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A quantitative meta-analytic examination of whole-body vibration effects on human performance

G. E. CONWAY*, J. L. SZALMA and P. A. HANCOCK

MIT[2] Lab, University of Central Florida, 3100 Technology Parkway, Suite 337, Orlando, FL 32826, USA

Whole-body vibration exerts a substantive influence in many work environments. The primary objective for this work was to quantify such effects by identifying those moderating variables that influence the degree to which performance is affected. To achieve this, a comprehensive meta-analysis was conducted, which synthesized the existing research evidence. A total of 224 papers and reports were identified and, from these 115 effect sizes were derived from 13 experiments that survived the screening procedure. Results indicate that vibration acts to degrade the majority of goal-related activities, especially those with high demands on visual perception and fine motor control. Gaps in the current research literature are identified and suggestions offered with regard to a more theoretically-driven approach to testing vibration effects on human performance.

Keywords: Whole-body vibration; Human performance; Stress; Meta-analysis

1. Introduction

The problem of vibration in work environments is an issue that has long been of concern (e.g. Ramazzini 1713). Although vibration disturbance to performance may be thought of as an 'old' problem, its pervasive effects are still recognized by contemporary engineers and behavioural scientists as a key ergonomic issue (see Fraser *et al.* 2004, Peacock *et al.* 2005). Vibration has traditionally been conceived in two distinct forms. The first of these forms concerns effects to single, exposed limbs. The second, but by far the more pervasive form concerns vibration of the whole body ('whole-body vibration'; WBV). It is the latter category that is the focus of this work. Clear examples of the potential disruptive influence of WBV can be seen in any number of work environments but perhaps most significantly in those that require the concomitant use of both transportation and information systems. Operator performance within aviation, maritime and land-based

*Corresponding author. Email: gc.human.performance@gmail.com

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vehicle operations are therefore constantly and consistently at risk from WBV effects (Mansfield 2004).

Vibration takes the form of a mechanical wave, which, in a manner analogous to noise effects, serves to transfer energy but not matter (Mansfield 2004). It is this energy transfer that proves problematic to performance since it is transmitted to and dissipated within the human who is in contact with the vibrating structure (Griffin 2004). Therefore, WBV manifests itself most often when vibrating surfaces, such as a vehicle in motion, support the human operator. Immediate effects cease only when the supporting structure itself stops vibrating, or when a decoupling between the user and the surface of support occurs. However, this immediate cessation of direct effects does not eliminate the possibility of after-effects, which are common occurrences in many other forms of stress exposures (e.g. Cohen 1980).

Vibration is a particular threat as it imposes a direct mechanical influence on several aspects of task response. If the dynamic adaptability model of stress and performance (Hancock and Warm 1989) is used as a framework for understanding such effects, then it can be seen that vibration manifests itself in each of the three components that make up the identified 'trinity of stress' (see figure 1). First, vibration is a function of the ambient environment at any given time and so can affect input-related activities (such as the collection of information through the different sensory modalities – mainly vision). Vibration can also influence 'output' response processes, reducing the effectiveness and efficiency of motor performance. Vibration also exerts an influence on adaptive processes – the individual's attempts to cope with their present environmental demands. Although vibration is known to have a pervasive influence on performance, the magnitudes of these effects are known to change according to the impact of a number of moderating factors.

2. Whole-body vibration and performance – the influence of moderating factors

Two specific groups of moderators are the characteristics of the vibration itself and the characteristics of the task at hand. These are discussed in turn. Vibration occurs and is measured in three translational axes in accordance with the standard biodynamic coordinate system (International Organization for Standardization 1997). Although recognition of these three basic axes of vibration is important, it is even more valuable to consider the interaction of the vibration axis with other factors. For example, the effect of the axis of vibration on performance is often dependent on task characteristics (e.g. which directions are the most important in a 2-D tracking task) or the frequency of the vibration

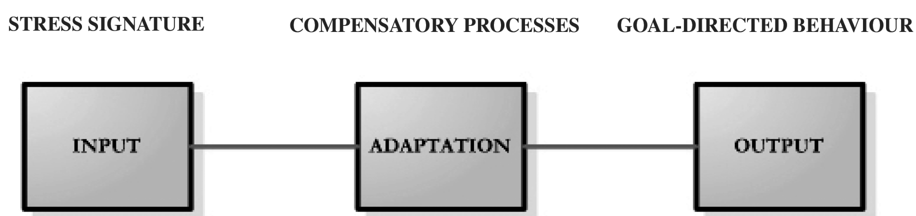

Figure 1. The 'trinity of stress' (Hancock and Warm 1989). A tripartite descriptive framework for describing the environmental origin of stress (input), its representation as a direct pattern of adaptive, regulatory responses (adaptation) and its manifestation in disturbance to on-going performance capacity (output).

(given that there may be differential performance effects of the three axes at different frequencies).

The second vibration characteristic to be considered is that of waveform. Vibration may be random, intermittent (non-periodic) or continuous (periodic). The most common vibration form encountered in the literature is that of continuous sinusoidal vibration, which consists of repeated cycles where the object or person oscillates about their original position. Within the sinusoidal wave, variation can occur in how far the object moves from its origin in the cycle (the magnitude), the number of complete cycles per s (the frequency) and in the amount of time for which the vibration persists (when this is in relation to the performer it is termed exposure duration).

The magnitude of vibration represents how far the vibrating object moves from its starting point at the extremes of each cycle. Although the magnitude of vibration transferred to the body is linearly related to the vibration from the supporting surface, the implications of this for task performance depend upon the interaction with the task characteristics and the vibration frequency (Griffin 1992).

The frequency of vibration is defined by the number of complete cycles per s (Hz). Again, it is difficult to quantify the effects of frequency in isolation; of specific interest here are the interactions with the direction of the vibration and the body parts that are used during performance (either for sensory or response processes). The latter interaction is of particular concern when one understands that different parts of the human body each possess their own individual ‘resonance’ frequency. Resonance refers to frequencies of vibration at which the effects on a given body part are maximized (i.e. the effects of the vibration on the body part are higher than would be expected if the vibration in the transmitting surface were studied in isolation).

The last characteristic of the vibration stimulus to be considered here is exposure duration. A key issue to recognize is that vibration (or any other stressor) effects take place within a 4-D environment, where the fourth dimension is time. Although the direct effects of vibration are well recognized, the full picture concerning the interaction of exposure duration and task type has yet to be elucidated.

Thus, an important additional moderating factor is the type of task to be performed. The principle here being that WBV can have differential effects on different types of task. Although there is no one universally accepted taxonomy for performance type, one method of categorizing tasks is through accepted information-processing models (e.g. see Wickens and Hollands 2000). This approach usually assigns tasks to processing stages that are most characteristic of the demands made. For example, one task may place the primary demand on sensory processes; another task may emphasize decision making and yet again a third task may hinge on the accurate use of fine motor control.

3. Purpose of current work

The introduction of numerous moderating factors can generate confusion with regard to performance effects. Further, current understanding of the mechanisms underpinning WBV effects specifically on information processing and the moderating influence of exposure duration is particularly low (Griffin 2004). Accordingly, the construction of a theory that is capable of explaining the role of each moderating factor and the mechanisms underpinning their effects is an important challenge. Indeed, the current lack of a single accepted theory is testament to the scale of this problem. Advances in understanding may be achieved via two general strategies. First, Griffin (2004) has emphasized that although an explanation of the numerous mechanisms underpinning

WBV effects is perhaps too ambitious, efforts that specify the relative importance of the various factors are highly valuable. Second, WBV research may benefit from considering methodological and theoretical developments in parallel areas of research. For instance, benefits may be gained from comparative analysis of progress made in the general field of stress and performance research over the past half-century (Hockey 1983, Hancock and Desmond 2001). The transfer of knowledge from areas of stress research can result in the identification of alternative ways through which to reconsider old problems. For example, an emphasis may be placed on new methods or the assessment of a broader range of impinging variables (Hockey and Hamilton 1983).

The current work therefore focuses on the first strategy and attempts to provide a comprehensive, quantitative analysis of all available empirical studies that assessed the influence of WBV on human performance. The goal is to determine the relative importance of the various moderating factors and to identify gaps in understanding that may be exploited by both short- and long-term research strategies. These effects have been quantified using formal meta-analytic procedures (see Hedges and Olkin 1985, Hunt 1997, Hunter and Schmidt 2004). There are many advantages associated with conducting a meta-analysis for this purpose. Meta-analysis provides a quantitative synthesis of the literature, allows effects drawn from different methods and measures to be combined, controls for sampling error and the low power of individual experiments, while permitting an examination of potential moderating variables (Lipsey and Wilson 2001, Lipsey 2003, Hunter and Schmidt 2004).

4. Method

4.1. *Literature accumulation*

To collect the relevant studies for the WBV meta-analysis, an exhaustive literature search was performed using the PsycINFO®, MEDLINE® and the Dissertation Abstracts International database. The following search term combinations were used as a primary keyword: 'whole body', 'vibration', 'performance', 'cognition', 'motor' and 'vigilance'. In addition, a number of web-based search engines were used, e.g. Google® and their specialist derivates, e.g. Google Scholar®, to seek further references not found in the initial formal scan. After a preliminary listing of articles was obtained, additional articles were collected by surveying the reference lists from those already available and by retrospectively examining article citations through Science Citation Index®. Following this initial, formal search procedure, subject matter experts (SMEs) were consulted concerning any remaining, pertinent references that may not have been identified by this primary search process. All such articles cited by the SMEs were then searched for additional references. The exhaustion of these dual processes composed the present listing of articles. This effort resulted in the identification of 224 articles, reports, dissertations and theses. The authors are, of course, well aware of the documented efficiency of such search procedures (e.g. Sommer 1987), as well as the perennial concern for 'file drawer' effects (Hunter and Schmidt 2004). From these collected works, 11 papers were identified, which met the following selection criteria.

4.2. *Criteria for inclusion*

Each selected study had to report an empirical examination of vibration stress in which the experimental manipulation employed an application of WBV. Next, the study had to address directly the issue of WBV effects on performance. For example, studies that sought to disturb sleep through the application of vibration and then assess the effect of sleep loss on performance were not considered suitable for inclusion (e.g. Arnberg *et al.* 1990). Then, each report was required to include a control group for comparison purposes. Most frequently, this took the form of one group (the 'control') receiving no vibration, whilst the second group (the 'experimental' or 'treatment' group) were exposed to vibration. If a within-participant design was used, then each individual had to perform in both the non-vibration and the vibration conditions. Subsequently, each study had to report at least one measure of performance (e.g. marksmanship, manual dexterity, response time, tracking error). Studies using physiological or subjective response alone were thus excluded (e.g. Meister *et al.* 1984). Finally, each study had to include sufficient information regarding performance results to determine effect size estimates. Founded upon these five selection criteria, 13 primary studies were accepted for use in the meta-analysis. The rejection of numerous primary studies in a meta-analysis is a common occurrence and necessary to ensure meaningful data when combining effect size estimates across studies. In the present analysis, the modal reason for exclusion of a study was the lack of performance variables (the papers referred to here generally examine WBV influences on comfort, e.g. Suzuki 1998). A total of 224 studies were collected. The screening process resulted in the qualification of 13 of these studies for inclusion. These emerged from a total of 11 different sources (i.e. articles, dissertations, technical reports, etc.) and resulted in 115 effect sizes.

4.3. *Calculation of effect size*

Effect sizes for this study were the standardized mean difference between the experimental and the control conditions, often referred to as Hedge's g (Hedges and Olkin 1985, see also Hedges *et al.* 1989). Many researchers are more familiar with Cohen's d (Cohen 1988), which is conceptually similar to Hedge's g but has different distributional properties (see Hunter and Schmidt 2004). When means and standard deviations were available, the effect size was calculated by using the term expressed in equation (1):

$$g = \frac{(\bar{X}_E - \bar{X}_C)}{s} \tag{1}$$

where $\bar{X}_E$ = mean of the experimental condition, $\bar{X}_C$ = mean of the control condition and s = standard deviation (for the control condition in within-subject designs; pooled standard deviation for between-subject designs). When the means and/or standard deviations were unavailable, effect sizes were computed with inferential statistics (e.g. t-ratios) or sums of squares/mean squares (e.g. from ANOVA tables) using equations presented by Hedges *et al.* (1989) and Lipsey and Wilson (2001).

The g scores were adjusted for statistical bias, which decreases the accuracy of the estimates, particularly in cases where sample sizes are small. This adjustment (see Hedges and Olkin 1985) provides an unbiased effect size.

$$d_u = g^* 1 - \left(\frac{3}{4N - 9}\right) \tag{2}$$

for $E(g)$ $x=N-2$. The need for this correction comes from the statistical bias associated with g as an estimate of the effect size parameter (δ). The expectation for g is given by $E(g)=\delta/J(N-2)$, where:

$$J(x) = 1 - \left(\frac{3}{4x-1}\right) \quad (3)$$

Thus, the expected value of g is not the population parameter δ but is proportional to it (see Hedges and Olkin 1985). In calculating the effect size, the directional sign of the effect size was controlled to ensure that positive scores represented better performance in the experimental group than the control group, whereas a negative score indicated worse performance. Vibration is a form of stress where the zero value on the ratio scale lies within the general comfort range of human tolerance (see Hancock and Warm 1989).

In addition to the adjustments noted above, effect sizes derived from studies using within-subjects designs were adjusted to a between-subjects metric using procedures described by Morris and DeShon (2002). This correction was necessary in order to account for differences in standard deviation units as a function of experimental design.

4.4. *Estimation of variances*

The variance associated with each effect size was calculated using equations provided by Morris and DeShon (2002). These were combined for estimates of sampling error variance (s_e^2) and the variance among the observed effect sizes (s_g^2) using procedures described by Hunter and Schmidt (2004). These estimates can be used to derive the variance due to differences in the population effect size (s_δ^2). Thus,

$$s_\delta^2 = s_g^2 - s_e^2 \quad (4)$$

A large s_δ^2 indicates that there is variability among the observed effect sizes that cannot be accounted for by sampling error and that there are likely to be one or more variables moderating the magnitude of the effect in question (see Hunter and Schmidt 2004). Note that if all of the variance in the effect sizes were accounted for by sampling error, then $s_\delta^2=0$. The 95% CI reported was computed using the standard deviation corresponding to s_e^2.

4.5. *Meta-analytic results*

The first result concerns the rejection rate of studies that failed to meet the selection criteria. The collective survey of 224 studies and reports generated 13 useable studies from 11 papers. While it is true that this value varies with the threshold set by the selection criteria, it is believed that the present criteria are not overly stringent. Hence, the extant empirical literature regarding WBV effects on performance is sparser than was initially anticipated. However, this attrition rate is similar to those reported in other published meta-analyses (e.g. Driskell and Mullen 2005). The results of the meta-analysis are presented in table 1.

According to guidelines proposed by Cohen (1988), an effect size magnitude of 0.2 represents a 'small' effect, a level of 0.5 a 'medium' effect and a magnitude of 0.8

Table 1. Formal whole-body vibration meta-analysis results.

Analysis	k	g	s_d^2	s_e^2	95% CI (var(e))
Global	13	−0.95	1.14	0.75	0.47
Task					
Perceptual	4	−1.79	2.02	2.96	1.69
Cognitive	1	−0.52*			
Fine motor continuous	8	−0.89	1.47	0.74	0.60
Fine motor discrete	3	−0.84	0.66	0.5	0.80
Dependent variable type					
Accuracy	9	−1.11	1.76	1.07	0.68
RT	5	−0.38	0.15	0.34	0.51
Duration					
Low	10	−0.87	0.94	0.48	0.43
High	3	−2.6	0.53	9.91	3.56
Intensity					
Low	3	−0.39	1.30	0.42	0.73
High	2	−0.05, −0.19*			
Frequency					
Low	10	−0.65	0.73	0.5	0.44
High	5	−1.98	0.97	1.66	1.13
Duration by intensity					
Low duration, low intensity	2	−0.02, −0.13*	1.35	0.25	0.44
Low duration, high intensity	2	−0.05, −0.19*	0.43	0.53	0.50
High duration, low intensity	1	−3.04*	1.42	3.37	2.54
High duration, high intensity	0				

*Where two or less studies exist in a category, each effect size is reported rather than a mean.

represents a 'large' effect. The global analysis shows an effect size of −0.95, which in meta-analytic terms represents a large overall deleterious effect. Since it includes 13 total studies, this represents a solid conclusion, as a number of other meta-analyses have been reported using a similar numbers of studies (e.g. Driskell and Mullen 2005).

Although the global analysis shows WBV generally causes decrement in performance, it is important to recognize that this outcome may be moderated by other factors. An additional, major aim here was therefore to establish what these factors are and to quantitatively assess their effects. The first moderator variable – the characteristics of the task – was assessed by categorizing it into four components, namely: perceptual processes; cognitive processes; continuous fine motor actions; discrete fine motor actions. An example of perceptual tasks would be in vigilance/target detection tasks (e.g. Warm 1984). Working memory and mathematical reasoning are both examples of cognitive tasks (e.g. Baddeley 1986). A continuous fine motor control task, such as required in tracking, and a discrete fine motor control task, such as seen in switch activations, represent the output component of this differentiation.

Table 1 shows a large effect of WBV on perceptual task performance ($k = 4$, $g = -1.79$), with all four contributing studies reporting effects showing considerable performance decrements under WBV. Table 1 also shows a moderate effect size of WBV on cognitive performance ($k = 1$, $g = -0.52$). However, this result should be interpreted with caution, as it is drawn from the one study that met the inclusion criteria for this category. A greater number of studies were found to meet the criteria for motor performance, with 11 effect sizes found. The effect of WBV on continuous fine motor performance ($k = 8$, $g = -0.89$) was found to be similar to the effect on discrete fine motor performance ($k = 3$, $g = -0.84$). Both categories therefore exhibited large degradation effects under WBV. The effects for continuous fine motor performance appear more stable than those of discrete fine motor performance as reflected in the variability results.

To further examine the moderating influence of the task at hand, two different reflections of response were investigated, with the data categorized according to whether the accuracy of the performance or the speed of the performance was recorded. This analysis showed a greater decrement of WBV on the accuracy of performance ($k = 9$, $g = -1.11$) compared with the speed of performance ($k = 5$, $g = -0.38$).

To evaluate the differential effects of the WBV characteristics itself, the separate influences of vibration intensity and vibration frequency were assessed. There is no fundamental performance theory through which to derive differentiation of frequency and intensity effects (although such a rationale exists for comfort and health; see International Organization for Standardization 1997). Therefore, a median split technique was used to differentiate this factor into the categories of either 'high' or 'low'. From this median split, vibration intensity under 0.07 Root Mean Square acceleration, relative to gravity (RMSg) was considered to be low, while intensity over that threshold was considered as high. As is clear from table 1, a larger effect was found for low as compared to high intensity (i.e. $k = 3$, $g = -0.39$, and $k = 2$, $g = -0.05$, respectively). Examination of the frequency component of WBV was also performed using a median split technique. Values greater than 5 Hz represent high frequency WBV and less than 5 Hz represent low frequency WBV. Table 1 reveals a similar trend to that observed for intensity. Thus, high frequencies exerted a substantial large negative effect on performance ($k = 5$, $g = -1.98$), while low frequencies exerted a moderate negative effect ($k = 10$, $g = -0.65$).

Another key factor in distilling WBV effects is exposure duration. The present results were categorized in two groups, studies that exposed performers to less than 30 min WBV and studies exceeding this duration. Shorter exposure times (< 30 min) produced a large effect on performance levels ($k = 10$, $g = -0.87$) while longer durations (> 30 min) produced a substantively larger degradation (k = 3, $g = -2.6$). The latter effect, however, must again be interpreted with caution due to the large variation found in the individual effects contributing to this calculated effect size ($s_e^2 = 9.91$).

A secondary analysis was carried out to determine the extent to which exposure duration moderates the intensity effects of WBV on performance. Due to the very limited number of studies and the resultant low stability, the findings are again tentative but suggestive. Performance decrement did appear to increase as a function of both exposure duration and intensity. When short exposure durations were assessed as a function of low and high intensities, small ($k = 5$, $g = -0.4$) and then moderate ($k = 8$, $g = -0.8$) effects were found respectively. When the long exposure durations were assessed, a substantially large effect was found for long duration/low intensity combination ($k = 2$, $g = -2.34$) and an even larger effect was found for the combination of long duration/high intensity ($k = 1$, $g = -3.84$). Performance decrements therefore may increase as duration and intensity increase in combination, but in the absence of any data in the long duration/high intensity category makes any conclusions impossible. While this does represent a concern, it is the present state of knowledge. However, this analysis did reveal the source of the intensity effect described above. It is clear that the stronger effect found for low intensity is due to one of the three contributing studies using a long duration exposure (see table 1).

5. Discussion

The meta-analysis shows that WBV has a negative influence on performance. The degree to which the vibration was found to be disruptive was moderated by the type of task being performed. The largest effect was found for perceptual tasks ($d = -1.79$). It is unsurprising to find that perception is disrupted by a physical stressor such as vibration, which exerts its influence through motion effects on the human body. Further support for this contention is evident in the effect sizes for the continuous and discrete fine motor tasks ($g = -0.89$ and $g = -0.84$ respectively). Again, the general mechanism of performance disruption is readily apparent, since these tasks require control of motor responses, which are easily disturbed when the vibration is absorbed within the body (Griffin 2004). Although a moderate negative effect was found for WBV on cognitive performance ($g = -0.52$), the effect size was derived from a single qualifying study (Guignard *et al.* 1981). However, the magnitude of this effect is lower than that observed for the perceptual-motor task categories.

The influence of WBV on performance was also considered with regard to other moderating variables. Performance in tasks emphasizing accuracy of response was found to be degraded more than those emphasizing the speed of response. Although these effects are not surprising (given the potential of WBV to cause unintended movements to body parts used in sensory and response processes), it is valuable to highlight that a better understanding of this type of effect may be achieved in future research by employing tasks that allow a direct trade-off between speed and accuracy, rather than looking at these as separate effects.

With regard to the characteristics of the vibration itself, it was found that performance decrements were larger for higher levels of frequency and intensity when compared against lower levels of these factors. The former is perhaps a little surprising, given that performance is generally expected to degrade more at lower frequencies.

Although the International Standardization Organization (ISO) no longer offers the guidance with regard to performance variation (International Organization for Standardization 1997), previous versions (e.g. International Organization for Standardization 1985) did provide fatigue decreased proficiency (FDP) thresholds, which indicated that the effect of vibration frequency was moderated by the axis of vibration. Hence, the present results may be a function of the present median split and the moderating effects of axis of vibration. Of course, other factors are capable of moderating the frequency effect on performance, such as the axes of movements necessary for the performance response and the resonance frequencies of body parts used in the performance. However, resolution of these issues awaits further empirical examination. Although the present results are somewhat sparse, they do represent a synthesis of the available data and it is important to recognize that the exact mechanisms underpinning WBV frequency effects are not yet fully understood (Griffin 2004). The data concerning the moderating effect of intensity show that lower intensities of WBV actually disrupted performance more than higher intensities. This could be considered to be somewhat surprising given that the general consensus in stress-performance theories is that the greater the magnitude of stress, the greater the potential level of disruption (Matthews *et al.* 2000, Hancock and Desmond 2001). However, this observed effect might be explained by its interaction with another moderator, *exposure duration*, as it was noted that one of the studies using a low intensity exposed the participants to the MBV stress over a long duration. Though the data for the interaction effect are somewhat sparse, it appears that the higher level of intensity causes more disruption that the lower level when the exposure duration is short

(<30 min). This interpretation is consistent with stress-performance theory, and is also coherent with the findings of Mansfield *et al.* (2000), who confirmed that higher magnitudes imposed a greater threat than low magnitudes, although the data were with reference to comfort rather than performance.

5.1. *Current state of knowledge*

Overall, two main themes emerge from the present results. First, it is evident that the current consensus is one of induced performance decrement; performance being degraded in all categories examined with the most deleterious associated with perceptual tasks. Second, this conclusion is based upon relatively few valid empirical investigations. This represents an example of what Laughery (1993) has referred to as the 'everybody knows' problem and one that Poulton (1976) has also articulated, especially in relation to stress effects. That is, since the general expectation is that vibration acts to degrade performance, few institutions or researchers are motivated to support or conduct extensive research to confirm an outcome that they think they already know. This is a potentially dangerous situation since, quite often, it is those very forms of consensus assumption that can prove fundamentally wrong. In the present context, the assumption of general degradation represents a conservative assertion but it is one that may cause the expenditure of unnecessary resources on mitigation technologies since decrement may not be ubiquitous under all combinatorial conditions.

In a recent review of WBV effects, Griffin (2004) concluded that although some general mechanisms are understood, there are no detailed models of WBV effects because the relationships among the many moderating factors are not fully understood. Griffin asserted that attempts to describe the extent of performance interference under WBV are not as valuable as attempts to uncover the reasons for the observed interference. That is, to paraphrase Griffin, work undertaken to examine whether or how performance is degraded is less important than work that seeks to explain why it is degraded. Griffin did, however, emphasize that an effort that seeks to specify the relative importance of the various factors would be highly valuable (Griffin 2004). Although the present effort does not answer this call for a mechanisms-led approach, the results of the present work go some of the way to detailing the relative influence that different moderators have on the WBV–performance relationship. In detailing the current state of the research, the present paper also highlights the gaps in the experimental literature. It is hoped that these current efforts can stimulate further work on two fronts. First, it is hoped that the quantitative (statistical) and qualitative (highlighting of areas with a lack of research) findings from the present meta-analysis can provide an impetus and direction for further empirical investigations. Second, the adoption of a different perspective is suggested, from which to tackle WBV-performance research.

5.2. *The adaptive human performer*

Understanding the specific WBV mechanisms stress on human may be better understood if future empirical studies derive from a 'top-down' theory-driven perspective. Humans are active agents in their world and are capable of adapting to environments when motivated to do so (Teichner 1968, Hockey 1997). A logical step therefore is to recognize that the understanding of stressor-performance relationships needs to place the human at the centre of the assessment methods. Two candidate models are considered below with a view to them being used to inform the choice of factors to manipulate and the variables to measure, in addition to being used as a framework on which to examine the outcome results. Hence, although the present paper does not suggest possible reasons for why performance is disrupted under WBV, it proposes candidate theoretical frameworks that may be used to uncover these mechanisms. This is illustrated by offering speculative explanations for the dose–response effect observed in the present data, in addition to WBV effects on cognitive performance, an area that has suffered from limited empirical examination (Sherwood 1987).

5.2.1. The maximal adaptability model. An example of how a theory or model can guide the selection of factors to manipulate is the adoption of Hancock and Warm's (1989) maximal adaptability model. Hancock and Warm described three facets of stress, which they referred to as the 'trinity of stress.' Stressors such as vibration would constitute one of the 'input' factors along with the characteristics of the tasks (e.g. display organization). It is to this facet of stress that the current meta-analytic results are most relevant. In regard to the effect of stress on behavioural and physiological adaptation, a central feature of the Hancock and Warm (1989) model is that under most environmental conditions individuals adapt effectively to the input disturbance and maintain performance capacity. A second feature is that adaptation occurs at multiple levels, particularly the physiological, behavioural (performance) and subjective/affective levels. These levels are represented as a nested structure (see figure 2), such that as the stress on the individual increases, by increased intensity, duration, or both, adaptation progressively fails. The first failure occurs in the subjective state, followed by performance, with physiological failure as the ultimate failure in adaptation. The threshold between stable adaptation and instability (adaptation failure) has been observed in high stress environments, including physiological failure manifested as unconsciousness (Harris *et al.* 2005).

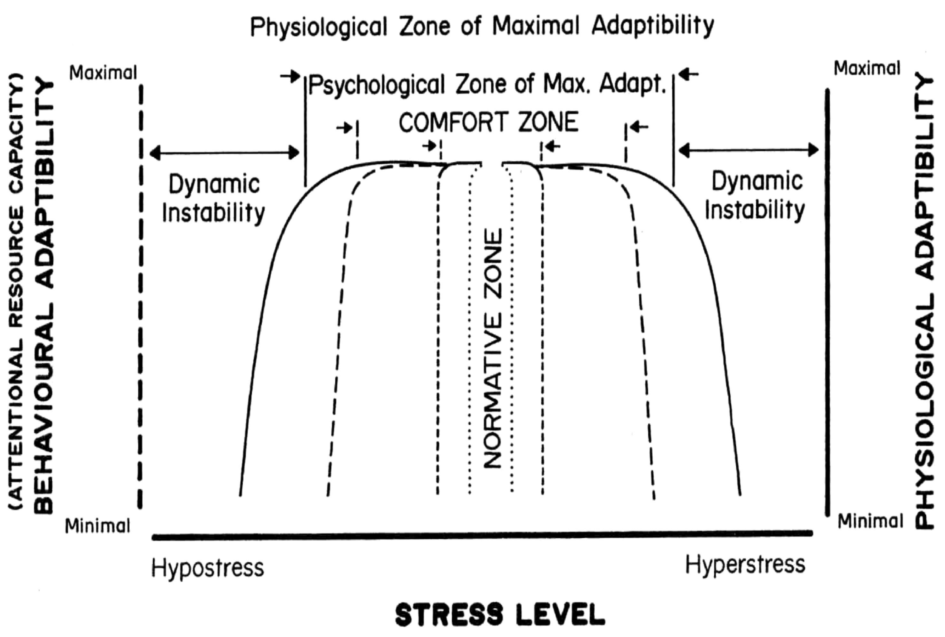

Figure 2. The extended-U relationship between stress level and response capacity, from the Maximal Adaptability Model (Hancock and Warm 1989).

This model is unique in that the input stress from the environment extends beyond the physical or social environment to include the task itself. Indeed, Hancock and Warm (1989) argued that the task is often the most proximal form of stress in many real-world circumstances. Thus, the task characteristics are important determinants of the adaptive state. This is represented in figure 3 by two base axes reflecting the spatial and temporal characteristics of the task. Information structure (the spatial dimension) refers to how the task elements are organized, including workload and task complexity. The temporal dimension is represented as information rate. Together, these dimensions can be used to form a vector (see figure 3), which serves to identify an individual's adaptive state (i.e. point on the surface). Environmental inputs such as vibration could be an additional term in the vector (suggesting an n-dimensional model) or it could be used as part of the input determining the position of a task along the two existing dimensions shown in the figure. While the current results provide quantitative estimates of vibration effects under different conditions, more research is needed to determine how such information can be integrated within the model shown in figure 3 and the relations among different sources of stress (i.e. multiple physical stressors and task-based stress; cf Broadbent 1971).

If the data from table 1 are considered in light of the maximal adaptability model, it is apparent that, as one might expect, the combination of stress intensity and duration exert multiplicative rather than additive effects. Performance degradation therefore reflects something beyond a simple additive effect. In spite of the arguments that may be made about the present median-split technique to derive high and low levels of intensity and duration, the outcome implies a non-linear change in performance deterioration (primarily expressed here as the duration effect). This apparent synergistic effect of intensity and duration moderators is therefore an area worthy of further empirical investigation.

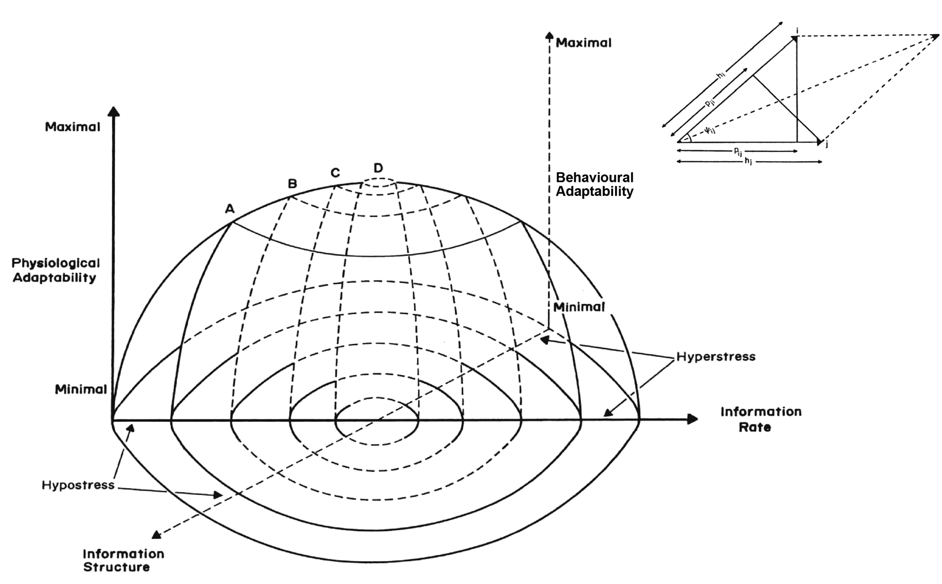

Figure 3. The description given in figure 2 is expanded into a 3-D representation by parsing the base 'hypostress–hyperstress' axis into its two component elements. These divisions are composed of information rate (the temporal axis) and information structure (the spatial axis).

The maximal adaptability model can be used as a guide for WBV research. For instance, the representation of environmental and task characteristics as a vector (see figure 3) indicates that one might systematically vary vibration characteristics (e.g. frequency, intensity, duration of exposure) and examine these at multiple levels of task characteristics (e.g. simple vs. complex information structure, high vs. low information rate). The multiplicative effects indicated in the Hancock and Warm (1989) model can then be evaluated empirically. Of particular interest is the interaction between intensity (the abscissa in figure 2) and duration of exposure. Examination of these interactive effects would fill a gap in stress research, which has traditionally neglected multiplicative effects (see Broadbent 1971 for an early discussion of this issue). In addition, according to Hancock and Warm (1989), individuals exert effort to adapt to stress by narrowing of attention (see also Easterbrook 1959), but such efforts become maladaptive when task relevant cues are excluded from attention and the duration of exposure (and effort to cope with the stress) exceed the capacity of the organism to maintain a stable level of adaptation. Thus, future investigation should examine the effect of vibration on mechanisms of selective and sustained attention, with specific emphasis on cognitive resource allocation. Finally, the maximal adaptability model recognizes that there are multiple levels of stress response (cf Matthews 2001). Thus, as stress increases, failures to adapt occur progressively from subjective comfort to physiological failure. Future research should empirically test this progression to the extent possible by examining the changes in cognitive state and performance as a function of time on task and exposure to WBV. Establishing the progression of multiple stress responses would also allow more precise identification of the transition points between levels of adaptation (e.g. between the comfort and psychological zones in figure 2) and the thresholds for adaptation failures.

5.2.2. The compensatory control model. Griffin (2004) proposed that one reason for the limited understanding of the mechanisms underpinning WBV effects may be the use of methods that do not capture the effects to a satisfactory degree (e.g. the use of simple reaction time measures of cognitive performance). This reasoning may be extended to actual concepts, with the definitions of the concepts not being sufficiently broad. Hence, certain WBV effects on performance may remain hidden from the experimenter, through the concept not being assessed to its full potential. A key example of this is the view of performance adopted in most empirical WBV research.

Hockey's Compensatory Control Model (CCM; Hockey 1997) points out that simple methods may not be sufficient to capture stressor effects, as the performer may choose to 'protect' the level of observable performance through the application of increased effort or a change in strategy (also see Teichner 1968, Kahneman 1973). Hence, performance can be maintained under high levels of both environmental stress and task demands. A framework is therefore required that can identify stressor effects on a different level. This is achieved through the recognition that although performance may be protected, it is at a cost to the performer on other levels. Uncovering these 'latent' effects may therefore identify when a performer may be in a high-risk 'strain' state, where performance may be in risk of breakdown even though observable levels may appear unthreatened.

A key tenet underpinning Hockey's model is the importance of recognizing the biological and motivational context in which performance takes place. Performance has to compete with other motivational goals (e.g. seeking rest) and, as such, goals may change over the duration of performance. When performance under high demand is sustained, performance goals are maintained in focal attention through the mobilization of effort. As effort is a key moderating factor, it can be seen why observed performance levels under stress may degrade, improve or stay the same – an observation also recognized by Griffin (2004). In order to identify strained performance, CCM proposes that a broad definition of performance should be used – one that considers not only performance effectiveness but also performance efficiency (i.e. a perspective that recognizes the costs of maintaining performance).

To assess performance efficiency, Hockey proposed four types of latent performance decrement that may occur. First, increased effort levels are biased towards the protection of high-priority task goals and therefore may be reflected in the relative neglect of lower-priority tasks. Although secondary tasks are less critical to overall performance levels, the decrements introduce risk into the system. This decrement is a robust phenomenon and was used initially to assess processing capacities in dual-task methodologies (e.g. Moray 1979, Hancock and Meshkati 1988). Second, performers under stress may adopt less resource-intensive, but more reactionary strategies (e.g. Sperandio 1978). Third, the protection of performance is at a cost to the performer, with increases in subjective levels of effort expenditure, fatigue and anxiety being reported, in addition to levels of psychophysiological sympathetic dominance. Finally, fatigue after-effects may be seen following prolonged effortful engagement. After-effects are considered to be the most valid test of fatigue levels (see Broadbent 1979, Holding 1983). In these situations, the tired operator is more likely to adopt low-effort (and therefore more risky) performance strategies, through being unable or unwilling to invest further effort.

Several other methodological considerations are emphasized by Hockey (1997), such as the importance of training participants when investigating stressor effects on performance. This yields increased ecological validity if the results are to be generalized to trained workers and minimizes the threat of learning effects masking any effect the stressor may have, as also recognized by Griffin (2004). As trained participants are more likely to seek to protect performance under high stress (as workers in operational work environments would), this further emphasizes the importance of assessing latent decrements in order to evaluate a threat to system performance.

In order to capture these hidden effects of stress on performance, WBV researchers are advised to adopt the convergent method approach advocated by CCM. As performers can protect the most salient aspects of performance but at a cost to less important tasks, the use of multi-level performance tasks allows this trade-off to be captured. Self-report methods allow the assessment of regulatory activities. For instance, the measurement of subjective effort, anxiety and fatigue can highlight changes in performance strategy and the costs of compensatory behaviour (psychophysiological measures can also be used to triangulate the data yet further). After-effects of WBV exposure can be captured through the use of probe tasks following the main performance task.

Although CCM has not been used as a framework on which to base the empirical investigation of WBV effects, it has been used to investigate other stressors. For instance, Hockey *et al.* (1998) manipulated the levels of sleep deprivation and interface control as stressors. They found that overt (primary task) performance levels were maintained under all levels of stress, with the only performance effects found for a secondary task under the most demanding of conditions. The results also showed that the protection of performance was achieved at a cost to increased levels of effort and fatigue. Conway (2005) found strong support for CCM over a series of five experiments in which the levels of task demand and environmental stressors (continuous broadband noise) were manipulated. Again, performers were able to protect primary task performance levels, although at a cost to secondary task performance levels. Increased effort mobilization was found under high demand, resulting in high levels of strain-related variables (fatigue and anxiety).

Although the FDP guidelines were omitted from the latest ISO standards (International Organization for Standardization 1997), viewing the dose–response effects found in the present paper with regard to CCM may actually offer speculative support for the role of fatigue in WBV effects on performance. It is important to be clear on what 'fatigue' is considered to be, however, to avoid the confusion that is common with this often-used but poorly-defined concept. Fatigue in CCM is considered to be an adaptive response to the interaction with task and environmental demands and is defined as the resistance to the investment of further effort. Hence, the objective levels of task demand or WBV do not cause fatigue; rather, it is the performer's attempts to adapt to the imposed demands. Griffin (2004) previously questioned the proposed FDP effect on the grounds of it being more likely to be a factor of motivation levels. However, these authors and others (e.g. Hockey 1997) stress that the two concepts, motivation and fatigue, are intimately connected, with reductions in task-directed effort being a possible mechanism for WBV dose–response effects. A tentative link can be made here between reductions in comfort and (short-term) health, as proposed by International Organization for Standardization (1997) and possible reductions in performance. As the individual becomes more uncomfortable or becomes aware of health issues, then goals (and attention) can shift slightly away from performance in an attempt to restore prior levels of comfort and/or health. For instance, the operator may think about, or may take, a short break away from the task.

It is therefore emphasized that for WBV mechanisms on performance to be understood to a greater degree, it is importance to capture the broad range of effects on the operator's functional state, as Hockey's CCM proposes. The model provides a framework on which to conduct empirical assessments of WBV-performance relationships, it provides hypotheses to be tested and can be used to interpret the results gained. In doing so, Hockey's CCM answers Sherwood's (1987) appeal for such a framework.

6. Conclusions and recommendations

The study of WBV effects has been a traditional concern of the physical ergonomist who is tasked with the protection of individuals in the workplace and beyond. WBV is an evident source of physical stress but the way in which cognitive and perceptual-motor performance is influenced has been a surprisingly underserved enterprise. Here, a quantitative assessment of the present state of knowledge has been presented, but the integration of WBV effects into the wider realm of stress theories has also been advocated. This strategy has the advantage of cross-referencing insights derived from such general formulations to guide future research on all vibration effects. Interestingly, WBV does have direct effects on tasks of almost purely cognitive content. This implies therefore that as well as the manifest disturbances to the physical surface of support, vibration exerts a more indirect effect on human cognition, perception and motor response.

While it is a moral imperative of the ergonomist to protect individuals from physical harm, the evolution of the workplace towards that of an information marketplace means that issues such as health and comfort can no longer dominate the vibration landscape. It is fundamentally immaterial if an individual exposed to WBV is both healthy and comfortable but still making such egregious performance errors that they endanger themselves, their co-workers and the greater society served by the complex technological systems that they control.

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