Interference in Reading an E-Paper under Whole-Body Vibration Exposure with Subject Posture

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There is increasing use of laptop computer in rail vehicles for performing various sedentary activities such as reading and typing. The vibration is a major factor influencing the reading performance during the journey. Therefore, an experimental study was conducted to investigate the extent of interference perceived in reading an e-paper in two seated postures (backrest support and leaning over the table) under random vibration. The study involved 30 healthy male subjects who were excited with vibration acceleration in mono-, dual, and multi-axes in 1–20 Hz at 0.4, 0.8, and 1.2 m/s^2 amplitudes. The task consisted of reading the given paragraph of an e-paper under various vibration stimuli, and it was evaluated by time taken to complete the task and subjective evaluation of reading difficulty. The subjective evaluation showed that the reading difficulty increased with vibration stimuli for both the subject postures. The subjects perceived higher difficulty and degradation in reading performance for vibration in dual and multi-axes, which was comparable to that for lateral and vertical directions also. The perceived difficulty and impairment in reading performance was greater while reading with the laptop on their lap for vibration in the x-axis, while the effect was just the reverse for other axes.

1. INTRODUCTION

Today, laptop computers are widely used by commuters in rail vehicles due to the lightweight and compact size of the LCD display. During travel, the vibration environment in trains affects the human visual system and reading performance, consequently making the reading activity more difficult and tiring. A number of authors have investigated the effects of ambient luminance, light source, polarity, font style, font size, and viewing distance on visual performance and visual fatigue of e-paper displays and compared them with conventional papers,[1–3] but only under stationary conditions. Khan et al. investigated the combined effect of noise and vibration on the performance of a readability task on a laptop computer under varying levels of noise and vibration.[4,5] Results showed that the individual effects of noise and vibration were statistically significant. However, the combined effect of noise and vibration was not found to be statistically significant. In order to investigate the effect of train vibrations on laptop personal computers (PC) and their users, Nagakawa and Suzuki[6] carried out surveys and related experiments. The results reveal that the majority of the passengers prefer to work with their laptops on their lap instead of the table. The reasons could be attributed to the inappropriate height and size of the table and as a means to attenuate the vibration.

Previous studies have confirmed that vibrations disturb a significant number of passengers in performing sedentary activities like reading. Whole-body vibration has been shown to affect both reading speed and reading accuracy in many studies.[7–18] Lewis and Griffin[19] found a degradation of reading performance during exposure to fore-and-aft (x-axis) vibration at frequencies between 5.6 and 11 Hz during reading leading articles from a national newspaper. However, it was pointed out that the effect was present only when a seat with a backrest was used, and so it may be assumed that vibration transmitted to the head by the backrest was the cause of the problem. In the same study, lateral (y-axis) vibration produced only a slight degradation in reading performance at about 5.6 Hz.

In a recent field study on various Indian Railways passenger trains, which included both questionnaire surveys and vibration measurements, it was found that the maximum difficulty was observed in writing activity, a smaller difficulty in working with laptop computers, and the comparatively smallest difficulty in reading.[21] It was also revealed that most of the laptop users preferred to work with laptops on their lap instead of the table. The reasons could be attributed to the inappropriate height and size of the table and as a means to attenuate the vibration. The same study reported that the vibration acceleration levels measured from floor of passenger compartment were found to be in the range of 0.2–0.67 m/s^2 rms in the longitudinal direction (x-axis); 0.23–0.83 m/s^2 rms in the lateral direction (y-axis) and 0.38–1.2 m/s^2 rms in the vertical direction (z-axis). As compared with vibration acceleration in the x-axis, the vibration acceleration level was found to be about 30% higher in the y-axis and approximately 80% higher in the z-axis. Therefore, these vibration acceleration magnitudes were considered for the study.

The objective of the study was to investigate the extent of interference perceived in reading e-papers by seated subjects in two postures under mono-, dual, and multi-axis Gaussian random vibration environment.

2. METHODOLOGY

2.1. Subjects

A total of 30 healthy male subjects with age in years (22.91 ± 4.58), weight in kg (68.91 ± 12.04), and height in cm (173.87 ± 5.86), all students of the Institute with normal eyesight (normal visual acuity 6/6 vision), participated in the experiment. The subjects participated voluntarily under informed

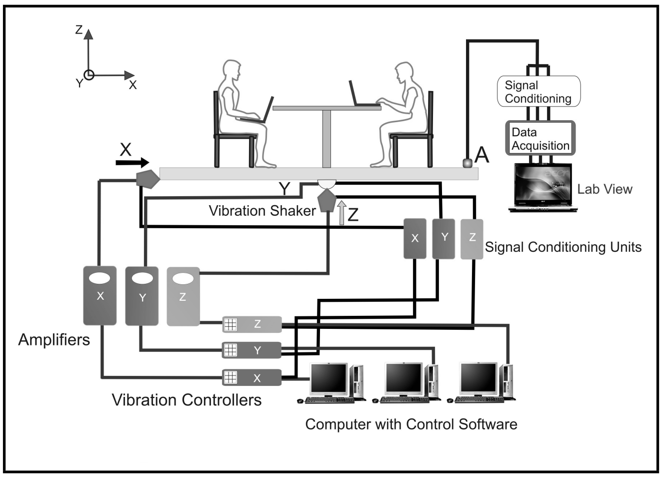

Figure 1. Schematic presentation of the equipment used for vibration measurements and subject posture.

written consent and were given a small remuneration. Ethical approval was obtained from the IIT Roorkee Human Ethical Committee. A screening questionnaire was collected from subjects on their personal background: level of education; experience of train travel; fitness; reading and writing habits; and musculoskeletal disorders[22] to assure the suitability of the subjects for the experimental task.

2.2. Subject's Posture

In the laboratory study, subjects performed the reading task in two postures as defined below, and shown in Fig. 1: (i) Lap posture: the subject is seated with backrest support with the laptop computer held on lap and (ii) Table posture: the seated subject leans forward with the laptop computer placed on the table.

2.3. Vibration Environment

The study was conducted on the vibration simulator developed as a mockup of a railway vehicle, in the vehicle dynamics laboratory, IIT Roorkee, India. It consists of a platform on which a table and two rigid chairs have been securely fixed (Fig. 1). The backrest of the chair was rigid, flat, and vertical. Neither the seat, nor the backrest, nor the table had any resonances within the frequency range studied (up to 20 Hz) in any of the three axes. Three Electro-Dynamic Vibration shakers are used to provide vibration stimuli to the platform in three axes; longitudinal (x-axis), lateral (y-axis) and vertical (z-axis). For simplicity and safety reasons the internal positioning accelerometers of the shakers were continuously used for motion feedback. The onboard vibrations of the platform were measured on line for continuous monitoring of the vibration signal by using a tri-axial accelerometer (KISTLER 8393B10), and the signal was transmitted to the Labview Signal Express software via a data acquisition card (NI 6218). Cross talk between vibration measurements in orthogonal axes was less than 5% of the vertical data at most frequencies of interest.

The simulator provides a controlled train atmosphere with a working illumination well above 250 lux using both direct and indirect light sources for constant and well-distributed illumination at all seats and tables. The test subjects were seated on the chairs rigidly mounted on the platform of the Vibration Simulator such that these were excited with the same frequency as the platform, up to 20 Hz. This range is considered critical since the structural dynamics of a passenger railcar usually give rise to several resonance peaks in the frequency range of 0.5 to 20 Hz,[23] and this range coincides with the most vulnerable range for reading activity also.

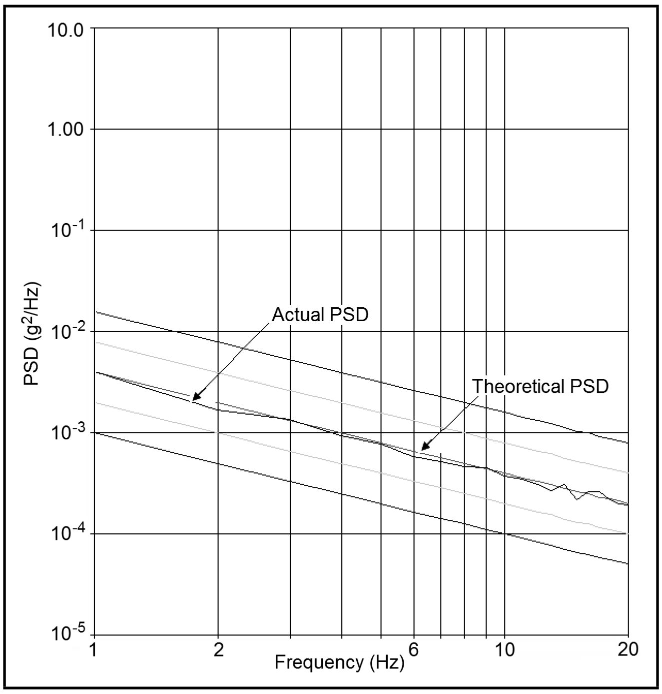

Figure 2. Power spectral density (g^2/Hz) curve.

2.4. Vibration Stimuli

In the study, for each subject's posture, a continuous Gaussian random signal over the frequency range 1–20 Hz was generated using a random vibration controller. The power spectral density curve (g^2/Hz) of the signal generated by one of the exciters over the frequency spectrum of interest is shown in Fig. 2. The three levels of acceleration amplitudes namely 0.4, 0.8, and 1.2 m/s^2 RSS were given in mono-axis, dual axis, and multi-axis. In mono-axis, three levels of acceleration amplitudes namely 0.4, 0.8, and 1.2 m/s^2 were given independently. In earlier discussion, the vibration level in Indian railway passenger train was found to be about 30% higher in the y-axis and approximately 80% higher in z-axis in comparison with x-axis vibration acceleration. Therefore, in the dual axis, any two mono-axes were excited simultaneously with the above relation, which resulted in RSS acceleration magnitudes of 0.4, 0.8, and 1.2 m/s^2. Similarly, for the multi-axis, three mono-axes are excited simultaneously for the given RSS acceleration magnitudes (Table 1). The RSS is the vibration total value, which is obtained from the square root of the sum of the squares of the measured rms values in the x-, y-, and z-directions.[24]

2.5. Reading Task and Performance

The task involved reading a given text paragraph of an e-paper at a comfortable speed with a one minute break between consecutive sessions on a laptop computer. For the study, various paragraphs of 126 words each were selected from "Mid-Day" a leading national newspaper.[25] For each vibration condition, the article for the reading task was different to prevent the learning effect. The reading performance was evaluated in

Table 1. Summary of various vibration stimuli used in the experiment.

Sti-mulus	Vibration Magnitude (m/s^2, unweighted)			
	x-axis RMS	y-axis RMS	z-axis RMS	RSS = $\sum$axes
1	0.4	-	-	0.4
2	0.8	-	-	0.8
3	1.2	-	-	1.2
4	-	0.4	-	0.4
5	-	0.8	-	0.8
6	-	1.2	-	1.2
7	-	-	0.4	0.4
8	-	-	0.8	0.8
9	-	-	1.2	1.2
10	0.25	0.32	-	0.4
11	0.5	0.63	-	0.8
12	0.75	0.94	-	1.2
13	0.2	-	0.35	0.4
14	0.4	-	0.7	0.8
15	0.6	-	1.0	1.2
16	-	0.24	0.33	0.4
17	-	0.45	0.65	0.8
18	-	0.7	1.0	1.2
19	0.17	0.22	0.3	0.4
20	0.33	0.43	0.6	0.8
21	0.5	0.63	0.9	1.2
Static	-	-	-	-

RMS = root mean square; RSS = root sum of squares.

terms of the time taken to complete the reading task for which an e-stopwatch was placed on the monitor screen of the laptop computer. The laptop computer (Lenovo R61) of size (13.2 × 9.3 × 1.37) in inches had a standard 89-letter keyboard with a 14.1 inch XGA TFT display screen and weighed about 2.35 kg. The pixel resolution was 1024 horizontally and 768 vertically, and the center-to-center pixel spacing was 0.2798 mm. Either the scrolling bar or the PageUp/PageDown buttons could control the texts on the screen of the laptop computer. The preset text/background color combination of the laptop was black-on-white. The measured maximum luminance contrast ratio (Lbackground/Ltext) was 192.8, which was fixed in each reading trial. The subjects maintained a viewing distance of 56 cm in both the seating posture, and they were seated in a rigid chair without armrests.

The subjective evaluation employed Borg's CR-10 scale.[26] Table 2 presents the CR-10 scale, which consists of 17 level points (9 labeled and 8 unlabeled). The scale is used by first finding the verbal label that best fits the stimulus attribute of interest, and then using the number scale to make adjustments to the rating. The value of 10 represents the maximum suggested intensity, but greater values can be chosen if the test participant so wishes. Due to its ease of use and reliability, the CR-10 scale has found wide application in the fields of physiology, psychology, and ergonomics to rate sensations of pain, fatigue, physical exertion, and discomfort.

2.6. Test Procedure

Each participant began the experiment by filling out a general questionnaire about his personal information. Then, a brief introduction about the experiment was given to each participant. After that, the participant performed the experiment task. The study involved about one hour of test each day to avoid the influence of fatigue. The test was conducted on two subjects at a time. Each subject was exposed to a total of 42 conditions from a combination of three levels of vibration magnitudes, two levels of subject's posture, and seven levels of vibration directions (mono-, dual and multi-axes) with a one minute break between consecutive sessions. A static condition with no vibrations was also used. The conditions were presented in random with Latin Square Design to minimize order effects. The test subjects were instructed to occupy themselves with the prescribed posture during the vibration exposure and rate their perceived difficulty of reading using Borg's CR-10 scale.

Table 2. Borg's CR-10 scale.

0	nothing at all
0.5	extremaly weak (just noticeable)
1	very weak
2	weak (light)
3	moderate
4	somewhat strong
5	strong (heavy)
6	
7	very strong
8	
9	
10	extremely strong (almost maximal)
·	maximal

3. DATA ANALYSIS

A factorial analysis of variance (ANOVA) was performed to evaluate the subjects' responses for which results at the $p < 0.05$ level are referred as significant. The statistical package for social sciences (SPSS Inc., Chicago, USA, version 16) was used for all statistical analysis.

In the ANOVA, the within-subjects design was used for all the independent variables: vibration magnitudes, subject's posture, and direction of vibration. Within-subject designs are often called repeated-measures designs since within-subjects variables always involve taking repeated measurements from each subject for all the test conditions. Two other statistical measures were considered for interpreting the ANOVA, (e.g., the estimate of effect size (partial eta-squared) and the observed power). Partial eta-squared is not dependent on how many factors there are—it gives the contribution of each factor or interaction, taken as if it were the only variable, so that it is not masked by any more powerful variable. Observed power is the ability to detect an effect if there is one. In the range from 0 to 1, an observed power of 0.95 would mean a 5% chance of failing to detect an effect that is there. A wilcoxon matched-pairs signed ranks test was also carried out on all the data to determine whether vibration magnitude, direction of vibration, and subject's posture had a significant effect on reading performance and reading difficulty. The two-tailed test was used, and statistical significance was accepted at the 5% level ($p < 0.05$).

4. RESULTS

The reading difficulty evaluated by subjective evaluation was represented as mean values of the level of difficulty as shown in Figs. 3 and 4. Similarly, the reading performance was evaluated by the objective measure of time taken to complete the reading task for each vibration condition and the increase in time with respect to the static condition was represented as the mean percentage decrement in reading performance (Figs. 5 and 6).

4.1. Reading Difficulty as Subjective Evaluation

The mean values of level of difficulty by subjective evaluation in mono-, dual and multi-axis vibration are shown in Figs. 3 and 4. Also the effect due to subject's posture can be distinguished in Fig. 4.

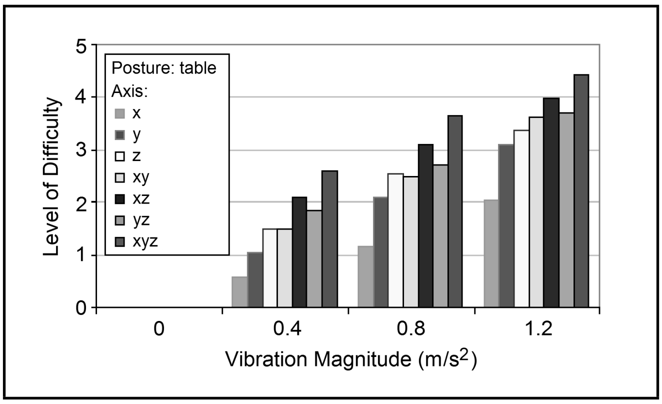

Figure 3. Effect of vibration magnitudes and directions on level of difficulty.

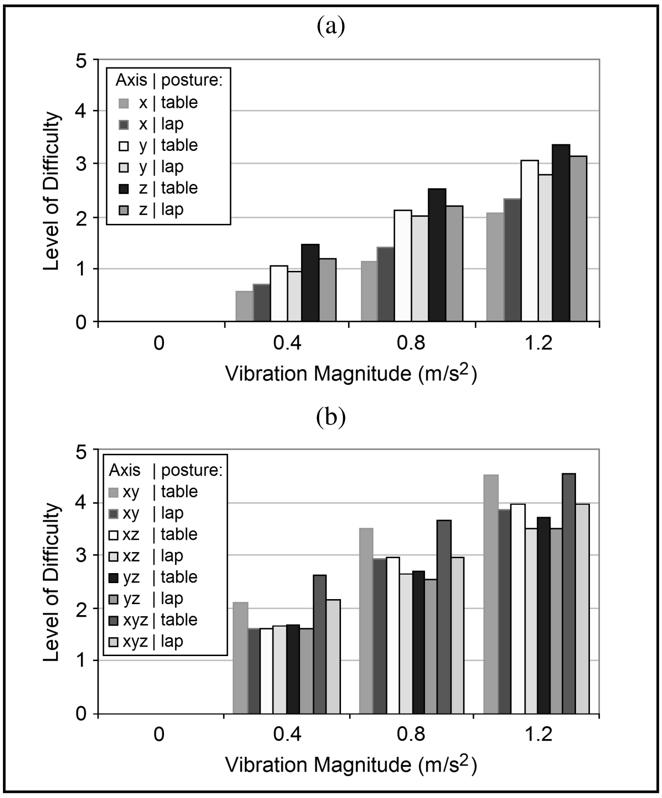

Figure 4. Effect of subject posture on level of difficulty for (a) mono-axes (b) dual and multi-axes.

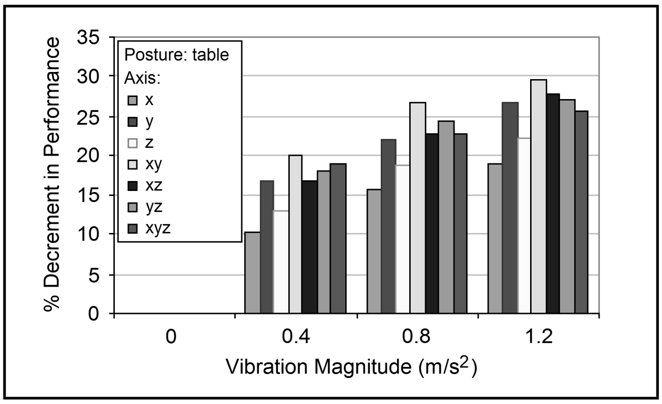

Figure 5. Effect of vibration magnitudes and directions on on performance decrement.

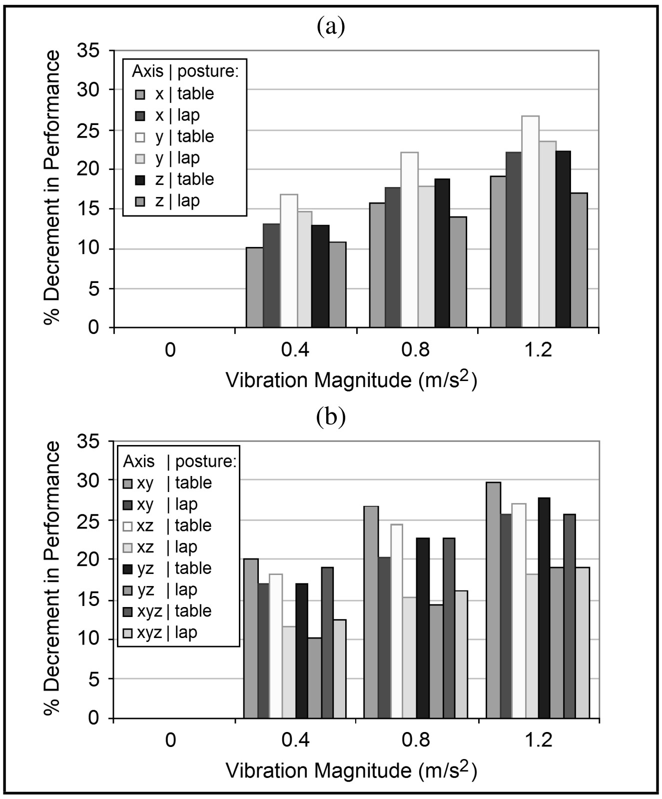

Figure 6. Effect of subject posture on performance decrement for (a) mono-axes (b) dual and multi-axes.

4.1.1. Influence of vibration magnitudes on subjective evaluation

Figures 3 and 4 show the effect of vibration magnitudes on perceived difficulty in all the mono-, dual and multi-axes for both the subject postures. It can be observed that the level of difficulty progressively increases with an increase in intensity of the vibration stimulus. It was also confirmed by observing statistically significant differences in the level of difficulty between the range of given vibration stimuli for both the subject postures in all the directions of vibration ($p < 0.05$).

4.1.2. Influence of direction of vibration on subjective evaluation

Among all mono-axes, the highest level of difficulty in table posture was observed with vibration in the z-axis and the least difficulty in the x-axis (Fig. 3). It was found that the effect of z-axis vibration on perceived difficulty is comparable to that of the y-axis since the difference in the level of difficulty was not significant between them ($p > 0.05$); however, it was found significant for other combinations of mono-axes at all vibration stimuli.

Similarly, amongst all combinations of dual axes (Fig. 3), no significant difference in level of difficulty was observed ($p < 0.05$). For vibration stimuli in all dual axes, the effect was greater than x-axis vibration ($p < 0.05$); nevertheless, as compared with the y- and z-axes, the effect was found to be insignificant at a higher vibration stimulus (i.e., 0.8 and 1.2 m/s^2) ($p > 0.05$).

The effect of vibration in mono-axes has been compared with their related dual axes in order to study their combined effect on reading difficulty (Fig. 3). It can be seen that the higher level of difficulty was observed with the dual xy-axis as compared to the x-axis for all vibration stimuli ($p < 0.05$), but insignificant difference was observed between the y- and xy-axes at higher vibration magnitudes (i.e., 0.8 and 1.2 m/s^2) ($p > 0.05$). Similarly, vibration in the dual xz-axis resulted in a higher level of difficulty than the x-axis at all vibration stimuli ($p < 0.05$), but the effect was found to be similar to the z-axis at higher vibration magnitudes only (i.e., 0.8 and 1.2 m/s^2) ($p > 0.05$). Moreover, the vibration in the dual yz-axis showed no significant difference with the y- and z-axes at higher vibration magnitudes only (i.e., 0.8 and 1.2 m/s^2) ($p > 0.05$).

It can also be seen from Fig. 3 that a higher level of difficulty was observed with multi-axis direction as compared to mono-axis direction ($p < 0.05$), but the difference in the level of difficulty was not found significant between multi-axis and dual axis direction at higher vibration magnitudes (i.e., 0.8 and 1.2 m/s^2) ($p > 0.05$).

4.1.3. Influence of subject posture on subjective evaluation

Whereas for vibration in the x-axis, the level of difficulty was found to be higher while reading on lap than on table (Fig. 4a) at all vibration stimuli ($p < 0.05$). The level of difficulty was found to be comparatively greater for the table posture for vibration in the z-axis at all vibration stimuli ($p < 0.05$). The response for multi-axis vibration (Fig. 4b) was similar to that for the z-axis. Comparatively greater difficulty while reading on the table is found for vibration in the y-axis also (Fig. 4a), but this difference is significant only at the highest vibration magnitude (i.e., 1.2 m/s^2) ($p < 0.05$). Subject posture had no significant effect on the level of difficulty in all dual axes (Fig. 4b) ($p > 0.05$).

4.2. Reading Performance as Percentage Performance Decrement

The mean values of the percentage decrement in reading performance in mono-, dual, and multi-axis vibration are shown in Figs. 5 and 6. Also, the effect attributable to subject's posture can be distinguished in Fig. 6.

4.2.1. Influence of vibration magnitudes on performance decrement

Figures 5 and 6 show the effect of vibration magnitude on percentage decrement in reading performance in all mono-, dual, and multi-axes. It was observed that the percentage decrement in reading performance increased with an increase in intensity of vibration stimulus in all mono-, dual, and multi-axes for both the subject postures ($p < 0.05$).

4.2.2. Influence of direction of vibration on performance decrement

Among all mono-axes, the higher percentage decrement in reading performance was observed with the y-axis and least with the x-axis (Fig. 5). Also, the difference in reading performance was found significant between all combinations of mono-axes at all vibration stimuli ($p < 0.05$).

In all the dual axes, the percentage decrement in reading performance was found to be higher with the xy-axis and least with the xz- and yz-axes (Fig. 5), but no significant difference in reading performance was observed between any combination of them at all vibration stimuli ($p < 0.05$). It can also be observed that the influence on reading performance for vibration in all dual axes was greater than that in the x-axis ($p < 0.05$) and similar to the y-axis ($p > 0.05$). The effect for vibration in dual axes was also similar to that in the z-axis ($p > 0.05$), excluding the xy-axis vibration ($p < 0.05$).

The effect of vibration in the mono-axes has been compared with its related effect in the dual axes in order to study their combined effect on reading performance (Fig. 5). It can be seen from Fig. 5 that the decrement in reading performance was higher with vibration in the dual xy-axis as compared to the x-axis ($p < 0.05$), but insignificant difference was observed for all vibration stimuli between the y- and xy-axes ($p > 0.05$). Similarly, percentage decrement in reading performance was found to be higher for vibration in the dual xz-axis as against that in the x-axis at all vibration stimuli ($p < 0.05$), but difference in reading performance remained insignificant between the xz- and z-axes at all vibration stimuli ($p > 0.05$). Moreover, the vibration in the dual yz-axis showed no significant difference with the y- and z-axes at all vibration stimuli ($p > 0.05$).

It can also be seen from Fig. 5 that the percentage decrement in reading performance increased with multi-axis vibration as compared to that in all mono-axes ($p < 0.05$), excluding the y-axis ($p > 0.05$), but a significant difference in reading performance was not found among multi-axis, dual axis, and y-axis at all vibration stimuli ($p > 0.05$).

4.2.3. Influence of subject's posture on reading performance

While comparing the effect due to postural differences (Figs. 6a and 6b), the vibration stimuli in all mono-, dual, and multi-axes except the x-axis, indicate a higher percentage decrement in reading performance with table posture than with lap posture ($p < 0.05$). Similarly, the difference in reading performance for vibration stimuli in all mono-, dual, and multi-axes was significant except for in the xy-axis, in which case it was significant only for higher vibration stimuli (i.e., at 0.8 and 1.2 m/s^2) ($p < 0.05$).

4.3. Results from Data Analysis

The overall effect on the reading performance in terms of subjective evaluation and percentage decrement was evaluated using the within-subject test for all the independent variables—that is, vibration magnitude, direction of vibration, and subjects' posture (Table 3 and 4). Table 3 shows that all the independent and interacted variables with interaction up to the second level exhibit significant value ($p < 0.05$), indicating that all the main parameters are significantly responsible for the judgment of difficulty. In general, the observed power takes high values for all the independent and interacted variables. The results also show that the vibration magnitude is the only variable that contributes the most to the perceived difficulty and that posture comes second, followed by direction of vibration. A similar outcome was observed for all the independent variables from the within-subject test for percentage decrement in reading performance. Moreover, the interacted variables ($D \times P$) and ($V \times P$) also show substantial contribution as compared to direction of vibration alone (Table 4).

5. DISCUSSIONS

Various national and international standards provide guidance on the measurement, evaluation, and assessment of

Table 3. Within-subjects effect of test parameters for subjective evaluation.

Source	Type III Sum of Squares	*df*	Mean Square	F	Sig.	Partial eta-Squared	Observed Power
Direction (D)	61.05	6	10.17	11.42	0.000	0.559	1.0
Vibration (V)	867.28	1.35	643.33	589.33	0.000	0.985	1.0
Posture (P)	2.00	1	2.00	16.27	0.003	0.644	0.94
$D \times V$	28.02	18	1.55	5.25	0.000	0.369	1.0
$D \times P$	5.45	6	0.909	6.54	0.000	0.42	0.998

Table 4. Within-subjects effect of test parameters for percentage decrement in reading performance.

Source	Type III Sum of Squares	*df*	Mean Square	F	Sig.	Partial eta-Squared	Observed Power
Direction (D)	1324.25	6	220.71	4.83	0.001	0.408	0.98
Vibration (V)	37510.65	1.48	25269.71	268.52	0.000	0.975	1.0
Posture (P)	1216.15	1.00	1216.15	25.06	0.002	0.782	0.98
$D \times V$	633.18	18	35.17	2.65	0.001	0.274	0.99
$D \times P$	816.96	6	136.16	12.34	0.000	0.638	1.0
$V \times P$	408.03	3	136.01	13.41	0.000	0.657	0.99
$D \times V \times P$	393.02	18	21.83	2.65	0.001	0.274	0.99

whole-body vibration in respect to perceived discomfort, but the standards differ in evaluation and assessment of vibration.[27] These standards are usually used as a tool for the train operators and manufacturers to ensure vibration levels in respect to ride comfort. Limits and procedures for the evaluation of discomfort caused by whole-body vibration are given in standards such as ISO 2631–4 and ENV 12299.[28,29] However, these standards have very little use in determining the extent of difficulty caused by vibrations in performing sedentary activities like reading or writing.

5.1. Effect of Vibration Magnitude

Generally, among all independent and interacted variables, the data analysis reveals that the highest contribution comes from the vibration magnitudes, for which the observed power takes high values. For all mono-, dual, and multi-axes vibration, the reading difficulty evaluated by subjective evaluation was found to increase for both subject postures with a corresponding increase in vibration stimuli. The findings are consistent with those of Mansfield and Maeda,[29] where subjective ratings of intensity increased with vibration magnitude for both single-axis and dual-axis vibration conditions. A similar outcome was reflected in the percentage decrement in reading performance, which progressively increased for both the subjects' postures with an increase in vibration stimuli.

For the reading task, it is observed that perceived difficulty increases with vibration magnitude, since at higher vibration magnitudes, it may be harder for the participants to maintain their performance. The quantum of interference may be partly dependent upon the posture adopted, but the interference could also be attributed to an excess of the three visual compensatory mechanisms used to counteract display vibration. The frequency components of the complex wave are in the range of 1–20 Hz, induced at random at one of the three magnitudes desired. Because the lowest frequency used is 1 Hz, the pursuit eye movements are not being used to compensate for the vibration during the task. Although active in the range of 2–3 Hz, saccadic movements are also unlikely to have been beneficial for the same reason. While the vestibulo ocular reflex may have a fast enough reaction time to account for unpredictable vibrations, it is only active in the ranges up to around 8–10 Hz, and so frequencies above this could not be compensated for. The reduced time-stable image on the retina also supports the assertion that a retinal image moving fast across the retina reduces legibility.[18] It is also likely that at higher vibration magnitudes, both the lines making up the letters and the rows themselves overlapped, further decreasing legibility. Both these effects would disrupt the visual analysis system that is responsible for recognizing letter and word features. As vibration also affects cognitive ability,[30,31] it is possible that the visual input lexicon could also have been affected, although this is hard to determine for certain.[32]

5.2. Effect of Subject's Posture

The second higher contribution was from subjects' posture as evaluated both from the perceived difficulty and performance measure. In a vibration environment, the posture becomes even more important as it helps in suppressing and compensating the motions to limit their effect on the performance of the work. Thus, the posture has a vital role in transmitting vibrations to the different body segments as well as to the working material.

Considering all vibration stimuli in the longitudinal direction, both the perceived difficulty and degradation in performance were found to be higher with lap posture as against table posture. The higher interference in reading task for backrest posture can be justified as follows: while working with lap posture, the upper body is supported by the back of the seat, and the legs are supported by the floor, which will affect the vibration transmitted to the head and arm over a wide range of frequencies[33] and perhaps will interfere with vision.

Considering the vibration in lateral direction, in table posture the upper body will lack support from the seat-rest, and the reading material (laptop) may obtain an oscillation that is almost equal to that of the table. The unsupported upper body is likely to move out of phase with the laptop, thus affecting the reading task. The result illustrates that the reading performance was affected greatly in table posture at all vibration stimuli in lateral direction, which can be confirmed by observing that the difference between the two seated postures was significant ($p < 0.05$). However, the subjects perceived difficulty only at higher vibration stimulus (i.e., 1.2 m/s^2), suggesting the adaptation capabilities of the participants to cope with the lower vibration stimuli (i.e., up to 0.8 m/s^2).

Considering the vibration in vertical direction, both the perceived difficulty and reading performance were affected more in table posture. Since the lap posture is comparatively a relaxed posture, sitting in this posture results in a softening of the biomechanical system, which in turn reduces the resonance frequency of the body and its amplitude as well. As the muscles relax, the body stiffness reduces and the damping increases.[34] Therefore, the reading task in lap posture could be less affected by vibrations in the vertical direction.

For vibration in all combinations of dual axes, the subjects perceived equal difficulty in both postures; however, reading performance was greatly hampered in table posture as compared to lap posture. This could be due to the higher contribution of vibration magnitude in the y- and z-axes as compared to the x-axis and also could be due to the higher performance degradation in these axes. This was also confirmed from the considerable effect of the interacted variable ($V \times P$) on reading performance (Table 4). A similar effect, attributable to the subjects' posture, was found with the multi-axis for both the perceived difficulty and reading performance.

5.3. Effect of Direction of Vibration

The direction of vibration was the least individual contributor as evaluated from both the subjective evaluation and the performance measure. The influence of the direction of vibration on perceived difficulty was found to be higher as compared to degradation in reading performance (Tables 3 and 4).

While comparing the perceived difficulty for vibration in all mono-axes, it was found to be higher in both the lateral and vertical directions; however, reading performance was impaired more for vibration in the lateral direction than in the vertical direction. The adverse effects of lateral vibration may have arisen from increased movement of the upper-body together with the head and therefore, more interference with vision. Similarly, in the vertical direction the reading task is impeded by simultaneous vibration of both the table and reading material (laptop).

The dual and associated mono-axes have been compared at the same RSS vibration magnitude. It was observed that the impairment in reading performance for given vibration stimuli was equally affected in all dual axes and associated components in y- and z-axes only. Although the subjective evaluation revealed a similar influence of vibration direction on reading difficulty, the influence was significant only for higher vibration stimuli (i.e., at 0.8 and 1.2 m/s^2). The performance measure shows good correlation with subjective evaluation for these combinations.

In the study, it was observed from subjective evaluation (Figs. 3 and 4) that the effect of multi-axis vibration has been similar to the effect of dual-axis vibration at higher vibration stimuli only (i.e., at 0.8 and 1.2 m/s^2) ($p > 0.05$), and the effect is higher than mono-axis vibration ($p < 0.05$). The impairment in reading performance was found to be similar between multi-axis, dual-axes, and y-axis. The y-axis is the only mono-axis in which higher impairment in reading performance was observed. Although to a limited extent, this outcome is consistent with that of Lewis and Griffin,[16] who reported that the effects of multi-axis vibration were found to be similar to that of single-axis vibration, corresponding to the RSS of the magnitudes in each axis.

It was observed that low levels of vibration in the mono-axes did not adversely affect task performance. This observation is consistent with previous studies.[12,13,35] Moreover, the results for multi-axis vibration indicate that a higher difficulty in reading e-papers was found even at the lowest vibration stimulus (0.4 m/s^2), suggesting that reading tasks are more sensitive to multi-axis vibration than to mono-axes vibration.

6. CONCLUSION

The present work is of high implication and relevance since the passengers use most of their traveling time for performing sedentary activities. In this study, consisting of reading e-papers using a laptop computer in a mock-up of the passenger compartment, both the perceived difficulty and reading performance was found to be affected by a given vibration magnitude in all of the combinations of vibration directions. The extent of the interference was found to increase with vibration stimuli. The subjects perceived difficulty in lateral and vertical direction equally; however, reading performance was found to be mostly affected in the lateral direction alone. The effects of multi-axis vibration have been found to be similar to dual-axes vibration and greater than mono-axes vibration; however, degradation in reading performance in multi-axis vibration was also found to be similar to that of the lateral direction. It was found that subject's posture had a great bearing on the reading task in each direction of vibration. It was revealed that the subjects perceived higher difficulty and impairment in reading performance while working on their lap for vibration in longitudinal direction, which could be a consequence of vibration being transmitted to the head and thereby leading to vision interference. While in all other directions, the difficulty perceived and impairment in performance measure were found to be higher on the table than on the lap. However, for vibration among dual axes, the perceived difficulty was found to be similar for both the postures.

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