better than the vibrated subjects. After the second session, it was found that the subjects could recall information that was learnt in one environment (static or vibratory) equally as well in the other environment.

Following the 1990 study of Sherwood and Griffin (25), Ljungberg *et al.* studied short-term memory using the same vibration conditions with the addition of helicopter noise (17). For the memory test, a Sternberg paradigm was used, in which sets of 2, 4 or 6 letters were presented to the subject for 1, 2 or 3 seconds respectively. The letters were then removed, and a probe letter appeared after a pause of 1 second. The subject gave a "yes" response if the probe letter had appeared in the set that was just presented, or "no" if it had not. Memory performance was assessed by speed of response. The test subjects were exposed to one of three intensity conditions: low (77 dBA noise, 1.0 m/s^2 rms vibration), medium (81 dBA, 1.6 m/s^2 rms vibration) or high (86 dBA, 2.5 m/s^2 rms vibration). There were no significant differences in response times due to intensity.

It is difficult to generalize the results of the studies

Table I: Rankings of test performance for the Schipani *et al.*'s field study on cognitive test performance (23).

Test Name (type of task)	Performance among tests (difficulty)		Performance change within tests over time (endurance)	
	% correct (1 = highest, 6 = lowest)	Completion time (1 = fastest, 6 = slowest)	% correct (1 = smallest decrease, 6 largest decrease)	Completion time (1 = smallest increase, 6 = largest increase)
Selective attention (continuous recall)	1	1	4	2
Inductive reasoning (mathematical processing)	3	5	4	4
Time sharing (grammatical reasoning)	2	2	6	5
Memorization (Sternberg's memory task)	5	4	1	1
Spatial orientation (route planning)	6	6	3	3
Speed of closure (missing items)	4	3	2	6

mentioned above to a workplace environment. Military personnel are exposed to multiple stresses that are often complex in nature, and combinations of stresses can have different effects on cognitive performance. Performing experiments in the field rather than the laboratory might produce findings that are more meaningful. One such experiment was performed by Schipani *et al.* (23). A battery of cognitive tests was administered to subjects as they conducted a field exercise similar to a mobile command and control situation. Four tests were chosen from the Criterion Task Set (CTS) and two from the Complex Cognitive Assessment Battery (CCAB) (23). The cognitive concepts tested were (with the type of task in parentheses): selective attention (continuous recall), inductive reasoning (mathematical processing), time sharing (grammatical reasoning), memorization (using Sternberg's paradigm described above), spatial orientation (route planning) and speed of closure (missing items). The M113 tracked armoured personnel carrier (APC) used for the experiment 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 performance on each test in terms of accuracy and completion time is shown by rank in Table I.

The general finding of Schipani *et al.*'s study was that the combination of increased vibration levels and increased amount of time spent inside the vehicle (endurance) significantly impaired performance. Noise levels were also measured, but the effect on performance was found to be small compared to vibration and endurance. Comparing the results among tests (test difficulty), the subjects performed the spatial orientation (route planning) test the most slowly and with the least accuracy. The subjects achieved the highest percent correct and fastest completion times on the selective attention (continuous recall) test. Comparing the results across sessions (endurance), performance on the time sharing (grammatical reasoning) test suffered the greatest decrease in accuracy over time, and the speed of closure (missing items) test was the worst in terms of increased completion time. Performance on the memorization (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). The results of these studies suggest that exposure to vibration alone does not affect the ability of humans to perform simple cognitive tasks. Impairment of cognitive performance appears to occur when 1) the task is complex, 2) vibration is combined with another stressor such as noise and 3) the vibration exposure is of long duration. The last two cases are important, because military vehicle operators are inevitably exposed to multiple stressors while on duty, and are sometimes required to drive for more than 12 hours at a time. Vibration-induced fatigue may be a factor in the decrement of cognitive performance over time.

3. DISCUSSION

Armoured vehicles are designed to be well-protected, durable and functional in adverse environmental conditions. This leaves little to no room for human factors engineering. As a result, whole-body vibration in armoured vehicles is different from the vibration that is experienced in other occupations such as truck drivers, construction workers and pilots. Passenger seatbelts are not always available or used when they are available. Lack of constraints causes the upper body movement of the passengers to be unpredictable and difficult to quantify, because both translational and rotational vibration in a moving coordinate system are occurring. There is also the issue of the crew commander, who often stands on

Table II: Exposure to vibration and repeated shock requiring attendance of a physician or medical doctor from ISO 13090-1 (18).

Duration of exposure in any one 24 h period	16 min	1 h	4 h	8 h
Acceleration magnitude, m/s^2 (frequency-weighted r.m.s. acceleration	2.2	1.6	1.1	0.9

the seat with their upper body exposed through the hatch. In this case, the vibration exposure is affected by bended knees and any contact of the upper body with the frame of the hatch. The adverse effects of the vibration exposure are further exacerbated by fumes, exposure to extreme temperatures, and, in the case of the passengers in the back of the vehicle, lack of an external field of view. These additional factors can contribute to disorientation, fatigue, nausea and dizziness.

The complex environment inside armoured vehicles makes it very difficult to replicate similar conditions in the laboratory. The International standard for experiments involving human exposure to vibration and shock (ISO 13090-1:1998 [16]) does not impose exposure limits, but gives limits for which the experiments can be performed without the presence of a physician or medical doctor; these are listed in Table II. Given these guidelines, experiments performed in the past in which subjects were exposed to high levels of vibration (22), or moderate levels of vibration for very long time periods (11, 13), would likely not be approved by an ethics committee today. As shown by Schipani *et al.* (23), the actual vibration levels in a vehicle can be very high (e.g. 8.6 m/s^2 at 3 Hz for the M113 travelling at 20 mph), making it impossible to expose test subjects to similar conditions in the laboratory. It may only be possible to study the effects of vibration in the field. However, in the field it would be difficult to isolate the effects of vibration from the effects of other stressors such as noise and heat.

There have been few studies on the effects of vibration exposure on communication. Previous research on the combined effects of noise and vibration on hearing have shown that vibration increased the amount of noise-induced TTS at the 4, 6 and 10 kHz octave bands (18, 19, 22, 24). Since the 4 kHz octave band is known to be crucial to speech understanding (1), this could have implications for speech intelligibility, and thus the use of communication systems. Helmet mounted systems used in military vehicles should be tested for combined exposure to noise and vibration for long durations, to assess any decline in speech intelligibility over time. The combination of the communication system with different types of hearing protection (ANR headsets, earplugs, etc.) should be considered, and both normal hearing and hearing impaired individuals should be tested.

While a number of studies have been done on cognitive task performance in vibration, the effects remain unclear. With the exception of the study by Schipani *et al.* (23), it seems that little attention has been paid to the effects of vibration on complex cognitive functions. Some problems with previous experiments that led to equivocal results were the variety of tasks used, differences in the mindset of the test subjects and inconsistent methods of evaluating cognitive performance. The use of defined tasks for performance evaluation of specific cognitive functions, such as the CTS and CCAB test batteries used by Schipani *et al.* (23), can help to reduce ambiguity. The test subjects should be encouraged to perform to the best of their abilities throughout the test sessions in order to eliminate lack of motivation or boredom as causes of performance degradation. Previous experiments have used one or both of accuracy and reaction or completion time as evaluation methods for cognitive tasks. Since performance on a given task can differ depending on which evaluation method is used, a combined result of the two measures might give an idea of the overall performance on the task.

4. CONCLUSION

It has been well-established that exposure to whole-body vibration has adverse effects on visual acuity and manual task performance. Design guides for visual displays and manual tasks in vibration environments have been written by Moseley and Griffin (21) and McLeod and Griffin (20). Although studies have been performed on whole-body vibration and hearing, the effects of vibration exposure on communication have not been investigated extensively. Since studies have indicated that vibration exposure may contribute to hearing loss when combined with noise, vibration effects should be considered in the design and evaluation of communication systems in vehicles and aircraft. For evaluating cognitive performance in vibration environments, well-defined cognitive tests should be used (i.e. from standardized test batteries), to avoid ambiguities in the interpretation of the results. Since is it difficult to produce realistic vibration stimuli in the laboratory, and acceptable vibration exposure levels for human subjects are much lower than what is encountered in practice, future human vibration experiments might have to be performed in the field. While they are less controlled, field experiments would likely give a more realistic evaluation of human performance in vibration environments.

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