A COMPARATIVE STUDY OF THE DISCONFORT INDUCED BY VEHICLES TO DRIVERS

Mihaela Picu

Regional Centre for Interdisciplinary Research in Vibro-Acoustic Pollution and Environmental Quality
"Dunarea de Jos" University of Galati, Domneasca Street, 47, Galati, 800008, Romania

Corresponding author: Mihaela Picu, mihaelapicu@yahoo.com

Abstract: This paper studies the way in which the vibrations from moving vehicles are transmitted to the drivers. The experiment took place on an asphalt road and a road with 5cm height obstacles, placed 10m apart. The measurements were made with and without an ergonomic seat cushion on the driver's seat. 10 drivers participated at this experiment. The vibrations parameters were determined: r.m.s. accelerations, using the accelerometers placed on the car floor, under the driver, on the lumbar area, on the fingers, on the neck bone and on the forehead; pitching acceleration; vibration dose value; Seat Effective Amplitude Transmissibility (SEAT) and maximum value of the r.m.s. weighted acceleration MTVV. In the second part of the paper was determined the discomfort made by the vibrations transmitted by the vehicle to the drivers on by 2 ways: by a direct questioning of the drivers, using the Likert scale and by the Vector Sum of Perceived Motions (VSPM). The obtained results were compared and we concluded that the best way to determine the discomfort is the direct questioning of the subjects, using the Likert scale because the discomfort induced to people by different types of stress cannot be quantified by a mathematical equation and the sensation one perceives is specific only to him and cannot be compared to the sensation felt by someone else subjected to the same stress.
Keywords: discomfort, vibration accelerations, vibration dose value; Seat Effective Amplitude Transmissibility (SEAT), maximum value of the r.m.s. weighted acceleration MTVV, Likert scale, Vector Sum of Perceived Motions (VSPM).

1. INTRODUCTION

The effects of the vibration depend on the waveform, magnitude, direction and duration, and can be broadly categorized in terms of issues of perception, comfort, health, performance (physical and cognitive) and motion sickness. It is important to minimize the effects of vibration on passengers and staff to protect their health, to maximize their productivity and in order to comply with relevant health and safety recommendations and legislation (Directive 2002/44/EC).

Drivers' comfort entered the researchers' attention for decades.

Kitazaki and Griffin (1998) commented that workers in vibration environments are more likely to suffer back problems than other workers not exposed to whole-body vibration (WBV). (Rehn et al. 2002) concluded that exposure to shock and vibration which occurs in vehicles may contribute to musculoskeletal disorders, as the driver/operator has tensed muscles in order to maintain balance and to work the controls. It was emphasized the importance of correct seat design in order to reduce stress and injury. Surveys of vehicle drivers have often found the prevalence of back pain to be greater than 25%, even when other risk factors, such as WBV, are small (Porter and Gyi, 2002). Lumbar pains which appear at urban traffic drivers were investigated in several studies (Nastac and Picu, 2010). In some of these studies the authors investigated some regnant symptoms of lumbar pain which occur for some buss drivers, who worked for a public transport company (Kyunga et all, 2008 I, II), (Porter et all, 2003). Most of these studies were not taken into account because the data was not well documented. Urban traffic drivers are exposed during their work hours to whole body mechanic vibrations and some of them suffer from lumbar pain because of their work (Andreoni et all, 2002), (Na et all, 2005). To prevent the occurrence of some diseases for drivers, because of vibrations, a study of oscillation motion are needed to make a connection between the bodies induced vibrations and the occupational diseases associated to vibrations (Griffin, 1990). Discomfort was highly dependent on frequency. Large amplitude movements of the hand-arm system were found at low frequencies, while higher frequencies tended to localise the vibration response to only those parts of the hand which were in the immediate vicinity of the hand tool (Picu and Nastac, 2011). Studies by (Paddan and Griffin 1988) showed that rolling vibration of the backrest of a seat can cause appreciable body vibration. It was demonstrated that this vibration can be a dominant cause of discomfort (Jönsson and Johansson, 2005). Human response to whole-body vibrations is also affected by local vibrations, i.e. steering wheel hand-arm vibrations and feet on the floor (ISO 2631-1, 1997).

2. MATERIALS AND METHODS

2.1 Theory

The EU Directive sets limits on both hand-arm and whole-body vibration in terms of risk, and does not cover passenger comfort. The exposure limits are defined as an "action value" and a "limit value" and both r.m.s. values and VDV values are given.

The resulting r.m.s. values should then be compared with the limit and action values stated in the directive which are given in Table 1 below.

Table 1. Daily exposure limit and action values for whole-body vibration as specified in the EU Physical Agents (Vibration) Directive (European Commission -2002).

Exposure Action Value (EAV)	Exposure Limit Value (ELV)
0.5 m/s^2 A(8) r.m.s.	1.15 m/s^2 A(8) r.m.s.
9.1 $m/s^{1.75}$ VDV	21 $m/s^{1.75}$ VDV

ISO 2631-1 Section 6 specifies an r.m.s. based method of evaluation of ride comfort. The weighted r.m.s. acceleration (in m/s²) of a discrete time-domain signal is given by (Picu and Nastac, 2011):

$$a_{r.m.s.} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} a_w(n)^2} \quad (1)$$

where $a_w(n)$ is the n^{th} sample of the weighted acceleration, and N is the total number of samples in the measurement.

The individual axes may be combined to give a total weighted r.m.s. acceleration value, given as:

$$A_W = \sqrt{\left(k_x^2 \cdot a_{wx}^2\right) + \left(k_y^2 \cdot a_{wy}^2\right) + \left(k_z^2 \cdot a_{wz}^2\right)} \quad (2)$$

where a_{wx} is the weighted r.m.s. vibration of the x-axis (similarly for y and z-axis) and k is the axis multiplier given in ISO 2631-1(1997).

For an analysis with respect to comfort, the total vibration magnitude is compared to the approximate indications of likely reactions to various magnitudes of overall vibration total values in public transport as stated in ISO 2631-1 and repeated here in Table 2.

Table 2. Approximate indications of likely reactions to various magnitudes of overall vibration total values in public transport as stated in ISO 2631-1.

Weighted vibration magnitude (total of three axes)	**Likely reaction in public transport**
Less than 0.315 m/s^2	Not uncomfortable
0.315 m/s^2 to 0.63 m/s^2	Little uncomfortable
0.5 m/s^2 to 1 m/s^2	Fairly uncomfortable
0.8 m/s^2 to 1.6 m/s^2	Uncomfortable
1.25 m/s^2 to 2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

The pitch motion at the occupant/seat interface, seat pitch (SP), was calculated by subtracting the accelerations in the x-direction on the top of backrest from the acceleration in the x-direction on the seat and then dividing the result by the distance between the measurement locations.

The MTVV takes into account occasional shocks and transient vibration by use of a short integration time. The MTVV is defined as the maximum value of the r.m.s. weighted acceleration calculated over a short time period (integration time) as given, in the discrete time-domain, by:

$$MTVV = \max\left(\sqrt{\frac{1}{\tau}\sum_{n=n_0}^{n_0+\tau} a_w\left(n^2\right)}\right) \quad (3)$$

$n_0 = 0, 1, 2, \ldots, N\text{-}1\text{-}\tau$

where $a_w(n)$ is the current sample of the weighted acceleration, τ is the integration time and N is the total number of samples in the measurement. ISO 2631-1 recommends the use of 1 second as the integration time, i.e. in the discrete time-domain set $\tau = f_s$, where f_s is the sampling frequency.

The VDV method uses the fourth power of the vibration magnitude, which is more sensitive to shocks than using the square as in the r.m.s. calculation. The unit of VDV is $m/s^{1.75}$, and VDV is given by:

$$VDV = \sqrt[4]{\frac{1}{f_s}\sum_{n=0}^{N-1} a_w(n)^4} \quad (4)$$

where $a_w(n)$ is the current sample of the weighted acceleration, f_s is the sampling frequency and N is the total number of samples in the measurement.

This relationship may be expressed numerically by the SEAT (Seat Effective Amplitude Transmissibility) value, which is given by:

$$SEAT\% = 100 \times \frac{r.m.s._{seat}}{r.m.s._{floor}}$$

$$SEAT\% = 100 \times \frac{VDV_{seat}}{VDV_{floor}} \quad (5)$$

When the SEAT value is greater than 100%, the seat is amplifying the vibration, and when the value is below 100%, the seat is attenuating the vibration. Note that for each axis in the examples presented, the SEAT is not below 100%, i.e. the seat does not attenuate the vibration magnitude.

2.2 Acceleration measurement

The first part of the experiment refers to Prima deals with accelerations measurements and determines the concerning parameters.

The vibrations were measured in normal working conditions, according to International Standard ISO 2631-1. The whole body vibration, in different conditions, was measured on the 3 axes x, y and z from the centre of the human body. The whole body vibrations were measured using:

- 01dB NetdB Multichannel digital recorders and real-time analysers with 12 activated channels acquisition,
- triaxial whole-body accelerometer SEAT-pad (Seat Effective Acceleration Transmissibility) mounted on the driver's floor, seat and lumbar,
- triaxial whole-body accelerometer PCB Piezotronics 356A16 mounted on the driver's fingers, cervical and forehead.

The accelerations generated by vibrations were calculated using the weight factors set by ISO 2631. The calibration of the accelerometers was made with VE-10 Rion.

2.3 Subjects

Ten men, professional drivers, were tested. Their ages ranged from 26 to 44 years and weights ranged from 71 kg to 94 kg (7 men had BMI<25, 3 men had BMI>25). Their heights varied between 1.72 and 1.80m. Their work experience is between 5 and 16 years. All were in good health, and none used vibration-producing tools as a regular part of their work or pastimes.

2.4 Discomfort determination using Likert scale

The second part of the experiment was to determine the subjects' discomfort exposed to vibrations, using the Likert scale (Nastac, Picu, 2010), correlating to three different perceived motions (shaking, rolling and vertical). A Likert scale is a psychometric scale commonly used in questionnaires, and is the most widely used scale in survey research, such that the term is often used interchangeably with rating scale even though the two are not synonymous. When responding to a Likert questionnaire item, respondents specify their level of agreement to a statement. The format of a typical five-level Likert item is: Strongly disagree, Disagree, Neither agree nor disagree, Agree, Strongly agree. To analyze how the vibrations transmitted by the driving wheel are felt by the drivers, we turn these terms into:

Degree of discomfort	Scale
Very strongly	4-5
Strongly	3-4
Slightly	2-3
A little	1-2
Not at all	0-1

Each individual vibration test lasted about 1 min. Intervals of at least 0.5h were introduced between each vibration exposure so as to avoid fatigue or learning effects.

2.5 Experimental procedure

Two spots were chosen on an asphalt road, 500m apart. The road is straight and level. Along the last 100m obstacles were placed 10m apart. The obstacles were symmetric rigid steel parallelepipeds 2.5 m in length in the x-direction, 5cm in width and 5cm in height. The rolling speed on this last sector was kept constant at 10km/h. The car used on these measurements had 55000km on board. The distance between the front and the rear wheels is 2.63 m. The emerged vibrations are: vertical, rolling and pitching. The vibrations were measured on the 3 directions, as explained above (Fig. 1).

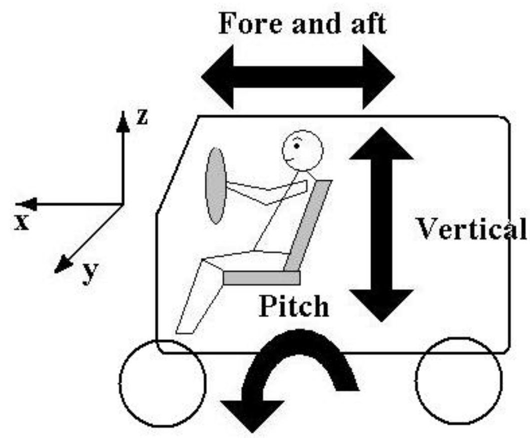

Fig. 1. Directions of vibration

The vibrations accelerations transmitted by the vehicle to the driver will be measured in 2 cases:

a) the driver sits directly on the car seat
b) the driver sits on ergonomic seat cushion

3. RESULTS

3.1 The determination of the vibrations parameters

Figures 2-6 present the results obtained after measuring the accelerations on the 3 axis and also the calculated values for: total weighted r.m.s. and pitching acceleration, Vibration dose value, SEAT A_w and SEAT VDV, and MTVV. In all the figures are shown the mean values obtained after measuring the 10 drivers.

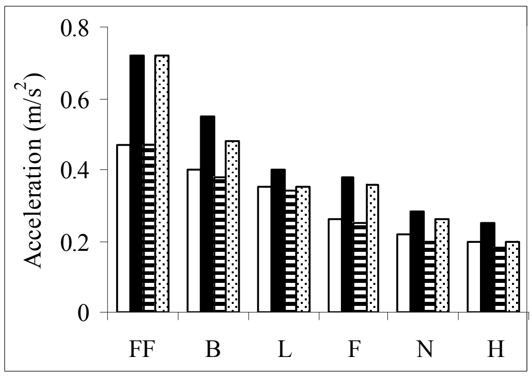

Fig. 2. Mean value of the A_W accelerations for the 10 drivers: (∏) - Without cushion - asphalt, (█) - Without cushion - obstacles, (▓) - Ergonomic seat cushion - asphalt, (≡) - Ergonomic seat cushion - obstacles.

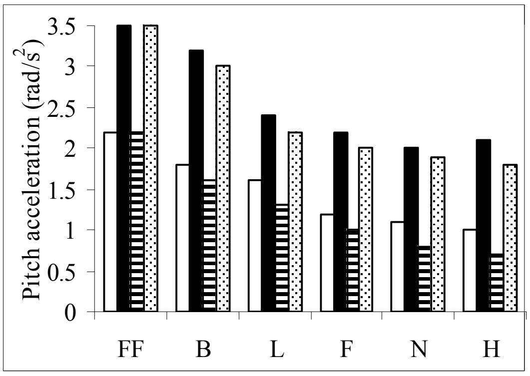

Fig. 3. Mean value of the pitching accelerations for the 10 drivers: (□) - Without cushion - asphalt, (■) - Without cushion - obstacles, (▩) - Ergonomic seat cushion - asphalt, (≡) - Ergonomic seat cushion - obstacles.

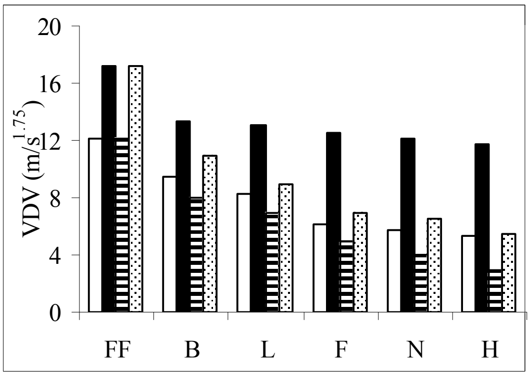

Fig. 4. Mean value of the vibration dose value VDV for the 10 drivers: (□) - Without cushion - asphalt, (■) - Without cushion - obstacles, (▩) - Ergonomic seat cushion - asphalt, (≡) - Ergonomic seat cushion - obstacles.

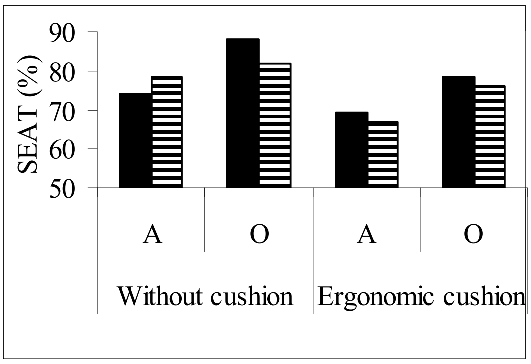

Fig. 5. Mean value of the Seat Effective Amplitude Transmissibility for the 10 drivers for A_w (■) and for VDV (≡); A- asphalt, O- obstacles

From these diagrams one can see, as obvious, that all the vibrations' parameters are higher on the obstacle road unlike the asphalt road. Also, the ergonomic seat cushion noticeable suppresses the impact vibrations have on the drivers' bodies.

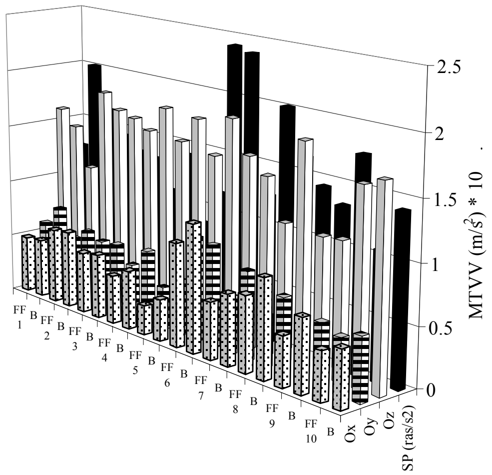

Fig. 6. Maximum value of the r.m.s. weighted acceleration MTVV for each driver, near the floor (FF) and under the body (B), on all 3 directions and for the pitch motion

3.2. Discomfort estimation using the Likert scale

The second step in the analysis of subject responses was to establish a relationship between judgments of overall discomfort and perceived motions. The determination of the perception size of the vibrations and its recording on the Likert scale was made by questioning the drivers while driving the car on the asphalt road and on the obstacle road, with and without the ergonomic seat cushion.

a) The drivers affirm that they only referred to the rolling and pitching motions, because the vertical motion did not annoyed them. The measurements were made while the ergonomic seat cushion was on the drivers' seat. In reality, the subjects gave different answers for the wholly comfort. The results are shown in Fig. 7.

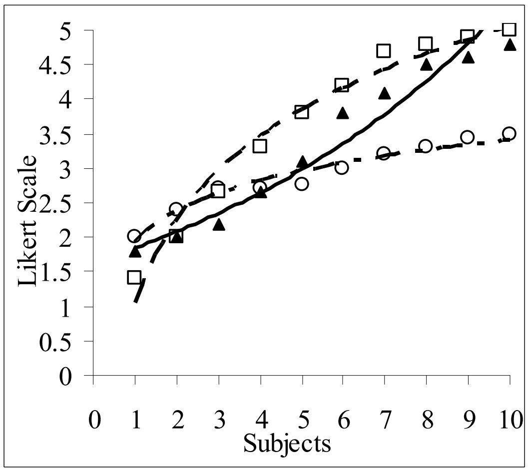

Fig. 7. The vibration perception on the Likert scale for the 10 divers: (➡□➡) Discomfort (D_r) made by the rolling motion, (➡O➡) Discomfort (D_p) made by the pitching motion, (➡▲➡) Discomfort (D_T) total

Figure 7 shows that each driver felt differently the discomfort made by the different types of movements. Therefore:

-The levelling made on the Likert scale for the discomfort (D_r) made by the rolling motion, places the obtained values on a logarithmic scale:

$$D_r=0.6405\cdot\ln(N) + 1.9346 \quad (R^2 = 0.9849) \qquad (6)$$

where N – the subject's number

-The levelling made on the Likert scale for the discomfort (D_p) made by the pitching motion, also places the obtained values on a logarithmic scale:

$$D_p=1.7393\cdot\ln(N) + 1.0478 \quad (R^2 = 0.9830) \qquad (7)$$

-The levelling made on the Likert scale for the total discomfort (D_T) total, places the obtained values on a exponential scale:

$$D_T=1.6384\cdot e^{0.1197N} \quad (R^2 = 0.9791) \qquad (8)$$

b) The vibrations were measured on the 3 directions, as explained above (Fig. 1). So the total discomfort also includes the vertical movement (not only the rolling and pitching motions) which was neglected by the subjects.

To determine the discomfort given by the vertical vibrations the experiments were reproduced on the same route but without obstacles, with and without the seat cushion on the drivers' seat. The speed was maintained constant at 10km/h. the results are shown in Fig. 8.

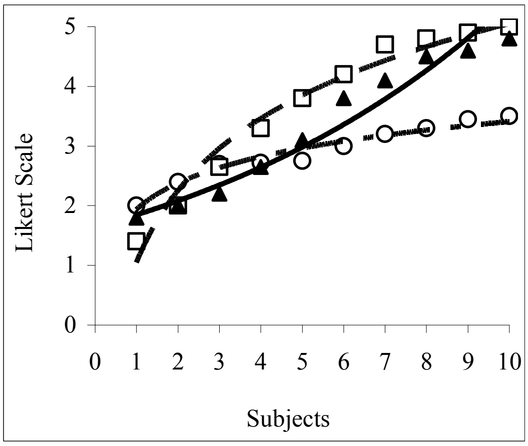

Fig. 8. The vibration perception on the Likert scale for the 10 divers: (➡□➡) Discomfort (D_{wc}) made by the vertical vibrations without cushion, (➡O➡) Discomfort (D_c) made by the vertical vibrations with cushion, (➡▲➡) Discomfort (D_T) total – is the same as in fig. 8.

-The levelling made on the Likert scale for the discomfort (D) made by the vertical vibrations without cushion, places the obtained values on a logarithmic scale:

$$D_{wc}=0.8049\cdot\ln(N) + 1.3943 \quad (R^2 = 0.9886) \qquad (9)$$

-The levelling made on the Likert scale for the discomfort (D) made by the vertical vibrations without cushion, also places the obtained values on a logarithmic scale:

$$D_c=0.9578\cdot\ln(N) + 0.5933 \quad (R^2 = 0.9678) \qquad (10)$$

From Figure 7 and 8 one can conclude that the contributions of the 3 types of movements can be sum up in order to obtain the total discomfort.

4. DISCUSSION AND CONCLUSIONS

If we add as a vector sum the discomforts made by the rolling and pitching motions we can obtain the Vector Sum of Perceived Motions (VSPM) (Jönsson and Johansson, 2005):

$$VSPM_{2motions}=(\text{for-aft motions}^2+\text{pitch motions}^2)^{1/2} \qquad (11)$$

Table 3. Calculated values for $VSPM_{2motions}$

Subjects	without cushion			with cushion		
	rolling	pitching	$VSPM_2$ (wc)	rolling	pitching	$VSPM_2$ (c)
1	2.1	1.4	2.44	2	1.1	2.28
2	2.4	2	3.12	2.1	1.5	2.58
3	2.7	2.6	3.78	2.4	1.8	3
4	2.7	3.3	4.27	2.5	2	3.20
5	2.7	3.8	4.69	2.5	2.2	3.33
6	3.1	4.2	5.16	2.6	2.3	3.47
7	3.2	4.7	5.68	2.8	3	3.75
8	3.3	4.8	5.82	3	4.1	5.14
9	3.4	4.9	5.99	3.1	4.2	5.28
10	3.5	5	6.10	3.2	4.5	5.52

It can be seen that for 5, respective for 3 of the subjects the result was higher than 5, which is false because the Likert scale goes up to 5.

If we add, as a vector sum, the additional discomforts made by the vertical vibrations we obtain:

$$VSPM_{3motions}=(\text{vertical motions}^2 + \text{rolling motions}^2 + \text{pitching motions}^2)^{1/2} \qquad (12)$$

Table 4. Calculated values for $VSPM_{3motions}$

Subjects	without cushion			
	vertical	rolling	pitching	$VSPM_3$ (wc)
1	1.5	2.1	1.4	2.93
2	1.9	2.4	2	3.65
3	2.2	2.7	2.6	4.34
4	2.5	2.7	3.3	4.94
5	2.6	2.7	3.8	5.33
6	2.8	3.1	4.2	5.92
7	3	3.2	4.7	6.42
8	3.1	3.3	4.8	6.59
9	3.2	3.4	4.9	6.76
10	3.3	3.5	5	6.93

Subjects	with cushion			
	vertical	rolling	pitching	$VSPM_3$ (c)

1	0.8	2	1.1	2.41
2	1.2	2.1	1.5	2.84
3	1.5	2.4	1.8	3.35
4	1.8	2.5	2	3.67
5	2	2.5	2.2	3.88
6	2.2	2.6	2.3	4.10
7	2.5	2.8	3	4.80
8	2.7	3	4.1	5.75
9	2.8	3.1	4.2	5.92
10	2.9	3.2	4.5	6.23

It can be seen that for 6, respective for 3 of the subjects the result was again higher than 5.
If we compare the 2 situations: the total discomfort percept by the subjects while driving with the ergonomic seat cushion under their body and the one obtained by a vector sum of the discomfort made by each type of motion, singly, we obtain the following results (Fig. 9).

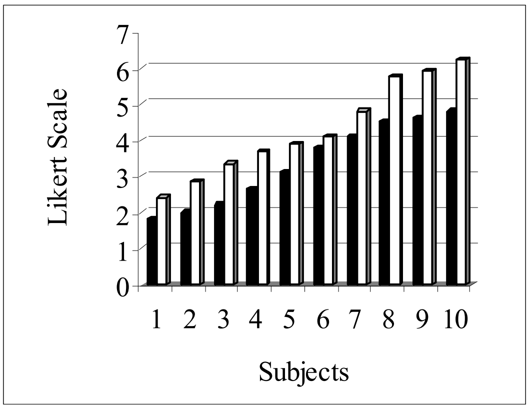

Fig. 9. The levelling made on the Likert scale for the total discomfort (■) and the Vector Sum of Perceived Motions (□) for the 10 drivers while driving with a seat cushion.

Figure 9 shows that calculating a discomfort using equation (12) does not give a correct result. First of all the peoples' discomfort given by different types of stress is unquantifiable by a mathematic equation because the sensation one perceives is specific only to him and cannot be compared to the sensation felt by someone else subjected to the same stress. Using this type of calculus the maximum value on the Likert scale was exceeded.
In conclusion, the best way to determine any type of discomfort given by any type of stress remains the interrogation method of each subject.

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