Human Factors Division
Institute of Aviation

University of Illinois
at Urbana-Champaign
1 Airport Road
Savoy, Illinois 61874

Vibration in Command and Control Vehicles: Visual Performance, Manual Performance, and Motion Sickness: A Review of the Literature

F. Jacob Seagull and
Christopher D. Wickens

Technical Report
HFD-06-07/FEDLAB-06-01

October 2006

Executive Summary of Findings

This document contains review of literature on the effects of vibration on human performance. It is intended to address the issues relevant to reported difficulties in the use of the XM4 Command and Control Vehicle while the vehicle is in motion. The focus of this review is on the effects of vibration on visual task, with additional consideration given to manual tasks, as well as motion sickness. Below are listed some of the main findings from the literature reviewed.

- Vertical (z-axis) sinusoidal translation induced by a vibration simulator is the most common way of testing the effects of vibration, and it is often used as an approximation for other forms of vibration.
- The research base for establishing the generalizability of single-frequency, Z-axis vibration to multiple frequency, multiple-axis vibration is very sparse.
- Seating and posture, as well as individual differences between operators, influence strongly the effects of vibration on human performance.
- Small increases in display size, resolution, and vertical spacing can yield large payoffs in legibility for text viewed during vibration.
- Collimation of visual displays improves performance under vibration.
- The considerations for legibility-during-vibration are only marginally different than those of legibility without vibration, with the exception of a recommendation for larger vertical text spacing.
- There is no evidence of research comparing different display-styles, such as graphic displays compared to text-based displays.
- There are a number of ways of simulating the effects of vibration, including specific techniques of blurring of visual stimulus, as well as computer modeling for the effects of vibration.
- Motion sickness (kinetosis) is extensively researched, and the mechanisms involved are only partially understood. While there are a number of possible interventions, including drugs, training, and artificial displays, they offer only a partial solution to the problem of kinetosis.

Motivation for Investigation

Coordinating troop movement in the modern battleground requires sophisticated equipment. To carry out the coordination task, computer consoles and communication equipment are enclosed in an armored vehicle, providing both security (safety) and mobility. The workstations at which the crew of such a vehicle are stationed provide adequately for operations while the vehicle is stationary. However, when the vehicle moves over terrain, the resulting motion renders the equipment exceedingly difficult to operate--not because of technological limitations, but because the vibration of the vehicle interferes with the operators' ability to perform their tasks. The work area is an enclosed cab/compartment with no direct view to the outside environment. When the vehicle moves, the passengers are jostled by bumps in the terrain, as well as vibrated as a result of the motion of the treads, wheels and engine of the vehicle. Cab motion induced by the terrain can be in any direction or axis, and is not necessarily vertical or constant. This vibration and motion permeates through the workspace, inducing motion in the displays, controls, chairs and operators. This situation degrades the ability of the crew to carry out their assigned duties, both due to problems of display legibility and due to problems with motion sickness. These problems have motivated the current investigation of the effects of vibration. By understanding the effects of vibration, it is hoped that countermeasures can be developed to return performance to acceptable levels.

Understanding the Different Types of Vibration

The corpus of vibration-related literature since the mid 1970s revolves around one investigator and his colleagues at the University of Southampton,---M. J. Griffin. Most of the vibration investigations undertaken at this laboratory involve controlled artificial vibration of subjects carrying out tasks in experimentally controlled conditions. Nearly all of the vibration was induced artificially via a vibrating platform upon which the subjects sat. Nearly all of the experiments involved some simplified form of vibration and some discrete task or set of tasks. In some cases, both the operator and the task environment were both subjected to vibration, while in others, only the operator or only the displays/controls were subjected to vibration.

This section of the report reviews these and other experiments, and describes their findings as well as the finding's implications. This begins with a discussion of various forms of vibration, effects of different types of vibration; variables which mediate these effects, including those influencing the legibility of text; methods of simulating vibration; and interventions to minimize the effects of vibration.

Forms and Frequencies of Vibration

In order to understand vibration, it is necessary to first understand its measurement, the different variations of vibration and their meaning. This section describes sinusoidal, random, and shock vibrations, as well as the forms and axes of vibration. Within each section, relevant research findings will be presented.

Issues in Measurement

A useful quantity for measuring vibration is the Root Mean Square (RMS) value, which has a direct relationship with the energy content of the vibration (Wasserman, 1987). It is measured by squaring the measure of displacement of a body along a given axis, and integrating that value over some amount of time, dividing by the amount of time, then taking the square root. The RMS measure of vibration is used in the standards for tolerance of vibration for varying durations, and for longitudinal (vertical, z-axis) and transverse (horizontal, x- and y-axis) whole-body vibration.

This RMS measure, however, is inadequate for describing vibration. Nakamura and Haverkamp (1991) bring up the issue that there can be many different types of vibration (different frequencies and peak-shock values) with the same RMS value. Similarly, Griffin (1978) carried out a field study examining seat-comfort in commercial cars and found that using the RMS measurement technique recommended by the ISO inadequately described vibration, and that the ISO standards inadequately defined the contexts within which levels of vibration are acceptable. While the RMS is a useful first-approximation for describing vibration, clearly, additional parameters are needed to adequately define it. These include form, frequency, bandwidth, spectral components and axis, as well as peak-value.

Since these parameters can vary while the RMS remains constant, systematic variation of these parameters is often carried out to elicit performance measures under "equivalent" vibration-energy conditions (i.e. equal RMS-values). This approach has been used to evaluate the form of the vibration (e.g. Nakamura & Haverkamp, 1991; Parsons Whitham & Griffin, 1979), frequency (e.g. Griffin) , bandwidth (e.g. McLeod & Griffin, 1990), spectral components (e.g. Moseley, Lewis, & Griffin, 1982; Parsons, Whitham, & Griffin, 1979), axis (e.g. Parsons, Whitham, & Griffin, 1979), and peak value (Nakamura and Haverkamp, 1991).

Griffin and associates (Lewis & Griffin, 1980; Moseley Lewis and Griffin, 1982) actually compared different measures of vibration magnitude to determine which measure reflected most accurately a measure of vibration's detrimental effects. The RMS, QMS (which is calculated the same as RMS, but takes the displacement to the fourth power, then takes the cube-root, instead of squaring it and taking the square-root), "worst-spectral component" and the arithmatic sum were used as measures of a vibration energy in a single axis. These measures were correlated to subjects' performance levels during vibration on a reading task. Results showed that while worst spectral component was most predictive, both RMS and RMQ were sufficiently correlated to serve as an approximate correlate of performance, and much easier to analyze. The RMQ measures weights extreme "peak" values more heavily than the RMS measure (Moseley, Lewis & Griffin, 1982).

Sinusoidal Vibration

Single axis, sinusoidal vibration is perhaps the most commonly studied (Griffin & Lewis, 1978; Griffin 1992). It is a simple harmonic motion at a single frequency (i.e. a bandwidth of zero). This vibration can then be described fully via its frequency, amplitude, and axis.

Sinusoidal wave-form in one axis, compared to random vibration in the same axis, has been shown to be the "most severe case" of vibration, leading to the largest decrements in visual performance in digit or letter reading during whole-body vertical vibration and stationary displays (Moseley & Griffin, 1986; Griffin, 1992; Lewis & Griffin, 1980). It is hypothesized that the degradation in visual performance during sinusoidal vibration is related to the speed of the visual image on the retina at any given instant (Moseley & Griffin, 1986). Lower velocity is equated with better legibility. Low image velocity at a given moment is much less likely during sinusoidal vibration than in random vibration, thus leading to the observed poorer performance in sinusoidal vibration (Moseley, Lewis, & Griffin 1982; Griffin, McLeod, Moseley, & Lewis, 1986).

Single Frequency Vs Multiple Frequency Vibration

In a given axis, different sinusoidal frequencies can be combined into a single signal. This vibration is then called "multiple frequency sinusoidal vibration." This specific type of combination of vibration waves has been examined by at the Southampton laboratories (Alexander, 1972 cited in Griffin & Lewis, 1978; Medic & Griffin, 1976). They examined a display consisting of the combination of two sine wave vibration forms of 3 Hz and 11 Hz. The original results revealed that multiple frequency sinusoidal waves disrupt visual performance in a predictable manner, related to "nodal" images--the extreme point of deviation at which the image changes direction, and thus is motionless. Visual performance in letter and digit reading is predicted well from image velocity resulting from the interference of the two sinusoidal waves. It is noted that for some pure sine-wave combinations, there can be an improvement over single frequency vibration due to the fact that when two vibration frequencies are combined, the corresponding wave-forms will be out of phase at times, thereby canceling each other out through destructive interference. This destructive interference causes the image to be motionless or nearly motionless for a longer proportion of the time during vibration, and can cause more stable, easy-to-read images (i.e. more stable nodal images). This finding was further supported by research showing that severe decrements in visual performance occurred when the two sinusoidal vibration forms in different axes were combined so as to create circular motion (Meddick and Griffin, 1976). This decrement is explained by the fact that in circular motion there are no "nodal images" where image velocity reaches a minimum. In circular motion, the image velocity is constant, and higher than minimum values in non-circular image motion.

In addition to visual task performance, manual performance under multiple (dual) frequencies can be predicted based on the effects of the individual frequencies. The relationship is not mathematically simple, though it is based largely on the simple principle of establishing the baseline performance as well as the *measured* disruption at each of the relevant frequencies (McLeod & Griffin, 1986). Measuring the disruption resulting from each of the frequencies separately should be carried out within an environment identical to that in which the multiple-frequency vibration will take place in order to maximize validity of the prediction. The prediction algorithm consists of multiplying the squared sensitivity-to-disruption function of the task with the power spectral density of the vibration acceleration, taking the integral of this value over the range of frequencies covered, then taking the square root of this integral. This value is then added to the base-rate performance of the task without vibration (McLeod & Griffin, 1986). Under the constraints of having to know the complete sensitivity function for every frequency, there is such an extensive requirement for measuring performance under similar conditions that this algorithm's utility is questionable for "predicting" performance under multiple-frequency vibration. Furthermore, these predictions apply only to zero- or first-order manual tracking tasks.

Random Vibration

Narrowband Vibration

In studies comparing random to sinusoidal vibration, generally there are small but statistically significant differences between sinusoidal vs. random vibration, most commonly indicating that the disruption of performance observed under sinusoidal vibration is more severe than under random vibration (Griffin, 1992; Moseley, Lewis, and Griffin, 1982). There is some conflicting evidence that with some visual tasks, when the vibration frequencies are within the spectrum of 2.5-4.0 Hz random vibration can lead to poorer performance (McLeod & Griffin, 1990). However, in most cases the magnitudes of the differences are small, thus practically negligible. For purposes of research, the sinusoidal vibration is taken to be a sufficient approximation for predicting performance with random. This approach is accepted as a conservative technique, since random vibration, as mentioned, is considered generally as a less severe form of vibration (Moseley, Lewis and Griffin, 1982; Griffin, McLeod, Moseley & Lewis, 1986)

Different types of random vibration that have been investigated include third-octave and multi-octave (Moseley, Lewis and Griffin, 1982; Corbridge & Griffin, 1991), and recorded-motion vibration (Griffin, McLeod, Moseley & Lewis, 1986; Griffin 1978; Nakamura and Haverkamp, 1991).

Broadband Vibration

Experiments comparing whole-body, or whole-body and display vibration on visual performance found that in general, random broadband vibration was either equally or less disruptive than equivalent energy sinusoidal vibration (Griffin, 1992; McLeod & Griffin, 1990). For limited frequencies, sinusoidal vibration of observer and display creates more performance difficulties than either random 1/3-octave broadband or random one- and two- and three-octave broadband-vibration, except in 2-2.5 Hz frequency band (McLeod & Griffin 1990). These findings support the assertion that sinusoidal vibration is an adequate approximation of random vibration for experimental purposes.

Vibration Recorded from Vehicles

In a small number of studies (Nakamura and Haverkamp 1991; Moseley, 1984, cited in Griffin, McLeod, Moseley & Lewis, 1986; Griffin, 1978; Jex Zellner, Johnson, & Klein, 1982; Parks, 1961), spectral components of vehicles -- land, sea or air-- were analyzed. In some cases, measurements were taken within the vehicles themselves (Griffin 1978; Parsons, et al., 1979; Jex, et al., 1982), and sometimes these recordings were used as data to drive directly the vibration of subjects (Nakamura & Haverkamp, 1991). In other cases, the spectral analysis was used to generate analogous vibrations in a simulator (Moseley, 1984, cited in Griffin, et al., 1986; Parks, 1961). This use of measured or simulated vehicle vibration improves the external validity and generalizability of the experimental findings. However, the studies employing these techniques investigate a diverse set of operational variables, such as comfort, seating transmissibility, manual control performance, and motion sickness. Therefore, these investigations will be discussed individually in the relevant sections of this report.

Shock Vibration

Shock vibration is another category of vibration. It is used specifically to describe the environmental disruption that is experienced in equipment such as earth moving machinery. In contrast to sinusoidal or broadband-random vibration, it consists of a high-amplitude single-peak "'shock" vibration combined with a noise component of lower-peak continuous vibration, usually broadband random. The shock-peaks may not be regular enough to be described by a frequency, therefore they can be considered qualitatively different than general broadband random vibration. Since the effects of the single "shock" vibrations are not weighted heavily within the RMS calculations, the effect of these shocks merited further investigation.

Nakamura & Haverkamp (1991) studied the effects of shock-type vibration on first-order manual tracking task performance. They varied the peak amplitude of the shocks, and the shock-event frequency in a vertical vibration simulator, as well as presenting vibration of similar magnitude recorded from earth-moving equipment. They found that shock type vibration was not detrimental to tracking performance beyond the effects of vibration without shock. No decrement in performance was observed, except in the most extreme peak-level values (8 ms^2 acceleration) vibration level. The null finding in all but the most extreme conditions prevents finer comparison regarding recorded versus randomly generated vibration. The overall findings, however, are in agreement with the recommended limits of peak values cited in the ISO standards (Nakamura & Haverkamp, 1991; Woodson, Tillman & Tillman, 1992).

Axis of Vibration

There are six axes for vibration, as the six degrees of freedom in motion. Motion can be present in any one of the three dimensions, and each of these dimensions can have vibration in either translational motion (translation) or in rotational motion (tortional). The human body responds differently to motion in each axis and frequency. Each type of motion, therefore, has different effects on performance (Griffin, 1992; Woodson, Tillman, & Tillman, 1992; Parsons, Whitham, & Griffin, 1979). Vertical axis (z-axis) translation is most disruptive of visual tasks. This occurs, it is hypothesized, because the head resonates most freely in the vertical axis, and resonates at the frequencies reported as between 2 and 10 Hz (Griffin, 1992), or "4-8 Hz, more particularly 5 Hz" (Wasserman, 1987, p. 655). This resonation transmits vibration motion to the eyes, thus disrupting visual performance.

It is widely accepted that the body resonates in the horizontal axes (combined x- and y-axis) at different frequencies than in the vertical axis. The ISO standard has outlined acceptable levels of vibration separately for vertical and horizontal motion (Griffin, 1978; Woodson, Tillman, & Tillman, 1992; McLeod & Griffin, 1986). However, since vertical translation is disruptive to human visual performance at these frequencies, most vibration studies examine this dimension, and examine primarily vibration frequencies under in the range thought to affect visual performance (Griffin, 1992).

Meddick & Griffin (1976) also note that multiple axis vibration is expected to be worse than single axis vibration. Furthermore (as noted above), if the multiple axes of motion combine to reduce or eliminate the "nodal images" produced by single-axis motion--such elimination as in circular vibration-- visual performance is severely degraded.

Compared to translational vibration, tortional vibration is not the prevalent form of vibration in vehicles (Griffin, 1978; Parsons, Whitham, & Griffin, 1989). Though tortional motion is not a common style of vibration simulation, tortional motion (pitch) of the head *does* arise from simple vertical translational motion (Griffin, 1980). In fact, tortional motion of the head resulting from translational motion is thought to be responsible for much of the disruption in visual performance (Griffin, 1992, McLeod & Griffin, 1990).

Styles of Vibration

It has been noted that vibration can take place in many different frequencies and forms. Additionally, these forms of vibration can be applied to displays, or to the operator, or to both display and operator simultaneously. Each of these paradigms will be discussed below.

Whole Body Vibration

When examining whole body vibration, one must understand the limitations of vibration research -- limitation based on inherent variability between people and between environments. One can examine experimental findings regarding the average response of experimental subjects to vibration in a specific environment, but it is emphasized that the effect of individual differences are significant.

Resonant Frequencies for Body Parts

In normal locomotion, such as walking, the human musculo-skeletal system dampens the effects of extraneous body motion from the head. The legs, torso, and neck all absorb shock and limit the amount of motion passed on to the head. However, when in a vibrating environment, these same body parts may resonate and amplify vibration. The components of the body of principal interest in vibration research are the head, torso, and arms. While other body parts may also resonate at given frequencies, their effects are not central to the performance of visual or manual tasks. The resonant frequencies for body parts that are considered to affect performance have an upper limit around 20 Hz for vertical vibration (Griffin, 1992; Lewis & Griffin, 1980). Horizontal resonant frequencies, are substantially lower, beginning around 3 Hz and below (Griffin, 1992, McLeod & Griffin, 1986). For this reason, vibration research regarding manual and visual tasks focuses on frequencies below the 20 Hz range, and most commonly below 10 Hz.

More specific modeling of resonant frequencies for body parts can be predicted by computer simulation of given environments. For example, for a operator of given size, and a given seat and posture, the Biodyne-78 computer model estimates that there will be maximum task disruption due to head resonance when the body is exposed to vibration at 4 Hz, and there will be significant torso resonance ("torso heave") when the body is exposed to vibration at 2 Hz (see Jex 1979 for further description).

Individual differences

The literature is full of qualifying statements regarding the differences between individuals. These differences can have dramatic effects on performance. Body mass as well as other anthropometric considerations can cause the resonant frequencies of a given operator to vary greatly from the predicted values. In considering the results of the literature reviewed, one should remain cognizant that the predicted values are only tendencies.

Posture

Posture, too, can have profound effects on the transmission of vibration, it is rarely formalized in detail. Even without documenting specific postures, it has been shown that sitting with one's back on the backrest of a chair can lead to more transmission of vibration to the body, when the chair is the source of the vibration (Griffin, 1980; Moseley & Griffin, 1987). This finding is based on a chair that neither amplifies nor dampens vibration (i.e. a transmissibility of 1.0). In other examples from the research, it was noted that when experiencing task interference due to body resonance, one subject shifted the angle of his pelvis by a few degrees, thus changing the resonant frequency of his body (Jex & Magdaleno, 1979). The authors note that posture in most vibration studies is improperly recorded; the previous example makes this case clearly. It is difficult to explain performance-in-general under conditions of vibration without considering posture in detail.

Seating Structure and Transmissibility

Different chairs have different effects on performance. Studies have compared seats with back-rests and arm rests with seats without (Lewis & Griffin, 1980; Griffin 1978). Data suggest that seating support, as well as safety harnesses and their tightness can change the transmission of vibration to the operator, with tight seatbelts generally increasing the transmission of vibration to the operator (Lewis & Griffin, 1980). In addition, the composition, structure, and use of the chair can all influence the effect of vibration on someone sitting in the chair (Griffin, 1978; Parsons, et al., 1979). Therefore, when discussing vibration, one must distinguish vibration of the components of the environment (such as the floor and chair) from the vibration of the person within that environment. Seating, as noted, can amplify or reduce the amount of vibration that is transmitted to a person. In an extensive study of vibration in automotive environments which included seating, Griffin (1978) investigated the 16 commercially available cars and trucks, and the level of vibration present in each on under 4 different road conditions. According to this study, 5 of the 16 vehicle seats had a transmissibility rating larger than 1.0, indicating that the seat amplified vibrations of the vehicle for the passengers. Furthermore, all 16 of the seats had transmissibility of greater than 1.0 for portions or the vibration spectrum between 2 and 4 Hz. The issue of transmissibility of vibration through the structure supporting the person becomes an essential consideration. Seating will be discussed further below.

In all the above mentioned domains of seating, posture and individual differences, the findings are, paradoxically, both valuable and un-generalizable. They are essential caveats warning of the differences between different operators, chairs and different tasks (Jex & Magdaleno, 1979; Griffin, 1992). It has been said that in order to make an accurate prediction of the effect of specific vibration on an individual operator in a given chair, one would have to test (experimentally) the specific vibration, chair, and user (Moseley & Griffin, 1986).

Display/Control Vibration

Some of the work done regarding legibility concerns studies in which the display itself vibrated, while the observer remained still (Meddick & Griffin, 1976; Moseley, 1984, cited in Griffin, McLeod, Moseley & Lewis, 1986;). This condition rendered important results regarding legibility, which will be discussed below. However, its generalizability is questionable. In conditions in which only the display is moving, compensatory eye-movements are less effective, since the vestibulo-ocular reflex (which senses head-movement and automatically compensates by moving the eyes) is not engaged (Barnes and Benson, 1978, Barnes, Besnson, & Prior, 1978). The absence of the compensatory eye-movement reflex may result in an over-estimate of the severity of the performance decrement actually caused by whole body vibration.

Few studies have directly compared whole-body-and-display vibration to display-only vibration and body-only vibration. One such study indicates that observer-only vibration is more detrimental to digit reading performance than both observer-and-display vibration, and display-only vibration leads to worst performance (Moseley & Griffin, 1986). This relationship held for frequencies between 0.5 and 5 Hz in a task of digit reading during vertical vibration of various magnitudes. This finding is important because display-only vibration is by far the simplest to implement for laboratory studies. The results of such studies however may be overly pessimistic in their assessments of performance decrements that generalize to full body vibration environments.

Long Duration Vibration and its Effects

Although there have been an number of studies in long-term exposure to vibration (see Griffin & Lewis, 1978; Griffin, 1992), usually, vibration studies are undertaken for short periods of time from a few seconds (e.g. Corbridge & Griffin, 1991) to a few minutes (e.g. McLeod & Griffin 1990). In a small number of investigations, longer duration exposure was examined. These studies exposed subjects to longer term vibration while they were required to complete a secondary task. While there are some conflicting reports, in general, the performance measures taken before, during and after long-term vibration failed to indicate a significant degradation that could not be attributed to issues of vigilance or the vibration itself, regardless of its duration (Griffin, 1992). Vibration effects did not increase as exposure to vibration continued, nor were there residual effects observed after vibration ceased.

A separate concern about vibration is that exposure to it poses a health risk. Health risks as a result of long term exposure to vibration have been cited as effecting circulation, as well as bone structure and injury rates, especially for back injuries (Wasserman, 1987). Discussion of these issues, however, is beyond the scope of the paper.

Effects of Vibration on a Range of Manual Tasks

Most investigations of vibration examine its effects on tasks involving computerized displays or carrying out manual control tasks associated with industrial or military activity.

These include performing manual tracking tasks (e.g. Parks, 1961); operating discrete manual controls, such as buttons and switches; and using continuous manual controls, such as knobs, dials. In addition, there has been some interest in a set of "passenger activities" such as holding a cup of coffee, reading a newspaper, and writing (Corbridge & Griffin, 1991). Griffin and his colleagues (Griffin & McLeod, 1986) have divided manual tasks into three classes for the sake of understanding the effects of vibration on such manual tasks. The three types of tasks include:

> Type A: Continuous manipulation of a hand in space without support, such as reaching, locating an object in space, holding an unanchored object, or pointing.
>
> Type B: Continuous manipulation of an object fixed in space. Joysticks, dials, and steering wheels are part of this category.
>
> Type C: Discrete operation of an object fixed in space. This includes pressing buttons and manipulation of switches.

We may understand the effects of vibration on these classes instead of listing specific task and the ways in which it is affected by vibration. Type A and B manual tasks generally show a linear relationship between vibration-acceleration magnitude and task disruption. Type B tasks are less affected by vibration than type A tasks. However, in tasks of type B, the orientation of the object being manipulated can change the relationship to the interference: performance is disrupted more when manipulating an object in the same axis as the axis of vibration than when manipulation is in an axis orthogonal to vibration. For this reason, recommendations are made to orient controllers such as joysticks so that the directions of manipulation are orthogonal to the main axis of vibration. Providing anchors such as handles is also recommended to help stabilize the hand or arm, which can sometimes change a task from type A to type B.

Acceleration in more than one axis simultaneously is expected to result in greater disruption that the same acceleration restricted to a single axis (Griffin & McLeod, 1986).

Type C tasks, being discrete and anchored to fixed objects, are relatively unaffected by vibration. It should be noted, though, that if the control needs to be located in space by the operator before the discrete manipulation is performed, this location is then considered a Type A task (Griffin & McLeod, 1986).

Specific accommodations that should be considered in designing for vibration include increasing the stiffness and reducing the gain of joysticks, as well as providing handles near controls for anchoring hands (Griffin & McLeod, 1986). The task of reading CRT displays will be described in the section dealing with information presentation.

For specific manual tasks, there may be resonant frequencies specific to that task at which even small magnitudes can cause large disruptions in task performance. An experimental investigation of passenger activities included the task of holding a cup full of liquid (Task Type A) during vibration (Corbridge & Griffin, 1991). Results revealed a very narrow band of vibration centered at 4 Hz which caused 85% of subjects to spill liquid even at the lowest magnitude of vibration. This compares to 10% spilling at a frequency below 3 Hz or above 5 Hz. This serves as a further indication of the limits on generalizability of results over tasks.

Environmental Variables

Road and Vehicle Effects

Evaluation of different vehicles in different road conditions has been carried out primarily to investigate the adequacy of ISO-standard guidelines for vibration, or to determine the effects of vibration on subjective comfort ratings (Griffin, 1978; Jex et al, 1982; Parsons, Whitham & Griffin, 1979). Typically in these studies, vibration measurement devices are affixed to commercially available cars and trucks at both the floor level and on the seat, then vibration measures are taken under different road conditions and at varying speeds. These studies are valuable as reference material for comparing vehicle vibration dynamics. Results of these studies indicate also that lower frequency vibration are associated with vehicle suspension, while higher frequency vibrations are associated with engine vibration and wheel revolution rates. Rough roads, however, increased all frequencies of vibration, not just the low-frequency components (Parsons, Whitham & Griffin, 1978). Dramatic differences in seat transmissibility spectrums were also revealed (Griffin, 1978).

Results emphasize the importance of determining the specific spectrum of vibration caused by a given vehicle, as well as the different transmissibility levels of different seating.

Information Presentation

Text Presentation

Overall, the guidelines for text presentation under vibration are, by default, the same as those for text recognition under non-vibrating conditions (Moseley & Griffin, 1986). There are a small number of empirical investigations of text presentation under vibration conditions. However, the results of these studies can be used as guidelines with very restricted generalizability. With few exceptions, research has failed to address the underlying mechanisms involved in text recognition under vibration in a comprehensive manner. A number of investigations were carried out on the subject of font shape, size, display resolution, as well as text spacing. These will be outlined, and the main findings listed and discussed.

Font

One of the few empirical investigation of fonts investigated two different fonts that were recommended by the previous investigations (Shurtleff, 1969, 1980, cited in Griffin, McLeod, Moseley & Lewis, 1986) to be used for information display (Moseley, 1982, cited in Griffin, et al., 1986). Subjects read letters displayed on a stationary screen during vertical whole-body vibration. One of these two fonts was found to be superior under conditions of vibration, though there was no meaningful discussion of theoretical differences in their makeup, nor a set of characteristics which distinguished one from the other. Although this work may be valuable for designers trying to decide between these two specific fonts, it does not contribute to our understanding of the underlying mechanisms which shape a font's success or failure. Moseley and Griffin (1987) did find that during whole-body vibration with a stationary display using a single font examined in the above investigation, differences in performance between different letters could be explained by a measure of the letter's complexity in the vertical axis. Individual letters with a high degree of complexity in the vertical axis (e.g. 8, B, S, E, 3, 5, 2, 6, 9) were more difficult to read than letters with low vertical complexity (e.g. 1, I, H, L, J, T, U, V). The authors suggests that the effects of vertical vibration on vision are similar to those of a vertically-defined low-pass spatial filter. This suggestion is tested in later studies of vibration simulation (Davies & Griffin, 1989), which is included in the discussion of simulation.

Display resolution

In combination with font style investigation, examination of CRT-displayed font style inherently considers the mapping of letters onto a matrix of pixels. In addition to the overall shape of letters (font), a relevant issue is the resolution or granularity of the pixels onto which the letter is mapped. Given a fixed size for each letter, increasing resolution can be attained by using a larger number of smaller size pixels. Similarly, this increased resolution could be attained by viewing a larger object from a larger viewing distance. Investigations of display resolution were carried out concurrently with studies of font style (Moseley, 1982, cited in Griffin, et al., 1986). In a character-reading task, two different font resolutions were presented for two different fonts while holding character size and viewing distance constant. The letters in each of the different fonts were constructed from matrices of either 5 X 7 or 7 X 9 pixels, but they subtended the same visual angle. The findings indicate that higher resolutions do improve legibility for both fonts under whole-body vibration and stationary display, albeit with varying degrees of effectiveness. Here, too, there was insufficient discussion of the causes for these differences, thus limiting the application of a principled approach to this topic. Nonetheless, the overall conclusion did indicate strongly that increased resolution improved performance on both fonts.

Font size

In addition to increasing display resolution, another simple and effective way of improving performance is to increase display size (Meddick & Griffin, 1976; Griffin & Lewis, 1978). Studies using a task of reading Landolt C stimuli during display vibration indicated that a 75% reduction of errors with 20% improvement in speed of task could be achieved with a 25% increase in display size (see Griffin & Lewis, 1978). The authors suggest that the larger display sizes might reduce the overlap of letters during vibration, thus reducing ambiguity. Others (Crook and associates, 1950, cited in Griffin & Lewis, 1978; Lewis & Griffin, 1979, cited in Griffin, et al., 1986) found similar effects for alphanumeric reading tasks--increasing font size improves performance.

Text Spacing

Investigations of text spacing examined the effects of the space between letters horizontally, and the space between lines (vertically), and how vibration influenced legibility when the amount of space separating letters, words and lines of text was varied. One set of experiments examined character reading for two sizes of character during whole-body vertical vibration at 3.15 - 5 Hz (Moseley & Griffin, 1986; Griffin, McLeod, Moseley & Lewis, 1986). It found that optimal horizontal spacing requirements for legibility were not very different from optimal spacing for normal viewing conditions. For vertical (line) spacing, however, it was noted that the vertical spacing for the smaller character set (5 minutes of arc) was optimal at a separation of 15 pixels--over twice the normally optimal level (Moseley & Griffin, 1986). For the larger character set (12 minutes of arc), the separation of characters improved legibility at the same pixel-separation as for the smaller characters (15 pixels). Thus increased vertical separation appears to be critical factor in legibility.

Because only vertical vibration (whole body) was induced, and no horizontal vibration components were examined, it is difficult to gauge whether the differences in findings between horizontal and vertical spacing is due to the axis of vibration used. It is also unclear whether specific separation-measurements (in pixels) is relevant under all conditions, or the extent to which these measures are dependent on object size and vibration magnitude.

Text color

No specific color guidelines are available based on vibration literature. By default, recommendations for color should conform to guidelines set forth for text viewed in static conditions.

Contrast

Contrast levels resulted in best performances when set high, but not maximum--generally between 60-80%. This finding echoes the results of non vibration legibility. It can be asserted that normal contrast levels are acceptable (Moseley & Griffin, 1986).

Comparisons Between Text, Symbology, and Graphic Representations

Based on the results of this search, there is no evidence of studies specifically investigating types of display format such as comparing graphics to text. There was no evidence of comparisons between different modes of presentation, and little evidence exists of visual performance measures being taken on non-lexical tasks other than simple vision testing tasks, or graphic displays associated with tracking tasks (see Griffin & Lewis, 1978; McLeod & Griffin, 1986).

Simulation

It is hypothesized by Griffin (Davies & Griffin, 1989; Griffin, 1992) that vibration influences visual performance in the same way that a low-pass filter affects visual performance. Based on this and other hypotheses, attempts were made to simulate the effects of vibration through distortion of static visual images. In an experiment investigating legibility, three conditions were compared: (a) static subject reading undegraded characters on a CRT, (b) subject reading undegraded characters on a CRT during full body vertical vibration at 8 Hz 2.5m/s2 RMS, and (c) stationary subject reading a CRT display that was degraded by blurring designed to simulate 8 Hz 2.5m/s2 RMS vibration. The blurring was achieved by taking a Fourier transformation of each vertical column of pixels in each letter, calculating the product of this transformation with a low-pass filter fitted to the performance degradation curve that was observed in previous experiments, and then taking the inverse Fourier transformation of this product. The result of these transformations was then written back onto the screen pixels of the CRT. The results indicate that the effects of this blurring is similar, but not identical to the effects of vibration. In actual vibration, the image velocity reaches zero at the extremes of deviation (i.e. the "nodes" of motion, as discussed earlier), at which point, the image hypothetically can be viewed more clearly– a case that is not true with blurred, degraded images. The blurring algorithms over-estimate the damage done by vibration in other phases of vibration. Thus this blurring is not sufficient to replicate all the complex effects of vibration--some of the individual letters that were problematic in true vibration were not problematic using the blurred simulation, and vice versa. Furthermore, while differences between blurred and vibrated images are small in sinusoidal, single frequency and single axis vibration, Griffin hypothesized that these differences may be accentuated or amplified in more complex, multi-axis random vibration.

Another approach to visual simulation of display vibration while taking into account the lower-velocity nodal images is through simulation of the specific smearing of the display so that it appears as it would at nodal and non-nodal points in its vibration cycle. This is accomplished by calculating the image-remnant left by the image motion combined with the image itself via computational model of retinal image-decay. In experimental conditions, Davies & Griffin (1989) successfully approximated the degradation observed in subjects experiencing display-only vibration by briefly presenting this static "smeared" image at the same frequency as the stimulus being simulated (8 Hz). The visual task in this experiment required the detection of a simple cross-shaped intrusion into an aviation-type attitude display. Accuracy of the simulation using this "decay-model smear" technique seems to be dependent on proper modeling of the decay function, and using smears that simulate the image at a particular phase of its vibration, specifically, as it appears slightly after the nodal points of vibration (Davies & Griffin, 1989). It should be noted, too, that this technique simulates image displacement only, and not full-body vibration specifically.

Interventions

Up to this point the parameters affecting performance under vibration have been discussed. Variations in these parameters, it has been noted, have varied effects under various conditions. These effects, however, were often byproducts of other aspects of task performance. In contrast to those parameters, this section of the review examines a number of interventions that are primarily intended to reduce the effects of vibration on performance. The interventions are display collimation and dampening, chair shape, and the use of Helmet-Mounted Displays.

Display Collimation

Collimation of images seems to be an effective intervention in reducing the effects of vibration on human performance. Wilson (1974) was the first researcher to examine the use of collimation specifically in the context of vibration. He examined 8 subjects carrying out a manual tracking task using on an analog "zero-reader" display for feedback. Whole-body vibration was induced at 2, 4, 6, 8, and 10 Hz of sinusoidal vertical vibration. This display was stationary, and either collimated or uncollimated. Results indicated that tracking performance improved in the collimated condition for frequencies of 4 and 6 Hz. A more extensive replication of these results was carried out by McLeod and Griffin (1990). They examined 14 frequencies between 0.5 Hz and 10 Hz, and used both sinusoidal and broadband vibration. Their results supported the original findings, indicating that the collimating optics did in fact improve performance at frequencies above 1.6 Hz. The reasons given for this improvement is that collimation eliminates the relative motion of the display in one axis of translational. The collimating optics presents the image of the display at a constant optical distance, regardless of the actual viewing distance between the subject and the display. Reduction of the perceived motion of the display in the distance-axis leads to increased reading performance.

Collimation is considered an effective intervention for improving performance under vibration. The surprisingly unambiguous results are rare for the realm of vibration research, where most findings are heavily qualified or constrained.

Dampening

While it is nearly impossible to remove the sources of the vibration from the environment, it may be possible to restrict the transmission of these vibrations to the operator through dampening. Isolation of operators from vibration can be achieved through selection of seating with low transmissibility, as discussed above. Extensive dampening of displays and operators may prove costly, with size and weight penalties (Wilson, 1974). Current research on vibration suggests that to be effective, dampening must reduce vibration within the 2-10 Hz range. The vibration literature reviewed does not discuss attempts at dampening vibration within operational environments. Instead in experimental environments, they strive to transmit pure vibration directly to the body of subjects. The body inherently dampens some of the vibration, but it is unclear from this literature whether improved dampening mechanisms in seating and display-housings would be effective in eliminating detrimental frequencies of vibration from the environment.

One issue that is unresolved by the literature concerns the finding that combined operator-and-display vibration (i.e. whole body & display) is more legible than display-only vibration (Moseley & Griffin, 1986). Though the findings were consistent within the experiment, the vibration was sinusoidal and restricted to the vertical axis. If these laboratory-tested results can be generalized to an operational environment, then dampening operator-seating while leaving displays un-dampened will cause performance degradation.

Chair Shape

As mentioned above, seat construction and seat shape both have an influence on performance under vibration. Materials, structure and construction of the seat can heavily influence the seat's transmissibilty (Parsons, Whitham, & Griffin, 1990; Lewis & Griffin, 1980; Griffin, 1978). Seat shape can influence resultant posture of the operator, which also can have profound influences on the effects of vibration (Jex & Magdaleno, 1979; Lewis & Griffin, 1980; Griffin 1978). In light of the above discussion of dampening, it is not clear what recommendations can be made for seating beyond the fact that they should not amplify vibration. In order to answer this question more fully, further empirical testing of chairs in operational conditions should be carried out.

Helmet-Mounted Displays

One proposed intervention for reducing the effects of whole body vibration is to present the operator with a display mounted on a helmet attached to the operator's head. This helmet-mounted display (HMD) potentially would couple the operator and display together, thereby eliminating the relative motion between the operator and display (see Wells & Griffin 1984; Wells & Griffin, 1987). While this approach seems like a simple and elegant solution, it too is susceptible to problems of vibration and resonance. Because of imperfect helmet-fit, as well as increased inertia of the helmet, the HMD will vibrate at a different rate than the operator's head and eyes, resulting in motion of the image relative to the eye.

In HMD-systems used in environments in which vibration occurs, such as aircraft cockpits (particularly rotocraft), it has been proposed that adaptive or predictive algorithms be applied to the HMD's display image in order to stabilize the image relative to the observer's eye. Work in this area generally shows improvement in performance as a result of stabilization filters (Wells & Griffin, 1984; Hart, 1988; Aponso & Jex, 1986). One such filter takes a measure of acceleration from the helmet, passes this signal through a hi-pass double-lag filter to obtain a measure of helmet vibration, then subtracts this component from the display-image angle, thus attaining a stabilized image that filters out high frequency vibrations while allowing lower-frequency tracking (Aponso & Jex, 1989). This type of filter, as well as other variants, is suited for environments where the head is used for tracking or pointing (e.g. So & Griffin, 1992; So & Griffin 1996). Various parameter values for the lag and hi-pass filters shape the response dynamics of the filter and influence the effectiveness of the filter, as does the mass of the HMD (Wells & Griffin 1984). These investigations examined performance under laboratory conditions and vertical sinusoidal vibration. [It should be pointed out that such stabilization systems when applied to HMD systems in fighter-jet cockpits involve only the insertion of the filter algorithm into the existing display- and tracking-technology. In an environment in which there is no HMD system in place, the entire system would be required including head tracking, helmet display technology, and stabilization algorithms.] Further investigation of HMD use in the context of the present vibration issues is needed before any conclusions can be drawn regarding the effectiveness of such an intervention.

Motion sickness

One of the major motivating factors in the current investigation is the complaints of motion sickness from operators of the XM4 vehicle. The literature on motion sickness (kinetosis) indicates that motion sickness often occurs when there is a mismatch between any of a number of physiological and psychological motion sensors (Jex, Riedel, & Smith, 1982). In the current setting, operators are subjected to vibration while enclosed in a moving workspace with no reference to an inertially stable perceptual anchor, such as would be provided by the horizon or a view of the outside world. Often, motion sickness in simulators is partially a result of mismatch between the motion of the visual field which comprises the "moving" outside world and the visceral sensations which fail to indicate motion. The literature examining flight simulators often describes variables such as field of view, peripheral motion cues, display lag as culprits leading to simulator sickness. In the present investigation, the focus is on an environment with no visual display representing the environment. For this reason, the transfer flight-simulator sickness principles is somewhat limited. In the present context, there is true motion (with its vestibular and visceral components), but no visual counterpart. Analogous situations inducing motion sickness have been examined, such as studies of space-sickness and sea-sickness (Jex & Magdaleno, 1991; Jex et al., 1982, Jex & Magdaleno, 1979). The conclusions from such work provide a complex and approximate model for mechanisms involved with motion sickness (Jex, et al., 1982). The authors admit that the model is incomplete and inadequate for explaining kinetosis. However, they do provide a number of known facts based on the results of extensive research. A small number of these facts are listed here in order of direct relevance to the current project

- In vehicles, the presence of a stationary horizon (or other inertially stable object) may ameliorated motion sickness. The visual system most sensitive to motion perception is the parafoveal -- not foveal -- region of the retina.
- Vestibular-visual conflict is often the culprit in motion sickness. Vestibular cues are weighted heavily when in conflict with visual cues, and lightly when confirmed by visual information.
- For general whole body vertical oscillation, motion sickness is most present at 0.2 Hz, and "negligible above 0.6 Hz."
- Tolerance for motion is increased if the subject is given prior knowledge of the motion profile, or if they have active control over the motion.
- Effective interventions against kinetosis include drugs, training, experience, and it is noted that tolerance of motion increases as workload increases

These facts may be applied to the present context in the following ways. The use of a parafoveal display to provide an inertial reference may be helpful in the present context. In so doing, the importance of the motion input from the vestibular system will be minimized, possibly leading to lower incidence of kinetosis. Furthermore, although the frequencies of vibration in the vehicle under investigation are not known, it may also be possible to dampen or otherwise avoid frequencies below 0.6 Hz. Finally, if these frequencies are present and no dampening is possible, there are other possible interventions such as exposure, training, and drugs.

Motion sickness has also been studied in the context of the problems of motion sickness (kinetosis) in naval vessels. These studies relate to the motion of a boat on rough seas, and the performance decrements associated with it. They differ in a number of dimensions from the context of interest. Motion sickness studies tend to be of longer duration (up to 2 days), examine low-frequency oscillation in the range of 0.5 Hz to 2 Hz, typically, and employ large displacement of up to 20 feet (Jex & Magdaleno, 1991). While this context is not directly applicable to issues of motion sickness induced from an enclosed ground vehicle, these investigations have helped to elucidate the mechanisms involved in the kinetosis.

Extent to which these issues have been adequately investigated

The issues examined by this report do seem to form a cohesive, or at least consistent, view of the effects of vibration. There are critical frequencies around which human operators experience the most performance problems, and there are predictable ways in which displays and the environment can be manipulated to reduce these errors. Seating and posture are identified as environmental elements which can have strong influence on performance levels. However, the sufficiency of vibration research is almost wholly dependent on one major assumption: the generalizability of single-axis vertical sinusoidal vibration to the domain of complex, multi-axis random vibration. Many assertions are made and recommendations given based on the results of simple, single-axis of vibration without testing these hypotheses in operational environments. There are experiments examining other forms of vibration, and vibration in multiple axes, and these studies note that the disruptions caused by multiple axis vibrations are likely to be more severe than the effects of similar amplitude of single-axis sinusoidal vibration. When "field" studies are carried out in actual vehicles, the dependent measures are generally limited to subjective measures of comfort, not objective performance data. Such data would be welcome.

This assumption and models of vibration do in fact point to the conclusion that sinusoidal vibration in the vertical axis is the primary cause of visual performance decrement, however, generalizability of the single axis work to real operational environments with random, multi-axis vibration is not certain.

A second shortcoming of the present body of research regards the atheoretical approach used in much of the visual performance literature. While many recommendations are made for improving legibility of visual displays (such as size, spacing and resolution), these recommendations are not easily generalizable due to the lack of a theoretical underpinning. Such a theory of display-effects under vibration would be useful in predicting the effectiveness of new types of displays. At present, this prediction would be most difficult.

Where Further Research is Needed

Even if the assumption about generalizability were valid, there would still be domains of research that have been largely neglected. Up to this point, research on visual performance in vibrating environments has been limited primarily to measures of visual acuity and digit reading. There is no salient evidence of adequate comparison of different visual tasks under vibration conditions. While there has been some target detection tasks or tracking tasks relying on graphic visual displays, there has been no adequate comparison between different types of display under vibration.

Motion sickness research presents a different set of issues. There is a great body of research regarding motion sickness, partially because it is a complex problem with no simple solutions. The small fraction of kinetosis research relevant to the situation at hand suggests possible interventions, but these interventions are not expected to eliminate the problem, just ameliorate it. Here, too, testing of possible interventions in an operational setting may be necessary before conclusions are drawn.

Additionally, in order to resolve the issues surrounding the specific operational problems that inspired this review of research, the cause of these problems in the specific vehicle must be clarified and specified. At this point, it is unclear how much of the reported decrement in performance is due to inability to process the visual image, and how much is due to motion sickness. The working assumption is that both aspects are equally important. Nevertheless, this question should be answered more fully before trying to conclude on the effectiveness of any intervention.

Conclusions

This report was intended to provide a preliminary review of literature relevant to performance problems experienced in the operational environment of the XM4 Command and Control Vehicle regarding motion sickness and visual performance. The literature focuses on issues relevant to this domain. This review should be considered as a preliminary investigation, not a comprehensive review. Findings indicate experimental evidence for a number of possible interventions both in the domain of visual performance and, to a lesser extent, in the domain of motion sickness.

Bibliography

Aponso, B., & Jex, H. R. (1986). Using a helmet mounted display with image stabilization as a head directed aiming device (Working Paper WP 2284-4). Hawthorne, CA: Systems Technology, Inc.

Barnes, G. R., Benson, A. J., & Prior, A. R. J. (1978). Visual-vestibular interaction in the control of eye movement. Aviation, Space, and Environmental Medicine, 49(4), 557-566.

Benson, A. J., & Barnes, G. R. (1978). Vision during angular oscillation: The dynamic interaction of visual and vestibular mechanisms. Aviation, Space, and Environmental Medicine, 49(1), 340-345.

Corbridge, C., & Griffin, M. J. (1991). Effects of vibration on passenger activities: Writing and drinking. Ergonomics, 34(10), 1313-1332.

Davies, A. K., & Griffin, M. J. (1989). Modeling the Effects of Vibration on Visual Performance (171). Southampton, England: Institute of Sound and Vibration Research, University of Southampton.

Gauthier, G. M., Roll, J. P., Martin, B., & Harlay, F. (1981). Effects of whole-body vibrations on sensory motor system performance in man. Aviation, Space, and Environmental Medicine, 52(8), 473-479.

Griffin, M. J., & Lewis, C. H. (1978). A review of the effects of vibration on visual acuity and continuous manual control, Part 1: Visual acuity. Journal of Sound and Vibration, 56(3), 383-413.

Griffin, M. J. (1978). The evaluation of vehicle vibration and seats. Applied Ergonomics, 9(1), 15-21.

Griffin, M. J., McLeod, R. W., Moseley, M. J., & Lewis, C. H. (1986). Whole body Vibration and Aircrew Performance: ISVR Technical Report 132. Southampton, England: Institute of Sound and Vibration Research, University of Southampton.

Griffin, M. J. (1992). Vibration. In D. M. Jones & A. P. Smith (Eds.), *Handbook of Human Performance, Vol. 1: The Physical Environment,* . London: Academic Press.

Hart, S.G. (1988). Helicopter Human Factors. In E.L. Wiener and D.C. Nagel (Eds.) *Human Factors in Aviation*. San Diego: Harcourt Brace and Jovanovich.

Jex, H. R., & Magdaleno, R. E. (1979). Progress in measuring and modeling the effects of low frequency vibration on performance. Paper presented at AGARD #253 Models and Analogues for the Evaluation of Human Biodynamic Response, Performance and Protection, Neuilly Sur Seine, France. A29-1 --A29-11

Jex, H. R., Riedel, S. A., & Smith, J. C. (1982). Development of a Comprehensive Systems Model for Motion/Space Sickness (TR-1157-1). Hawthorne, CA: Systems Technology, Inc.

Jex, H. R., & Magdaleno, R. E. (1991). Review of some STI activities in measuring and modeling the effects of motion on kinetosis and performance (WP-465). Hawthorne, CA: Systems Technology, Inc.

Lewis, C. H., & Griffin, M. J. (1980). Predicting the effects of vibration frequency and axis, and seating conditions on the reading of numeric displays. Ergonomics, 23(5), 485-501.

McLeod, R. W., & Griffin, M. J. (1986). A Design Guide for Visual Displays and Manual Tasks in Vibration Environments; Part II: Manual Tasks (ISVR-TR-134). Southampton, England: Institute of Sound and Vibration Research, University of Southampton.

McLeod, R. W., & Griffin, M. J. (1990). Effects of whole-body vibration wave-form and display collimation on the performance of a complex manual control task. Aviation, Space, and Environmental Medicine, 61(3), 211-219.

Meddick, R. D., & Griffin, M. J. (1976). The effect of two-axis vibration on the legibility of reading material. Ergonomics, 19(1), 21-33.

Moseley, M. J., Lewis, C. H., & Griffin, M. J. (1982). Sinusoidal and random whole-body vibration: Comparative effects on visual performance. Aviation, Space, and Environmental Medicine, 53(10), 1000-1005.

Moseley, M. J., & Griffin, M. J. (1986). A Design Guide for Visual Displays and Manual Tasks in Vibration Environments; Part I: Visual Displays (ISVR-TR-133). Southampton, England: Institute of Sound and Vibration Research, University of Southampton.

Moseley, M. J., & Griffin, M. J. (1987). Whole-body vibration and visual performance: An examination of spatial filtering and time-dependency. Ergonomics, 30(4), 613-626.

Nakamura, H., & Haverkamp, M. (1991). Effects of whole-body vertical shock-type vibration on human ability for fine manual control. Ergonomics, 34(11), 1365-1376.

Parks, D.L. (1961). A Comparison of Sinusoidal and Random Vibration Effects on Human Performance (Tech. Report D3-3523-2). Wichita, Kansas: Boeing Company.

Parsons, K. C., Whitham, E. M., & Griffin, M. J. (1979). Six axis vehicle vibration and its effects on comfort. Ergonomics, 22(2), 211-225.

So, R. H. Y., & Griffin, M. J. (1992). Compensating Lags in Head-coupled displays using head-prediction and image deflection. Journal of Aircraft, 29(6), 1064-68.

So, R. H. Y., & Griffin, M. J. (1996). Experimental Studies of the use of phase lead filters to compensate labs in head-coupled visual displays. IEEE Transactions on Systems, Man, and Cybernetics–Part A: Systems and Humans, 26(4), 445-454.

Wasserman, D. E. (1987). Motion and Vibration. In G. Salvendy (Ed.), *Handbook of Human Factors*. New York: John Wiley & Sons.

Wells, M. J., & Griffin, M. J. (1982). Sinusoidal and random whole-body vibration: Comparative effects on visual performance. Aviation, Space, and Environmental Medicine, 53(10), 1000-1005.

Wells, M. J., & Griffin, M. J. (1984). Benefits of helmet-mounted display image stabilization under whole-body vibration. Aviation, Space, and Environmental Medicine, 55(1), 13-18.

Wells, M. J., & Griffin, M. J. (1987). A review and investigation of aiming and tracking performance with head-mounted sights. IEEE Transactions on Systems, Man, and Cybernetics, SMC-17(210-221), 13-18.

Wilson, R. V. (1974). Display collimation under whole-body vibration. Human Factors, 16(2), 186-195.

Woodson, W. E., Tillman, B., & Tillman, P. (1992). *Human Factors Design Handbook*. (2nd ed.). New York: McGraw-Hill.