Risks of Occupational Vibration Exposures

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Title: Experimental studies of acute effects of hand-transmitted vibration on neurosensory function

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SUMMARY

The objective was to investigate the acute effects of hand-transmitted vibration on measures of neurological function (vibration perception thresholds and thermotactile thresholds) in order to confirm current knowledge and better define the effects of vibration magnitude, frequency and duration.

Four controlled laboratory experiments were set up with a similar study design. The first experiment addressed the acute effects of HTV on vibrotactile perception thresholds and the second experiment on thermotactile perception thresholds. In the third and fourth experiments the acute effects of continuous and intermittent vibration on vibrotactile and thermotactile perception thresholds respectively were investigated. In the different experiment 10 subjects, five male and five female, participated.

From the results was concluded (Table 1) that the vibration frequency and magnitude gave an acute effect on the vibrotactile threshold, but the exposure time does not. It could also be concluded that the vibration magnitude and exposure time affect the cold and warmth thresholds, but the frequency of the vibration stimuli does not.

The results show that vibration exposure dived into shorter period of exposure and with the same energy-equivalent frequency weighted acceleration lead to lower temporary vibrotactile threshold shift. Moreover, no significant acute effects was found on the thermal perception thresholds for the sensation of cold or warmth as well as on the neutral zone were found between combinations of vibration with different periods of exposure and rest periods.

Table 1. Summary of different variables acute effect on the measures of vibration perception thresholds and thermotactile thresholds.

Measure	Vibration magnitude	Vibration frequency	Vibration exposure duration	Intermittent vibration exposure
Vibration perception thresholds	YES	YES	NO	YES
Thermotactile perception thresholds	YES	NO	YES	NO

CONTENTS

Task 3.1.2: Laboratory studies of neurological effects of HTV

The objective was to investigate the acute effects of hand-transmitted vibration on measures of neurological function (vibration perception thresholds and thermotactile thresholds) in order to confirm current knowledge and better define the effects of vibration magnitude, frequency and duration.

Four controlled laboratory experiments were set up and the study design was similar to Task 3.1.1 – vascular effects.

The first experiment addressed the acute effects of HTV on vibrotactile perception thresholds and the second experiment on thermotactile perception thresholds. In the third and fourth experiments the acute effects of continuous and intermittent vibration on vibrotactile and thermotactile perception thresholds respectively were investigated

1 Acute effects of vibration on vibrotactile perception thresholds

The aim of the first experimental study was to investigate the acute effects of vibration and how vibrations influence the measures of the vibrotactile thresholds during different vibration magnitudes, frequencies, and durations.

1.1 Methods

Ten healthy subjects, five male and five female, with no prior history of regular use of hand-held vibrating tools in occupational or leisure activities participated in the study. All ten subjects were non-smokers and reported no cardiovascular or neurological disorders in their dominant hand. The subjects mean age was 23.3 years (range 21-25), mean height 173.1 cm (range 160-183) and mean weight 66 kg (range 51-80). The Ethical Committee of Umeå University approved the study.

The experiments were performed in a room with an ambient temperature of 22ºC (± 2ºC) and with airflow less than 0.2 m/s. The subjects were asked to avoid alcohol 12 hours before testing and to avoid nicotine and caffeine consumption 1 hour before testing. During the experiment the subjects were dressed in light indoor clothing and they wore hearing protections during the entire test. After an acclimatisation period of 15 minutes, finger temperature was measured by a thermocouple attached to the distal phalanx of the examined index finger (digit 2). The finger skin temperature was not allowed to be less than 28°C. When the fingers were at lower temperature the subjects used hand warmers to increase the temperature.

A computer-based system was used to measure vibrotactile thresholds (thresholds at 31.5 Hz and 125 Hz) via the von Békésy method in a manner compliant with the methods in ISO 13091-1 (2001). The system consists of a laptop with a special developed program in LabView, a DAQ-card (National Instrument 6221M) and a vibration exciter (Brüel & Kjaer 4809) with an external amplifier (Sentec PA9). Thresholds were measured on the distal phalanx of the index finger of the dominant hand. Subjects were instructed to place their finger such that the centre of the whorl was situated over the centre of the probe of the applicator. The subjects were seated in a chair in front of the instrumentation setup and instructed to apply a downward (push) force of 0,5 N (± 0.25 N) during the tests. The applied force could be controlled by the research leader on a pointer instrument. During the test, the hand of the subject was supported at the wrist. Subjects were instructed to press and hold the response button down as soon as they perceived a vibration sensation and to release the response button as soon as they did not perceive the vibration.

A measure of the vibrotactile perception was conducted before the different exposures to vibration. After completing pre-test the subjects were instructed to place their index, middle finger and their ring finger on a horizontal wooden platform (70x70mm) mounted on a vibrator (Ling Altec Model 40). Their elbows rested at a comfortable angle on an adjustable supported platform. The exposed area of the fingers ranged from the fingertip to the second phalange. The subjects were instructed to apply a downward force of 5 N during the entire exposure time. The force was monitored by both the subjects and research leader. Immediately after the vibration exposure, the vibrotactile threshold measurements were conducted on the exposed index finger. The acute effect was measured continuously for the first 75 seconds and the analysis was made for a time intervals of 15 to 45s.

Each subject was exposed to vibration under 16 conditions (Table 2) with a combination of different frequency, intensity, and exposure time. The subjects were only allowed to conduct one test per day, and the test order was distributed with a repeated measures design. The vibration, a sinusoidal vibration at a frequency of 31.5 Hz and 125 Hz, was generated by a computer based system. The vibration was sent via an amplifier (Sentec PA 9) to the vibrator, producing motions in the vertical direction. The frequency-weighted vibration intensity ranged from 2.50 to 14.14 m/s^2, corresponding to an unweighted acceleration magnitude between 4.82 and 111.36 m/s^2. According to ISO 5349-1, the calculated energy-equivalent frequency weighted acceleration magnitude for the whole experimental time of 16 minutes was either 2.5 m/s^2 or 5.0 m/s^2 (Table 2).

Table 2. Conditions of exposure used in this study (the r.m.s. acceleration magnitude of vibration and the energy-equivalent frequency weighted acceleration magnitude for the whole experimental time of 16 minutes)

Experimental condition (number)	Vibration frequency (Hz)	Frequency – weighted acceleration magnitude (m/s^2)	Unweighted acceleration magnitude (m/s^2)	Exposure duration (min)	Equivalent acceleration magnitude (m/s^2)
1	31.5	7.07	13.62	2	2.5
2	31.5	5.00	9.63	4	2.5
3	31.5	3.54	6.81	8	2.5
4	31.5	2.50	4.82	16	2.5
5	31.5	14.14	27.25	2	5.0
6	31.5	10.00	19.27	4	5.0
7	31.5	7.07	13.62	8	5.0
8	31.5	5.00	9.63	16	5.0
9	125	7.07	55.68	2	2.5
10	125	5.00	39.37	4	2.5
11	125	3.54	27.84	8	2.5
12	125	2.50	19.69	16	2.5
13	125	14.14	111.36	2	5.0
13	125	10.00	78.74	4	5.0
15	125	7.07	55.68	8	5.0
16	125	5.00	39.37	16	5.0

Computer software SAS was used for the statistical analysis. In the analysis, the measured vibrotactile thresholds at 30 s after exposure for each subject and condition were compared with the corresponding measured thresholds before the exposure to vibration (the pre-test). The difference was used as an indication of response on the perception sensation. For the statistical analysis, repeated measures analysis of variance (ANOVA) with mixed model was used to test the hypothesis of "no difference" in the responses for the different exposure conditions.

1.2 Results

The mean vibrotactile perception thresholds at the index finger, calculated for all experimental conditions and measurement times, at the pre-test were 104.5 dB. Analysis shows that there was no significant difference ($p<0.074$) in the thresholds due to gender.

In Table 3 the results from the conducted experiments presented as the mean changes in the vibrotactile thresholds compared to the pre-test for the different experimental conditions (Table 2).

The frequency of the vibration stimuli (31.5 or 125 Hz) had significant ($p<0.001$) influence on the vibrotactile thresholds. The increase of the thresholds was greater at 125 Hz compared to 31.5 Hz ($p<0.001$) and 30 s after the exposure the mean difference was about 13 dB.

The thresholds were also significantly affected by the exposure levels ($p<0.0001$). An increase of the equivalent frequency weighted acceleration from 2.5 m/s^2 to 5.0 m/s^2 resulted in a mean increase of the thresholds with about 2.1 dB at 30 s after exposure. For 31.5 Hz the differences are significant for the first 2 min and for 125 Hz for 25 min.

The influence of different frequency weighted accelerations was significant for the test frequency of 31.5 Hz between the lowest and highest accelerations. The difference was about 3.6 dB at 30 s after exposure. None of the other acceleration were significant different. For the test frequency of 125 Hz none of the frequency weighted accelerations were significant different. For the different frequency un-weighted accelerations the same results as for the weighted accelerations was found.

The exposure time (2, 4, 8, 16 min) for the vibration stimuli had no significant influence on the thresholds ($p=0.7591$).

1.3 Conclusion

It could be concluded that the vibration frequency and magnitude gave an acute effect on the vibrotactile threshold, but the exposure time does not.

2 Acute effects of vibration on thermal perception thresholds

This second experiment focuses on the acute effects of vibration and how vibrations influence the measures of the thermal perception thresholds during different vibration magnitudes, frequencies, and durations.

2.1 Methods

Ten healthy subjects, five male and five female, provided a written consent on the basis of the principles in the Declaration of Helsinki to participated in the study. The Ethical Committee of Umeå University approved the study. The subjects had no prior history of regular use of hand-held vibrating tools in occupational or leisure activities. All ten subjects were non-smokers and reported no cardiovascular or neurological disorders in their dominant hand. One subject had neurological disorder in the none-dominate hand due to previous hand surgery. The subjects mean age was 25 years (range 22-28), mean height 174.6 cm (range 160-183) and mean weight 70 kg (range 55-89).

All subjects were asked to avoid alcohol 12 hours before testing and to avoid nicotine and caffeine consumption 1 hour before testing. The experiments were performed in a room with an ambient temperature of 22ºC (± 2ºC) and with airflow less than 0.2 m/s. The subjects were dressed in light indoor clothing and they wore hearing protections during the entire test. After an acclimatisation period of 15 minutes, finger temperature was measured by a thermocouple attached to the distal phalanx of the examined index finger (digit 2). The finger skin temperature was not allowed to be less than 28°C. When the fingers were at lower temperature the subjects used hand warmers to increase the temperature.

Thermal perception was measured using instruments outfitted with a flat contact thermo stimulator, Peltier contact thermode. The instruments were provided by Somedic (Thermo test; Somedic, Sales AB, Sweden). When measuring the perception of coldness and warmness, the volar surface of the distal phalanges of the index finger was gently applied to the probe (25x50 mm). The measured area of the index finger ranged from the fingertip to the distal interphalangeal joint. During the test, the hand of the subject was supported at the wrist. The perception threshold of cold and warmth was assessed by the Marstock method. The rate of the temperature change was linear and about 1°C/s. The subjects were seated in a chair in front of the instrumentation setup and instructed to apply a downward (push) force of 1 N during the tests. The applied force could be controlled by the subject and the research leader on a pointer instrument. The subject was instructed to press a switch whenever he or she experienced the onset of a change in the sensation of temperature (cold or warm). After a response, the temperature of the thermo stimulator changed direction from warmth to cold and vice versa. In-between measurements, the subjects continuously rested their finger on the probe but with no force applied.

A measure of the thermal perception of cold and warmth was conducted before the different exposures to vibration. The finger skin temperature was used as the reference temperature (starting point). After completing pre-test the subjects were instructed to place their index, middle finger and their ring finger on a horizontal wooden platform (70x70mm) mounted on a vibrator (Ling Altec Model 40). Their elbows rested at a comfortable angle on an adjustable supported platform. The exposed area of the fingers ranged from the fingertip to the second phalange. The subjects were instructed to apply a downward force of 5 N during the entire exposure time. The force was monitored by both the subjects and research leader. Immediately after the vibration exposure, the temperature threshold measurements were conducted on the exposed index finger. The acute effect was measured continuously for the first 75 seconds and the analysis was made for a time intervals of 15 to 45s.

The subjects were exposed to vibration under 16 conditions with a combination of different frequency, intensity, and exposure time. The conditions were the same as in experiment 1 (Table 2).

Computer software SAS was used for the statistical analysis. The thresholds were taken as the mean of the cold and warm measurements and the average number of measures for each threshold and test period was 3.5 (SD 1.8). The neutral zone was defined as the temperature difference between the warmth and cold perception thresholds. In the analysis, the measured thermotactile thresholds at 30 s after exposure for each subject and condition were compared with the corresponding measured thresholds before the exposure to vibration (the pre-test). The difference was used as an indication of response on the perception sensation. For the statistical analysis, repeated measures analysis of variance (ANOVA) with mixed model was used to test the hypothesis of “no difference” in the responses for the different exposure conditions. The test-retest correlation was calculated as the intraclass correlation coefficient.

2.2 Results

The total mean perception thresholds at the index finger calculated for the all 16 pre-test were 33.6°C (SD 1.39°C) for the sensation of cold and 38.0°C (SD 1.69°C) for warm. The mean calculated neutral zone for all subjects was 4.4°C (SD 2.41°C). Analysis shows that there was a significant difference ($p<0.001$) in the thresholds and the range of the neutral zone due to gender and height. Female subjects have a narrower neutral zone and consequently a higher cold and lower warmth threshold. The influence of the height was also significantly correlated to gender. The test-retest correlation between the pre-tests for the different measurements conditions was found to be 0.66 for the cold threshold and 0.62 for the warmth threshold. The female subjects had a better correlation than the male subjects (cold 0.80 vs. 0.46; warmth 0.70 vs. 0.49).

In Table 4 and 5 are the results from the conducted experiments presented as the mean temperature changes in the thresholds compared to the pre-test for the different experimental conditions (Table 2). In the tables are shown the changes for the first 10 min after the vibration exposure for the vibration frequency of 31.5 Hz and 125 Hz, respectively. Moreover, are given in the tables the calculated neutral zones. The mean changes of the thresholds, for all experimental conditions and measurement times, were found to be between –1.5°C and 0.7°C. The corresponding changes in the neutral zone were found to be less then 1.8 °C.

The frequency of the vibration stimuli (31.5 or 125 Hz) had no significant ($0.67<p<0.95$) influence on total mean perception thresholds for the sensation of cold or warmth as well as on the neutral zone.

However, the thresholds for the cold and warmth sensation were significantly affected by the exposure levels ($0.001<p<0.003$) regardless of the how the exposure levels were expressed (frequency weighted, unweighted or equivalent). An increase of the equivalent frequency weighted acceleration from 2.5 m/s^2 to 5.0 m/s^2 resulted in a mean decrease of the cold and warmth thresholds with about 0.2°C and 0.1°C respectively. For the frequency weighted acceleration or the unweighted acceleration, no clear exposure response relationship could be found. If the acceleration is divided into two categories, low and high acceleration levels, a significant difference could be found ($p=0.005$; $p=0.006$ respectively). Higher acceleration level produced a decrease of both thresholds with about 0.1°C. The neutral zone was significantly ($p=0.001$) affected by the unweighted acceleration, but not for the other two measures ($0.150<p<0.158$).

The exposure time (2, 4, 8, 16 min) for the vibration stimuli had a significant influence on the thresholds for cold and warmth sensations ($p=0.002$; $p=0.003$ respectively), but the neutral zone was not affected ($p=0.127$). There was a significant difference ($p=0.015$) between short exposure time (2 and 4 minutes) and long exposure time (8 and 16 minutes). Longer exposure time resulted in a decreased threshold of about 0.1°C.

2.3 Conclusion

It could be concluded that the vibration magnitude and exposure time affect the cold and warmth thresholds, but the frequency of the vibration stimuli does not.

3 Acute effects of intermittent vibration on tactile perception thresholds

In the third experiment, the acute effects of continuous and intermittent vibration on the tactile perception thresholds were investigated by combinations of vibration with different periods of exposure and rest periods.

3.1 Methods

The subjects and experimental procedure were the same as in experiment 1. The subjects were exposed to vibration under 4 conditions (Table 6) of vibration with different periods of exposure and rest periods. The subjects were only allowed to conduct one test per day, and the test order was distributed with a repeated measures design. The vibration, a sinusoidal vibration at a frequency of 125 Hz, was generated by an IBM computer based system. The vibration was sent via an amplifier (Sentec PA 9) to the vibrator, producing motions in the vertical direction. The frequency-weighted vibration intensity was 5 m/s^2, corresponding to an unweighted acceleration magnitude of 39.37 m/s^2. According to ISO 5349-1, the calculated energy-equivalent frequency weighted acceleration magnitude for the exposure time of 16 minutes was 5.0 m/s^2 (Table 3) and calculated for the experimental time include vibration free periods it varied between 3.6 to 5.0 m/s^2.

The combination is: 1 period of 16-min continuous vibration (rest period 0 min), 2 periods of 8 min, separated by a 8-min period with no vibration (rest period 8 min), 4 periods of 4 min, separated by 4 min periods with no vibration (rest period 12 min) and 8 periods of 2 min, separated by 2-min periods with no vibration (rest period 14 min).

Table 6. Conditions of exposure used in this study (the r.m.s. acceleration magnitude of vibration and the energy-equivalent frequency weighted acceleration magnitude for the whole experimental time of 16 minutes)

Experimental conditions (number)	Vibration frequency (Hz)	Frequency – weighted acceleration magnitude (m/s^2)	Unweighted acceleration magnitude (m/s^2)	Exposure duration (min)	Equivalent acceleration magnitude (m/s^2)
1	125	5.00	39.37	2+2+2+2+2+2+2+2	5
2	125	5.00	39.37	4+4+4+4	5
3	125	5.00	39.37	8+8	5
4	125	5.00	39.37	16	5

Computer software SAS was used for the statistical analysis. In the analysis, the measured vibrotactile thresholds at 30 s after exposure for each subject and condition were compared with the corresponding measured thresholds before the exposure to vibration (the pre-test). The difference was used as an indication of response on the perception sensation. For the statistical analysis, repeated measures analysis of variance (ANOVA) with mixed model was used to test the hypothesis of “no difference” in the responses for the different exposure conditions.

3.2 Results

In Table 7 the results from the conducted experiments presented as the mean changes in the vibrotactile thresholds compared to the pre-test for the different experimental conditions (Table 6).

The influence on the thresholds, 30 s after the exposure, was significant different due to the combination of exposure ($p=0.037$). The observed significant differences were between the one with shortest (2 min) exposure periods and the longest (16 min ($p=0.039$; 8+8 min $p=0.018$). For the other combination no significant influence was found. The 2 min exposures lead to a mean lower temporary threshold shift of 3.5 – 4.5 dB.

3.3 Conclusion

The results show that for the same energy-equivalent frequency weighted acceleration lead shorter period of exposure to lower temporary threshold shift.

4 Acute effects of intermittent vibration on thermal perception thresholds

The fourth experiment covered the acute effects of continuous and intermittent vibration on the thermal perception thresholds due to different combinations of vibration with different periods of exposure and rest periods.

4.1 Methods

The subjects and experimental procedure were the same as in experiment 2. The exposure conditions as well as the statistical analysis were the same as in experiment 3

4.2 Results

In Table 8 are the results from the conducted experiments presented as the mean temperature changes in the thresholds compared to the pre-test for the different experimental conditions (Table 6). In the table are shown the changes for the first 10 min after the vibration exposure. Moreover, are given in the table the calculated neutral zones.

The combinations of exposure had no significant ($0.242<p<0.413$) influence, 30 s after the exposure, on total mean perception thresholds for the sensation of cold or warmth as well as on the neutral zone.

4.3 Conclusion

No significant acute effects on the thermal perception thresholds for the sensation of cold or warmth as well as on the neutral zone were found between combinations of vibration with different periods of exposure and rest periods.

Table 3. The mean changes (dB) in the vibrotactile perception thresholds compared to the pre-test for the different experimental conditions (Table 2). The results are presented for the 30 min (1800 s) after the vibration exposure. Within parenthesis the standard deviation is given.

	Time (s)														
Con.	30	60	120	180	240	300	360	420	480	540	600	900	1200	1500	1800
1	7,28 (1,88)	6,42 (2,95)	3,50 (2,73)	3,58 (2,76)	2,72 (2,29)	2,17 (4,04)	2,13 (2,79)	2,31 (2,42)	1,20 (3,07)	1,63 (2,42)	0,53 (2,80)	0,73 (2,30)	0,22 (0,68)	0,00 (0)	0,00 (0)
2	7,15 (2,84)	6,26 (3,17)	3,46 (2,59)	2,38 (3,32)	2,00 (3,50)	1,64 (3,01)	1,23 (2,75)	0,70 (3,03)	1,35 (3,58)	0,05 (3,43)	-0,27 (4,77)	0,10 (0,33)	0,00 (0)	0,00 (0)	0,00 (0)
3	5,89 (2,74)	5,84 (3,30)	3,45 (2,77)	2,71 (3,17)	3,26 (3,79)	2,57 (3,44)	2,32 (3,59)	2,17 (4,51)	2,17 (4,10)	1,61 (4,64)	1,14 (3,63)	1,02 (1,93)	0,58 (1,83)	0,58 (1,83)	0,26 (0,82)
4	4,61 (4,08)	4,72 (4,90)	2,78 (3,63)	1,73 (2,75)	0,15 (4,48)	1,13 (3,22)	1,05 (2,97)	0,26 (3,74)	0,87 (2,99)	0,59 (3,18)	-0,06 (4,41)	-0,01 (0,28)	0,00 (0)	0,00 (0)	0,00 (0)
5	17,10 (3,94)	14,91 (4,77)	10,21 (3,46)	9,57 (4,01)	8,24 (4,13)	7,54 (4,13)	6,32 (4,29)	6,07 (4,20)	5,50 (4,09)	4,88 (3,55)	5,36 (3,69)	2,43 (2,70)	0,81 (2,49)	0,45 (1,28)	0,00 (0)
6	17,74 (3,93)	14,60 (3,86)	10,36 (3,11)	8,67 (3,30)	7,42 (3,18)	6,37 (2,38)	5,57 (2,65)	5,10 (2,51)	4,44 (2,69)	4,09 (2,97)	3,79 (3,44)	1,01 (2,16)	0,38 (1,19)	0,35 (1,12)	0,00 (0)
7	19,67 (4,61)	15,61 (5,26)	11,08 (3,65)	8,58 (3,72)	6,27 (2,98)	5,63 (2,48)	4,29 (2,33)	3,67 (2,88)	2,97 (2,99)	2,28 (2,62)	1,47 (2,81)	0,36 (1,44)	0,35 (1,10)	0,00 (0)	0,00 (0)
8	19,33 (3,78)	16,50 (4,12)	10,71 (3,61)	8,26 (3,34)	6,42 (3,22)	5,09 (3,16)	5,10 (2,87)	4,27 (2,63)	4,14 (2,47)	3,05 (2,99)	2,81 (2,32)	1,38 (2,09)	0,39 (1,22)	0,00 (0)	0,00 (0)
9	7,71 (3,89)	7,80 (2,85)	5,36 (3,81)	4,21 (3,76)	3,46 (4,53)	2,56 (4,72)	2,11 (4,18)	0,96 (2,65)	1,77 (3,92)	1,74 (4,66)	1,16 (3,49)	0,54 (1,76)	0,27 (0,86)	0,00 (0)	0,00 (0)
10	6,91 (3,91)	6,37 (3,19)	4,98 (3,44)	3,44 (3,96)	1,42 (3,72)	1,63 (4,18)	2,20 (2,86)	1,77 (3,26)	1,45 (3,09)	1,07 (3,35)	0,41 (3,18)	-0,14 (0,45)	0,00 (0)	0,00 (0)	0,00 (0)
11	7,48 (4,68)	6,55 (4,15)	4,60 (4,24)	2,51 (3,12)	0,95 (2,26)	1,10 (2,30)	0,74 (2,87)	1,13 (2,48)	-0,17 (2,19)	0,08 (1,70)	0,07 (2,06)	0,00 (0)	0,00 (0)	0,00 (0)	0,00 (0)
12	8,17 (4,70)	8,37 (4,84)	4,72 (4,19)	2,68 (3,40)	1,70 (3,23)	0,40 (3,81)	1,25 (3,21)	1,81 (3,29)	1,21 (3,53)	0,66 (4,18)	0,71 (3,80)	0,72 (2,50)	0,86 (2,73)	0,70 (2,22)	0,63 (1,99)
13	19,54 (3,92)	15,16 (4,78)	10,31 (3,94)	9,36 (4,34)	7,97 (4,06)	6,99 (3,18)	6,22 (3,38)	5,18 (3,35)	5,29 (3,23)	4,49 (3,53)	3,58 (3,81)	2,54 (2,87)	2,12 (4,27)	1,43 (3,42)	1,34 (4,20)
14	20,87 (3,89)	17,77 (3,76)	11,23 (3,27)	9,67 (3,02)	8,81 (3,51)	8,06 (3,49)	7,36 (3,06)	6,63 (3,11)	6,28 (3,01)	5,41 (2,51)	4,88 (2,80)	2,16 (3,59)	1,49 (2,61)	0,99 (2,25)	0,54 (1,71)
15	23,49 (2,67)	19,90 (3,51)	13,18 (3,11)	10,90 (3,83)	9,52 (3,70)	9,23 (4,20)	6,76 (3,83)	6,50 (3,80)	5,91 (4,08)	5,65 (4,00)	4,58 (4,06)	3,36 (3,41)	1,43 (3,46)	1,10 (2,48)	0,97 (2,28)
16	21,44 (6,03)	19,08 (5,77)	11,67 (5,66)	9,38 (5,84)	8,20 (5,29)	7,03 (4,88)	6,71 (4,64)	5,18 (4,95)	4,87 (4,48)	4,12 (4,87)	3,64 (4,49)	2,56 (4,54)	0,85 (2,74)	0,00 (0)	0,00 (0)

Table 4. The mean changes (ºC) in the warm and cold thresholds compared to the pre-test for the different experimental conditions (Table 2) that contains a vibration frequency of 31.5 Hz as well as the corresponding calculated neutral zones.
The results are presented for the first 600 s after the vibration exposure. Within parenthesis the standard deviation is given.

Experimental condition	Measure	Time (s) 30	60	120	180	240	300	360	420	480	540	600
1	Warm	-0,24 (1,75)	-0,14 (1,73)	0,47 (0,67)	0,33 (0,67)	0,24 (0,77)	0,16 (0,63)	0,43 (0,91)	0,36 (0,86)	0,23 (1,10)	0,20 (0,99)	0,01 (1,12)
	Cold	0,00 (0,61)	0,07 (0,72)	0,34 (0,50)	0,32 (0,45)	0,32 (0,45)	0,22 (0,35)	0,36 (0,77)	0,43 (0,33)	0,42 (0,39)	0,47 (0,70)	0,34 (0,68)
	Neutral zone	-0,25 (1,57)	-0,21 (1,28)	0,13 (0,81)	0,01 (0,75)	-0,08 (0,93)	-0,06 (0,70)	0,07 (1,17)	-0,07 (0,84)	-0,19 (1,13)	-0,27 (1,04)	-0,33 (1,10)
2	Warm	0,10 (0,81)	0,59 (1,29)	0,19 (0,69)	0,29 (0,63)	0,32 (0,82)	0,39 (0,80)	0,45 (0,69)	0,29 (0,52)	0,22 (0,85)	0,38 (0,99)	0,21 (0,73)
	Cold	-0,34 (0,79)	-0,22 (0,99)	0,09 (0,83)	0,21 (0,74)	0,17 (0,82)	0,26 (0,61)	0,36 (0,70)	0,22 (0,56)	0,16 (0,79)	0,10 (0,63)	0,03 (0,70)
	Neutral zone	0,44 (0,68)	0,81 (1,47)	0,10 (0,77)	0,08 (0,69)	0,15 (0,79)	0,13 (0,65)	0,09 (0,74)	0,07 (0,69)	0,06 (0,71)	0,28 (0,88)	0,18 (0,80)
3	Warm	0,11 (0,45)	0,12 (0,83)	0,41 (0,56)	0,51 (0,84)	0,11 (0,70)	0,38 (1,11)	0,49 (1,17)	0,45 (1,21)	0,42 (1,20)	0,32 (1,08)	0,54 (1,23)
	Cold	-0,15 (1,06)	-0,37 (1,12)	0,05 (0,74)	0,33 (0,65)	-0,17 (1,06)	0,10 (0,58)	-0,13 (0,39)	0,27 (0,70)	0,17 (0,61)	-0,01 (0,60)	0,29 (0,44)
	Neutral zone	0,26 (0,93)	0,48 (0,98)	0,36 (0,71)	0,18 (0,92)	0,28 (0,99)	0,28 (1,10)	0,62 (1,18)	0,18 (0,95)	0,25 (1,03)	0,33 (0,91)	0,25 (1,19)
4	Warm	-0,13 (1,23)	0,11 (1,45)	0,42 (0,99)	0,61 (1,29)	0,58 (1,04)	0,25 (1,11)	0,56 (0,98)	0,46 (0,79)	0,31 (0,93)	0,41 (0,96)	0,73 (0,89)
	Cold	-0,56 (1,07)	-0,21 (0,96)	0,14 (0,65)	0,24 (0,69)	0,28 (0,77)	0,36 (0,75)	0,47 (0,69)	0,23 (0,73)	0,26 (0,99)	0,12 (0,88)	0,32 (0,88)
	Neutral zone	0,43 (1,39)	0,33 (1,34)	0,28 (0,82)	0,37 (1,27)	0,30 (1,16)	-0,11 (1,13)	0,09 (0,86)	0,23 (0,82)	0,05 (0,81)	0,29 (0,78)	0,41 (0,77)
5	Warm	-0,02 (1,02)	0,45 (0,95)	0,32 (0,63)	0,45 (0,73)	0,46 (0,63)	0,42 (0,92)	0,43 (0,96)	0,32 (1,05)	0,49 (1,02)	0,37 (0,96)	0,35 (1,12)
	Cold	-0,75 (0,71)	-0,41 (0,86)	-0,15 (0,47)	-0,06 (0,61)	-0,02 (0,59)	-0,01 (0,67)	0,08 (0,82)	-0,02 (0,75)	0,04 (0,53)	0,05 (0,80)	-0,12 (0,56)
	Neutral zone	0,72 (1,08)	0,86 (1,04)	0,47 (0,77)	0,51 (0,96)	0,48 (0,70)	0,43 (0,93)	0,35 (0,94)	0,34 (0,96)	0,45 (0,89)	0,32 (0,94)	0,47 (0,88)
6	Warm	-0,45 (1,47)	-0,22 (1,35)	-0,19 (1,21)	-0,17 (1,14)	0,15 (1,38)	0,13 (1,79)	-0,05 (1,37)	0,10 (1,66)	-0,08 (1,75)	-0,10 (1,68)	-0,17 (1,51)
	Cold	-1,00 (1,27)	-0,79 (1,21)	-0,12 (0,79)	-0,12 (0,71)	-0,28 (0,77)	-0,14 (0,70)	-0,11 (0,76)	0,06 (0,64)	-0,03 (0,73)	-0,43 (1,02)	-0,24 (0,91)
	Neutral zone	0,55 (1,17)	0,57 (1,31)	-0,07 (0,83)	-0,05 (1,22)	0,43 (1,51)	0,27 (2,01)	0,06 (1,43)	0,04 (1,42)	-0,05 (1,57)	0,33 (1,71)	0,07 (1,66)
7	Warm	0,26 (1,08)	0,23 (1,13)	0,17 (0,89)	0,16 (0,68)	0,43 (1,01)	0,25 (0,98)	0,17 (1,08)	0,30 (0,98)	0,21 (1,17)	0,04 (0,80)	0,17 (0,95)
	Cold	-0,53 (0,52)	-0,29 (0,55)	0,17 (0,66)	0,30 (0,65)	0,34 (0,48)	0,28 (0,73)	0,33 (0,77)	0,22 (0,72)	0,15 (0,76)	0,28 (0,57)	0,25 (0,67)
	Neutral zone	0,79 (1,38)	0,52 (0,88)	0,00 (1,21)	-0,14 (0,87)	0,09 (0,97)	-0,03 (1,03)	-0,16 (1,20)	0,08 (1,01)	0,06 (1,51)	-0,24 (0,92)	-0,08 (1,39)
8	Warm	-0,35 (2,21)	-0,15 (2,18)	-0,21 (1,67)	0,07 (1,53)	-0,03 (1,63)	-0,05 (1,58)	-0,07 (1,59)	-0,06 (1,76)	-0,09 (1,62)	-0,18 (1,81)	-0,17 (1,80)
	Cold	-1,17 (1,94)	-0,95 (2,04)	-0,40 (1,17)	-0,01 (0,96)	-0,18 (0,65)	-0,10 (0,74)	-0,05 (0,68)	-0,03 (0,83)	-0,02 (0,75)	-0,21 (1,01)	-0,05 (0,96)
	Neutral zone	0,82 (1,56)	0,81 (1,33)	0,19 (1,29)	0,08 (1,23)	0,15 (1,48)	0,05 (1,23)	-0,02 (1,41)	-0,03 (1,20)	-0,07 (1,08)	0,03 (0,91)	-0,12 (1,08)

Table 5. The mean changes (ºC) in the warm and cold thresholds compared to the pre-test for the different experimental conditions (Table 2) that contains a vibration frequency of 125 Hz as well as the corresponding calculated neutral zones. The results are presented for the first 600 s after the vibration exposure. Within parenthesis the standard deviation is given.

Experimental condition	Measure	Time (s) 30	60	120	180	240	300	360	420	480	540	600
9	Warm	0,51 (0,94)	0,45 (1,27)	0,60 (0,93)	0,60 (0,80)	0,38 (0,94)	0,51 (0,73)	0,57 (0,87)	0,32 (1,13)	0,44 (1,08)	0,39 (1,21)	0,15 (1,28)
	Cold	-0,41 (0,99)	-0,46 (1,16)	0,19 (1,05)	0,40 (0,96)	0,55 (1,02)	0,67 (0,97)	0,55 (0,93)	0,48 (0,84)	0,40 (0,98)	0,60 (1,02)	0,54 (0,97)
	Neutral zone	0,92 (1,27)	0,91 (1,02)	0,41 (1,33)	0,20 (1,14)	-0,17 (1,22)	-0,16 (0,91)	0,02 (1,08)	-0,16 (1,22)	0,04 (1,16)	-0,21 (1,39)	-0,39 (1,39)
10	Warm	0,21 (0,45)	0,18 (1,17)	0,49 (0,68)	0,57 (0,83)	0,60 (0,74)	0,63 (1,10)	0,60 (0,91)	0,33 (0,88)	0,50 (1,02)	0,17 (0,90)	0,45 (1,11)
	Cold	-0,73 (0,78)	-0,57 (0,78)	0,19 (0,47)	0,51 (0,81)	0,53 (0,77)	0,42 (0,69)	0,46 (0,63)	0,32 (0,92)	0,38 (0,64)	0,31 (0,51)	0,27 (0,52)
	Neutral zone	0,94 (1,02)	0,75 (1,11)	0,30 (0,77)	0,06 (1,08)	0,07 (0,91)	0,21 (1,25)	0,14 (0,91)	0,01 (1,20)	0,12 (0,95)	-0,14 (1,01)	0,18 (1,18)
11	Warm	0,43 (0,94)	0,23 (0,78)	0,22 (0,71)	0,26 (0,93)	0,04 (0,87)	-0,24 (0,67)	0,02 (0,99)	0,19 (0,95)	0,34 (1,38)	0,33 (1,26)	0,23 (1,20)
	Cold	-0,47 (1,14)	-0,39 (0,90)	-0,19 (0,73)	0,08 (0,88)	0,00 (0,86)	-0,09 (0,97)	-0,06 (0,86)	-0,12 (0,89)	-0,10 (0,96)	-0,11 (1,05)	-0,02 (0,94)
	Neutral zone	0,89 (1,32)	0,62 (0,79)	0,41 (0,78)	0,18 (0,90)	0,04 (0,77)	-0,15 (0,69)	0,08 (0,91)	0,31 (0,80)	0,44 (1,00)	0,44 (0,87)	0,25 (1,28)
12	Warm	-0,07 (0,87)	0,09 (0,94)	-0,08 (0,63)	-0,18 (0,80)	-0,20 (0,52)	-0,18 (0,65)	-0,05 (0,51)	-0,27 (0,93)	-0,04 (0,93)	-0,01 (1,18)	-0,23 (0,96)
	Cold	-0,84 (1,58)	-0,55 (1,31)	0,00 (1,04)	0,09 (1,17)	0,00 (0,79)	0,15 (0,99)	0,07 (0,82)	0,09 (1,29)	0,05 (0,85)	-0,05 (0,62)	0,00 (1,07)
	Neutral zone	0,77 (1,37)	0,64 (1,21)	-0,08 (1,01)	-0,27 (0,84)	-0,20 (0,53)	-0,33 (0,73)	-0,12 (0,57)	-0,36 (0,57)	-0,09 (0,54)	0,04 (0,75)	-0,23 (0,61)
13	Warm	0,18 (1,65)	0,45 (1,69)	0,27 (0,84)	0,26 (0,56)	0,05 (1,03)	0,04 (1,08)	0,01 (1,04)	-0,31 (1,10)	-0,09 (0,95)	0,01 (0,95)	-0,07 (1,24)
	Cold	-0,94 (1,34)	-0,52 (1,61)	0,02 (0,81)	0,28 (0,71)	0,27 (0,99)	0,31 (1,06)	0,13 (0,76)	0,03 (0,86)	0,13 (0,99)	0,11 (0,88)	0,12 (1,13)
	Neutral zone	1,12 (0,97)	0,96 (0,74)	0,25 (0,27)	-0,02 (0,43)	-0,22 (0,74)	-0,27 (0,80)	-0,12 (0,48)	-0,34 (0,71)	-0,22 (0,44)	-0,10 (0,56)	-0,19 (0,68)
14	Warm	-0,13 (1,28)	0,10 (1,24)	0,02 (0,70)	0,07 (1,03)	-0,13 (0,91)	0,06 (0,93)	-0,10 (1,04)	0,05 (0,95)	-0,05 (1,23)	0,06 (1,42)	0,23 (1,43)
	Cold	-1,50 (1,23)	-1,08 (1,28)	0,04 (0,60)	-0,01 (0,46)	-0,02 (0,71)	-0,01 (0,70)	0,15 (0,59)	0,28 (0,50)	0,03 (0,85)	0,13 (0,58)	0,26 (0,59)
	Neutral zone	1,37 (1,28)	1,18 (1,32)	-0,02 (0,78)	0,08 (0,96)	-0,11 (0,62)	0,07 (0,50)	-0,25 (0,66)	-0,23 (0,79)	-0,08 (0,76)	-0,07 (1,04)	-0,03 (1,05)
15	Warm	0,49 (0,55)	0,54 (0,88)	0,51 (0,97)	0,42 (0,86)	0,40 (0,88)	0,52 (1,05)	0,50 (0,93)	0,28 (0,62)	0,24 (0,62)	0,46 (0,79)	0,31 (0,80)
	Cold	-0,53 (0,82)	-0,40 (0,72)	0,07 (0,31)	0,05 (0,80)	-0,02 (0,42)	-0,07 (0,43)	0,23 (0,73)	0,07 (0,37)	0,00 (0,72)	0,11 (0,70)	0,10 (0,91)
	Neutral zone	1,02 (0,75)	0,94 (0,87)	0,44 (0,98)	0,37 (1,06)	0,42 (0,85)	0,59 (1,06)	0,27 (1,24)	0,21 (0,84)	0,24 (0,96)	0,35 (1,06)	0,21 (1,20)
16	Warm	-0,07 (0,60)	-0,19 (0,99)	0,04 (0,93)	-0,11 (0,82)	-0,20 (0,87)	0,08 (0,66)	0,10 (0,86)	0,12 (0,61)	0,27 (0,89)	0,13 (0,68)	0,19 (0,74)
	Cold	-0,86 (0,85)	-0,90 (1,08)	-0,08 (0,62)	-0,03 (0,63)	-0,24 (0,49)	0,07 (0,70)	-0,27 (0,76)	0,03 (0,64)	0,13 (0,78)	-0,11 (0,62)	-0,07 (0,60)
	Neutral zone	0,79 (0,39)	0,71 (1,18)	0,12 (0,92)	-0,08 (0,90)	0,04 (0,75)	0,01 (0,69)	0,37 (0,96)	0,09 (0,65)	0,14 (0,94)	0,24 (0,76)	0,26 (0,75)

Table 7. The mean changes (dB) in the vibrotactile perception thresholds compared to the pre-test for the different experimental conditions (Table 6). The results are presented for the 30 min (1800 s) after the vibration exposure. Within parenthesis the standard deviation is given.

	Time (s)														
Con.	30	60	120	180	240	300	360	420	480	540	600	900	1200	1500	1800
1	21,44 (6,03)	19,08 (5,77)	11,67 (5,66)	9,38 (5,84)	8,2 (5,29)	7,03 (4,88)	6,71 (4,64)	5,18 (4,95)	4,87 (4,48)	4,12 (4,87)	3,64 (4,49)	2,56 (4,54)	0,85 (2,74)	0 (0)	0 (0)
2	22,43 (5,41)	20,09 (5,75)	13,48 (5,88)	10,28 (6,13)	9,13 (5,58)	8,07 (6,35)	7,4 (5,61)	6,66 (5,32)	5,7 (5,14)	4,49 (5,34)	5,03 (4,99)	2,88 (4,75)	1,91 (3,54)	1,28 (2,94)	1,43 (3,19)
3	19,18 (2,73)	16,29 (3,08)	9,82 (4,21)	9,05 (2,92)	7,42 (2,94)	6,29 (3,2)	5,6 (3,28)	5,04 (3,12)	4,67 (3,15)	3,47 (2,93)	3,6 (2,95)	1,06 (2,38)	1,02 (2,16)	0,48 (1,06)	0 (0)
4	17,94 (3,95)	14,7 (5,15)	10,17 (4,78)	8,26 (4,87)	7,26 (4,73)	6,75 (4,7)	5,77 (4,26)	5,34 (4,16)	4,59 (4,4)	4,2 (3,67)	3,87 (3,72)	3,04 (3,91)	1,48 (2,49)	0,74 (1,67)	0,19 (0,6)

Table 8. The mean changes (ºC) in the warm and cold thresholds compared to the pre-test for the different experimental conditions (Table 6) as well as the corresponding calculated neutral zones. The results are presented for the first 600 s after the vibration exposure. Within parenthesis the standard deviation is given.

Experimental condition	Measure	Time (s)										
		30	60	120	180	240	300	360	420	480	540	600
1	Warm	-0,07 (0,60)	-0,19 (0,99)	0,04 (0,93)	-0,11 (0,82)	-0,20 (0,87)	0,08 (0,66)	0,10 (0,86)	0,12 (0,61)	0,27 (0,89)	0,13 (0,68)	0,19 (0,74)
	Cold	-0,86 (0,85)	-0,90 (1,08)	-0,08 (0,62)	-0,03 (0,63)	-0,24 (0,49)	0,07 (0,70)	-0,27 (0,76)	0,03 (0,64)	0,13 (0,78)	-0,11 (0,62)	-0,07 (0,60)
	Neutral zone	0,79 (0,39)	0,71 (1,18)	0,12 (0,92)	-0,08 (0,90)	0,04 (0,75)	0,01 (0,69)	0,37 (0,96)	0,09 (0,65)	0,14 (0,94)	0,24 (0,76)	0,26 (0,75)
2	Warm	-0,15 (1,17)	-0,09 (1,08)	-0,06 (0,85)	-0,06 (0,70)	-0,07 (0,70)	-0,12 (0,94)	0,21 (0,54)	-0,08 (0,80)	0,17 (0,76)	0,02 (1,12)	0,25 (0,82)
	Cold	-0,74 (0,94)	-0,81 (1,11)	-0,13 (0,76)	0,02 (0,70)	-0,11 (0,50)	0,08 (0,64)	0,26 (0,50)	0,07 (0,51)	0,13 (0,51)	0 (0,37)	0,25 (0,39)
	Neutral zone	0,58 (0,97)	0,72 (0,77)	0,07 (0,94)	-0,08 (0,86)	0,04 (0,69)	-0,20 (0,84)	-0,05 (0,67)	-0,15 (0,81)	0,04 (0,89)	0,02 (1,08)	0 (0,89)
3	Warm	-0,30 (1,02)	-0,38 (0,99)	-0,17 (0,68)	-0,07 (0,44)	-0,08 (0,33)	-0,10 (0,54)	0,15 (0,66)	-0,08 (0,78)	0,09 (0,47)	0,08 (0,62)	-0,05 (0,66)
	Cold	-0,47 (1,11)	-0,69 (1,19)	-0,15 (0,92)	-0,07 (0,69)	-0,09 (0,84)	-0,10 (0,79)	0,18 (0,69)	0,03 (0,67)	0,11 (0,76)	0,21 (0,89)	0,20 (0,66)
	Neutral zone	0,17 (1,02)	0,31 (1,11)	-0,02 (0,87)	0 (0,66)	0,01 (0,72)	0 (0,62)	-0,03 (0,69)	-0,11 (0,49)	-0,02 (0,54)	-0,13 (0,60)	-0,25 (0,58)
4	Warm	-0,54 (1,15)	0,12 (1,34)	0,14 (0,75)	0,08 (0,86)	-0,03 (0,49)	-0,04 (0,71)	-0,20 (0,61)	-0,19 (0,50)	-0,10 (0,76)	0 (0,67)	-0,04 (0,88)
	Cold	-0,72 (1,14)	-0,37 (0,99)	-0,06 (0,66)	-0,10 (0,51)	-0,07 (0,72)	0,05 (0,54)	-0,11 (0,77)	-0,13 (0,73)	-0,17 (0,87)	-0,28 (0,73)	-0,07 (0,60)
	Neutral zone	0,19 (1,11)	0,48 (1,06)	0,20 (0,96)	0,18 (1,15)	0,04 (0,99)	-0,09 (1,01)	-0,09 (1,27)	-0,06 (0,89)	0,07 (1,16)	0,28 (1,10)	0,03 (1,24)