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Temporary Threshold Shift of the Vibration Perception Threshold following a Short Duration Exposure to Vibration

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The objective of this study is to analyze the evolution of the vibration perception threshold (VPT) following a short duration exposure to vibration. The literature reports experiments with 3 to 10 min exposure to vibration after which a steady state is not necessarily reached. The temporary threshold shift (TTS) of the VPT is extrapolated from data recorded during the recovery period. The assumption of a linear decrease with the logarithm of time gives erroneous results for the TTS extrapolated at the end of the exposure.

81 experiments were conducted on 9 young subjects without any neurological problem, exposed to acceleration amplitudes of 5, 20 and 80 ms^{-2} at frequencies of 31.5 (conditions 1 to 3), 125 (conditions 4 to 6) and 500 Hz (conditions 7 to 9). The exposure to vibration lasted 32 min and was interrupted shortly at time 2, 4, 8, 16 to record the VPT at 31.5 and 125 Hz. The VPT was also recorded before the exposure and several times during the recovery.

The evolution of the VPT appears to follow a first order model characterized by a maximum amplitude TTS, a time constant (τ) and a residual value (r, as a fraction of the TTS). The correlation coefficients between observed and predicted values in the 81 experiments are 0.881 at 31.5 Hz and 0.885 at 125 Hz. The TTS is influenced by the exposure amplitude and frequency and is different at the two test frequencies. It varies also significantly between the subjects and with their initial VPT value. The time constant is about 3 minutes at both test frequencies, while the residual fraction is of the order of 0.14 at 31.5 Hz and 0.07 at 125 Hz. Both parameters appear to be independent of the exposure parameters. © 1998 Published by Elsevier Science Ltd on behalf of BOHS.

INTRODUCTION

The vibration perception threshold (VPT) test has become widely used, particularly in the field of hand arm vibration, to detect alterations of the mechanoreceptors and the development of peripheral neuropathy (Lundborg *et al.*, 1986, 1987; Aatola *et al.*, 1990; Lundström *et al.*, 1992).

A few studies are reported in the literature concerning the transient variation (Temporary Threshold Shift: TTS) of VPT following a short term exposure to vibration. All these studies are aimed at determining the amplitude of the TTS at different tests frequencies (corresponding to different mechanoreceptors) as a function of the amplitude and frequency of the vibration. Typically, subjects were exposed for 3 to 10 minutes and, from the VPT recorded before and just after exposure, the TTS was derived. The analyses of the data and the protocol of these experiments appear to raise some problems for the following reasons:

- Most of the authors concluded at a recovery of the TTS linearly as a function of the logarithm of time (Bjerker *et al.*, 1972; Tominaga, 1973; Harada, 1978a; Harada, 1978b; Harada and Griffin, 1991). They used this law to extrapolate the TTS at time 0.5 min, as clearly the extrapolation at time 0 of recovery (end of exposure) would lead to infinity and was not acceptable. Nishiyama and Watanabe (1981) and Nishiyama *et al.* (1994) were the only authors suggesting a different recovery function, as a first order system.
- As will be shown later, the VPT follows indeed a first order system with time constant varying between subjects but of the order of magnitude of 3 minutes. Therefore, after 3 minutes of exposure, for an average subject, the TTS reached is about 63% of the steady state TTS, and, due to inter-

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*Author to whom correspondence should be addressed. Tel.: 32 2 764 32 29, Fax: 32 2 764 39 54, e-mail: malchaire@hytr.ucl.ac.be individual differences in time constants, the values recorded after such short exposures do not describe adequately the phenomenon.

For these reasons, a study was conducted in order to analyze the validity of the first order system, both for the development of the TTS and its recovery after exposure, and to determine how it varies as a function of the test frequency and as a function of the amplitude and frequency of vibration.

DESCRIPTION OF THE MATHEMATICAL MODEL

Fig. 1 describes the evolution of the VPT according to a first order system during and after exposure.

The mathematical expression during the exposure is

$$\mathrm{VPT}(t) = \mathrm{VPT}_0 + \mathrm{TTS}[1 - \exp(-t/\tau)]$$

and during the recovery

$$\mathrm{VPT}(t) = \mathrm{VPT}_m - \mathrm{TTS}[1 - \exp(-t/\tau)]$$

where $\mathrm{VPT}(t)$ is the vibration perception threshold at a given test frequency at time t ($t = 0$ at the beginning of exposure); VPT_0 is the initial preexposure value of VPT; VPT_m is the maximum value of VPT; TTS is the maximum increase of VPT, equal to $\mathrm{VPT}_m - \mathrm{VPT}_0$; t is the time; τ is the time constant.

As shown by Malchaire (1991), this expression can be translated to an iterative expression

$$\mathrm{VPT}_i = \mathrm{VPT}_{i-1} \cdot k + A.(1-k)$$

showing that the VPT at time i is equal to

- a fraction k of the VPT reached at time $(i-1)$, Δt seconds earlier
- plus a fraction $(1-k)$ of the steady state final value A, which is equal to VPT_m during the exposure and VPT_0 during the recovery period.

The fraction k is given by $\exp(-\Delta t/\tau)$.

The potential advantages of this expression are that:

1. the response can be studied not only to a constant vibration condition (and therefore only one value of VPT_m), but to any condition and in particular to an intermittent exposure;
2. it is possible to study whether the time constant for the development of the TTS during exposure (τ_e) and its recovery (τ_r) are the same.
3. it is possible to study whether the VPT returns to the initial value VPT_0 directly after the exposure or whether there is a residual value (r in fraction of the TTS) in the short term.

It assumes, however, that a steady state value VPT_m is reached after an exposure sufficiently long to vibration.

MATERIAL AND METHODS

Nine male subjects, aged between 25 and 35, gave free consent to participate in the experiments. They had to be in good health and free of any past history to exposure to toxics/drugs and vibration (except incidental), of any neurological central or peripheral pathology and of upper limb disorders.

They underwent 9 exposure conditions at 3 frequencies (31.5, 125 and 500 Hz) and 3 amplitudes of acceleration (5, 20 and 80 m s^{-2}).

The vibration perception threshold (VPT) was recorded at two test frequencies (31.5 and 125 Hz) according to the method described by Lundborg *et al.* (1986). A Madsen Micromate 64 audiometer (Madsen Electronics, DK) was modified in order to generate

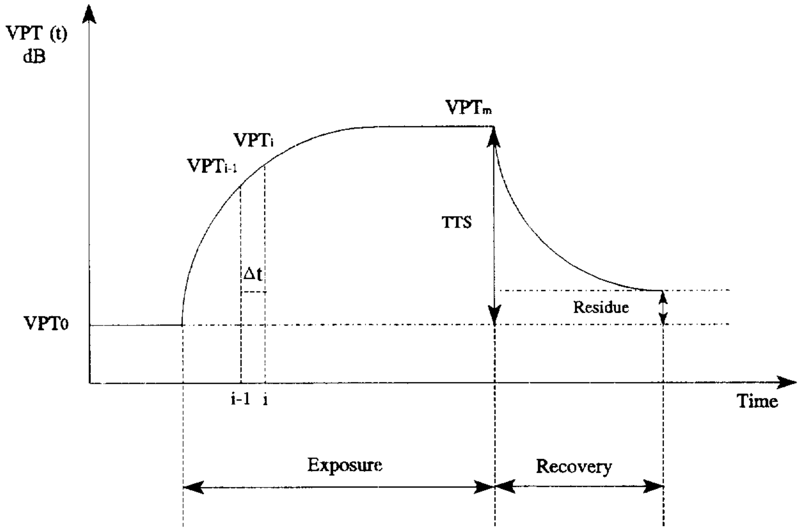

Fig. 1. Evolution of the Vibration Perception Threshold according to a first degree system during and after exposure to vibration.

the octave centre frequencies from 8 to 500 Hz. The headphones were replaced by a Brüel & Kjaer 4810 minishaker (Brüel & Kjaer, DK). The shaker was equipped with a stem with a section of 5 mm^2 and was mounted on a balance in order to exert a constant force of 0.20 N on the pulp of the finger. The shaker was mounted under a small box on which rested the forearm and hand of the subject. A hole was provided for the pulp of the finger, slightly bent to be placed on the stem. The system had a dynamic range from 50 to 160 dB (ref 10^{-6} ms^{-2}) (0.3 mm s^{-2} to 100 ms^{-2}). It was calibrated every day.

The test was started at 120 dB. The subject was invited to press an hand held switch with the other hand as soon as and for as long as he perceived the stimulus. The duration of the stimuli was varied at random between 1 and 3 seconds. The stimulus level was increased or decreased by steps of 5 dB until the subject perceived or no longer perceived the stimulus. The tendency was then reversed in order to cross the threshold several times. The recorded value was the lower vibration level at which the subject responded 3 times consecutively.

The test was performed systematically on the second finger of the right hand and lasted 30 s at a maximum.

Exposure vibration was generated using a single frequency signal generator (Tektronix TM 503), a power amplifier (Harfield 2U600 MOS FET) and a Brüel and Kjaer type 4808 shaker, on which was mounted a handle grasped by the subject. The axis of vibration was the Y axis as defined by ISO 5349 (1986). The handle was thermoregulated at a temperature of 32°C and the grip force was continuously controlled at 20 N using a strain gauge system mounted on the handle; the actual force was digitally indicated in front of the subject. The shaker was hung and counterbalanced so that the lifting force and torque exerted by the subject on the handle was nil. The posture adopted was the subject sitting with the back straight, the arm along the trunk and the forearm at 90°, with the hand in neutral position holding the handle of the shaker. The exposure to vibration lasted 32 minutes but was interrupted as briefly as possible (about 60 s) after 2, 4, 8 and 16 minutes to record the VPT levels at frequencies of 31.5 and 125 Hz. The VPT levels were also recorded prior to the exposure and at time 0, 5, 10 and 15 minutes during recovery, after exposure. Additional recordings were taken if a steady level was not reached after 15 min of recovery. The protocol therefore involved at least 9 recordings of the VPT. The exact times at which the VPT values were taken and at which the exposure was interrupted or started again were recorded to the nearest second.

The fitting of the model was done iteratively, assuming $\mathrm{VPT}_0 = 0$ and $\mathrm{VPT}_{\infty} = 1$. The calculations were made using one time constant or two time constants (for the development and for the recovery) with successive values from 1 to 20 minutes, by steps of 0.1 minute and the residual fraction ranging from 0 to 1 by steps of 0.05.

For each combination of the three parameters, the linear regression and the correlation coefficient were calculated between the observed VPT values and the predicted values. Fig. 2 shows typical variations of the correlation coefficients with the time constant (in the case of a single time constant and a residual value equal to 0) and illustrates that very high correlation coefficients were reached for a single value of τ (case 1), or a range of τ values (case 3). The combination (τ_e, τ_r, r) providing the highest correlation coefficient was adopted. In the case of a plateau, the middle value of the range of τ values for which the correlation coefficient varied by less than 0.05 was adopted.

The corresponding correlation line was

$$\mathrm{VPT} = aX + b$$

with VPT the observed value; X the value predicted by the first order model (between 0 and 1); a the slope, which corresponds to the amplitude of the TTS; b the intercept, which is equal to the initial value VPT_0.

The results of this analysis were

- VPT_0 given by the model (b factor), which must be independent of the vibration exposure;
- TTS, the steady state increase in VPT following the given exposure to vibration;
- τ or τ_e and τ_r, the time constants in the models using the same or different time constants for the development and the recovery of the TTS.
- r the residual fraction of the TTS after some 15 minutes of recovery.

STATISTICAL ANALYSIS

An analysis of variance was conducted on the above parameters, including the subject effect and the exposure condition effect. A multiple regression analysis was performed to determine the relationship between these parameters and the exposure conditions.

RESULTS

Figure 3 illustrates the crude results for the mean values of VPT at 125 Hz for the 9 subjects in the 9 conditions (numbered from 1 to 9) and clearly shows the significant evolution of the VPT with vibration exposure. The results were similar at the test frequency 31.5 Hz.

The results of the first computation of the model using τ_e, τ_r and r showed that the same value of the correlation coefficient could be reached for different pairs of values (τ_e, τ_r), which were completely different (for example (4, 9 min) and (10, 1 min)) and providing TTS values differing by more than 25% in some instances. It had therefore to be concluded that the limited number of data points and the low resolution of the data (at ±2.5 dB) did not make possible to

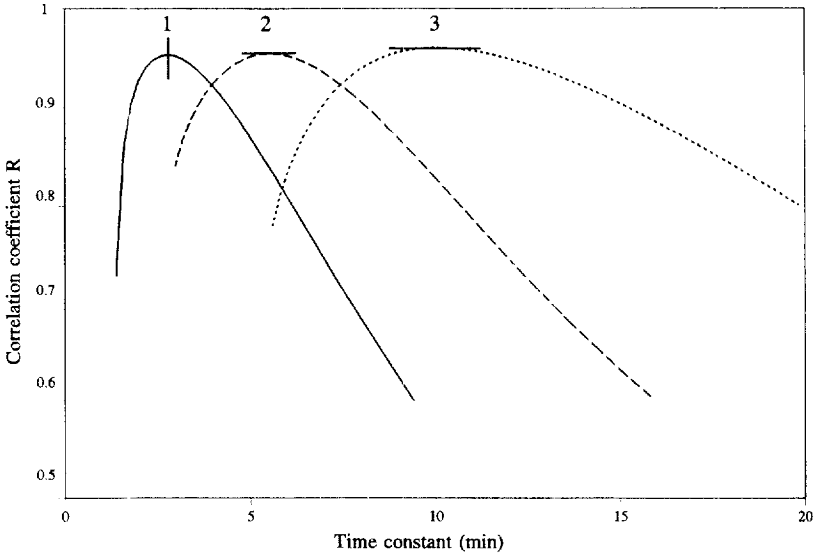

Fig. 2. Variation of the correlation coefficient between the observed and predicted Vibration Perception Thresholds in three typical cases (model with one time constant).

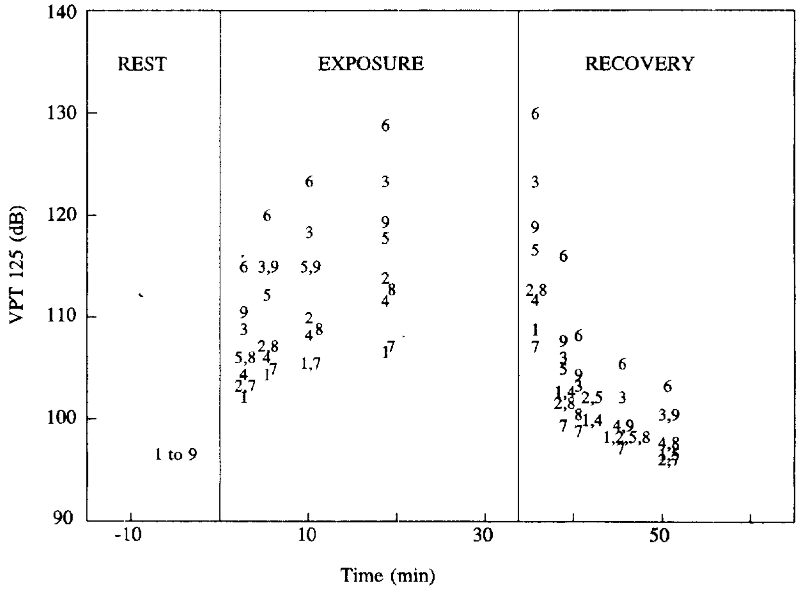

Fig. 3. Mean values of the Vibration Perception Threshold at test frequency 125 Hz during exposure and recovery in the 9 exposure conditions.

derive a model with 2 time constants τ_e and τ_r. The two time constants were henceforth assumed to be identical.

The values τ, r, VPT$_0$ and TTS were then computed independently for each of the 81 experiments.

Figure 4 illustrates the variations of the time constant τ and Fig. 5 those of the residual fraction r between the 81 experiments (test frequency 125 Hz). These graphs, as well as the analyses of variances of these two parameters, taking into account the differences between subjects and between the 9 exposure conditions, showed that both parameters varied considerably and without consistency from one experiment to the other for the same subject (both subject and condition effects non-significant). No explanation can be given for these apparently random variations of τ and r, except the low resolution of the data (VPT recorded at the nearest 5 dB) and the limited number of points per experiment. It was therefore decided to increase the reliability of the TTS predictions by treating all the data from the 9 exposure conditions of each subject at once and assuming that both τ and r values were constant for a given subject. These τ and r values are reported on Figs 4 and 5 respectively, where they clearly are about equal to the average of the values found separately for the 9 conditions of each subject.

The mean time constants are equal to 2.6 ± 0.5 min

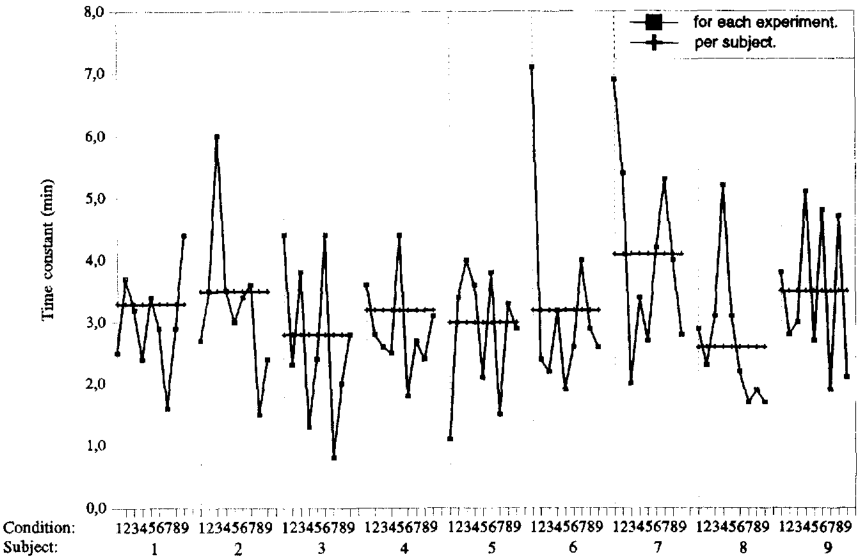

Fig. 4. Time constant of variation of the Vibration Perception Threshold at test frequency 125 Hz for each subject in the nine exposure conditions (values per experiments and values per subject).

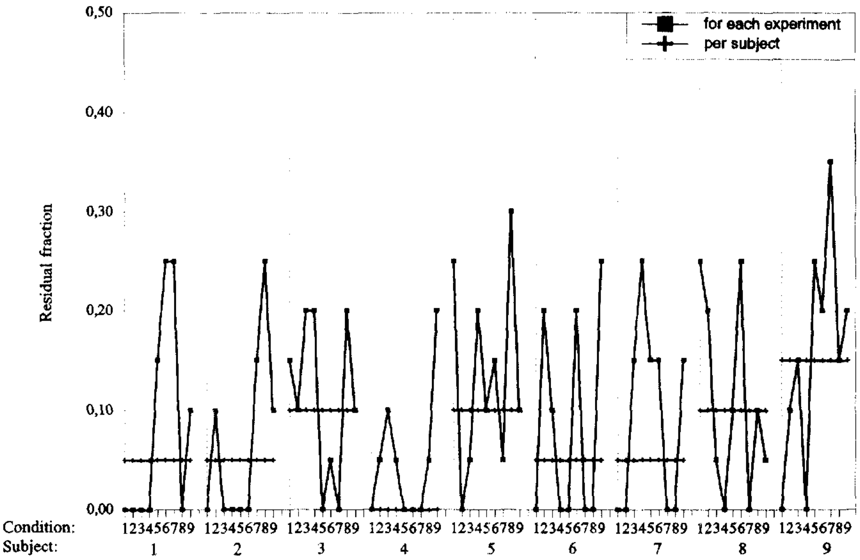

Fig. 5. Residual fraction at test frequency 125 Hz for each subject in the nine exposure conditions (values per experiments and values per subject).

for the test frequency 31.5 Hz and 3.2 ± 0.4 min for 125 Hz and the residual TTS fractions respectively 0.14 ± 0.06 and 0.07 ± 0.04.

The analysis of variance confirmed that the VPT_0 values derived using the first order model are independent of the exposure conditions. They varied between subjects with mean values 113.5 ± 2.3 dB at the test frequency 31.5 Hz and 96.6 ± 3.2 dB at 125 Hz.

The mean steady state TTS values are given in Table 1 for both test frequencies and for the 9 conditions.

No simple linear relationship could be found between TTS and the exposure frequency, but the TTS values obeyed the following expression as a function of the initial VPT_0 value and of the exposure acceleration amplitude (a in ms^{-2}): At test frequencies:

$$31.5\,\text{Hz: TTS} = 103.4 - 0.87\,VPT_0 + 8.3\log(a)$$

$$(R = 0.804)$$

$$125\,\text{Hz: TTS} = 47.1 - 0.46\,VPT_0 + 14.5\log(a)$$

$$(R = 0.848)$$

when systematic increases of 1.8 and 6.3 dB respectively were taken into account for the exposure frequency of 125 Hz compared to the other 2 frequencies.

DISCUSSION

This paper is mainly focused on the evolution of the VPT as a function of time and, secondly, as a

Table 1. Means and standard deviations of the TTS values of VPT at 31.5 Hz and 125 Hz in the 9 exposure conditions

Exposure condition	Exposure frequency (Hz)	Exposure acceleration (m s^{-2})	TTS (in dB) at test frequency	
			31.5 Hz	125 Hz
1	31.5	5	10.5±3.0	13.4±4.1
2		20	16.0±3.2	20.9±5.0
3		80	21.6±5.3	30.8±5.0
4	125	5	13.3±4.3	17.9±3.8
5		20	17.5±3.6	26.5±5.1
6		80	22.1±4.1	37.8±5.1
7	500	5	11.7±3.7	14.4±4.6
8		20	13.6±3.5	20.5±5.2
9		80	19.8±3.0	27.5±6.3

function of exposure conditions to vibration. The prehension force, the lifting force and torque on the handle, and the hand temperature were controlled. The VPT were studied at test frequencies 31.5 and 125 Hz as they relate respectively to mechanoreceptors FA I (Meissner corpuscules) and FA II (Pacini corpuscules) (Lundborg *et al.*, 1987; Ochoa and Torebjörk, 1983; Vallbo and Johansson, 1984; Johansson and Vallbo, 1979).

The TTS appears to follow a first order model. It was not possible however to study whether the time constants for the development and the recovery of the temporary threshold shift are different and vary with the exposure conditions. A more sophisticated protocol with more recordings of the VPT during and after exposure, and with a greater resolution would be needed to study these two time constants. Therefore, a model with a single time constant and a residual value (expressed as a constant fraction of the TTS reached) was used.

For the same reasons, it appears that the separate determination of each of these two parameters in the 81 experiments led to inconsistent results. Therefore, the time constant and residual fraction were taken as constant values for each subject. This does not demonstrate, however, that these parameters are independent of the exposure conditions.

The assumption of a systematic residual fraction for a given subject is not likely to be valid as this fraction should reasonably be 0 for small TTS and should increase with the amplitudes of these shifts. This alternative hypothesis could not be tested again and therefore the results presented in Table 1 provide only a first description of the phenomenon. This residual fraction could well also be an artefact of the computation, taking somewhat into account a possible difference between the time constants τ_e and τ_r.

Apparently however, the vibration perception threshold decreases rather rapidly during recovery (time constant of about 3 minutes) toward a residual value of about 10% of the TTS reached during exposure. As the VPT eventually recovers completely, this would suggest a two stage recovery process, possibly from mechanical and metabolic origin.

Figure 6 compares the TTS reported by Harada and Griffin (1991) after 5 min of exposure and the asymptotical TTS recorded in our study, in the same exposure conditions (20 ms^{-2} at 31.5, 125 and 500 Hz) and for the same two test frequencies (31.5 and 125 Hz). This shows the systematic lower estimation of the TTS in the first study.

This lower estimation may be due to the fact that, after 5 minutes of exposure, a steady state condition was not reached. It could also be due to differences in the instruments used for the evaluation of the VPT, the presence of a 'surround' in their instrument leading to lower perception thresholds (Harada and Griffin, 1991). On the other hand, as mentioned in the introduction, their extrapolation of the TTS to the beginning of the recovery period using a linear relationship with the logarithm of time, would lead to overestimation of the TTS. It appears clear that both sets of data should be reanalysed in parallel in order to be compared.

The present study describes the evolution and the order of magnitude of the TTS during an exposure to vibration at a single frequency and in a single axis. The *Y* axis was chosen for convenience and based on a limited previous study (not reported here) showing that, for an exposure at 100 ms^{-2}, 160 Hz, the TTS values would not be statistically different if the vibration were in the *X*, *Y* or *Z* axis. A more extensive study will be conducted to confirm this equality and investigate how they combine in case of an exposure in the 3 axes, as it is the case with any vibrating tool.

The lifting and grip forces were controlled as well as the torque and the hand temperature. A value of 20 N for the grip force was chosen based on a pilot study. This force could be tolerated by all subjects, without muscular pain, during 30 minutes. It is about equal to 5% of the average maximum voluntary grip force for the working population of men. These conditions are not met in real practice when the subject has to work in cooler environment and to exert a definite force to hold the tool and/or to perform the task.

Finally, the exposure durations encountered in industry vary largely from cases with very short but

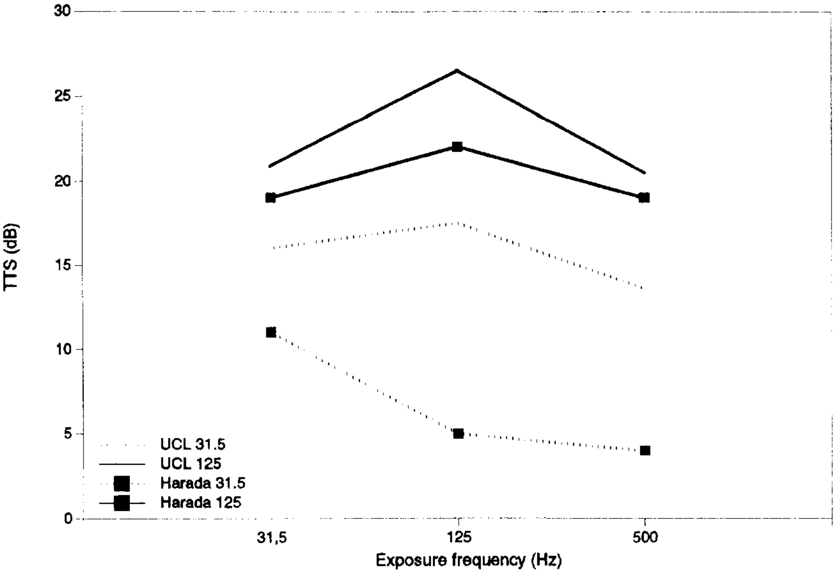

Fig. 6. Comparison of the TTS from Harada and Griffin (1991) and the present study (UCL) following exposure to vibration at 20 $\mathrm{m\,s^{-2}}$ at 31.5, 125 and 500 Hz and for the two test frequencies (31.5 and 125 Hz).

repetitive exposures (such as sewing or screwing), to cases with almost continuous exposure for four hours (such as chiselling) and intermediary cases with exposure durations of the order of 15 to 30 minutes (polishing). The TTS should be studied in each scenario. However, from the symptoms reported by the workers, the hypothesis can be made that, for long exposure durations, the TTS might increase with a longer time constant beyond the TTS reported for exposure of 30 min and the recovery might be slower.

It also remains to be determined how this temporary increase of the VPT ends up in a permanent elevation of the VPT after months and years of exposure and how both temporary and permanent increases in VPT influence the manual dexterity and the performances and safety at work.

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