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Post-effects of long-term hand vibration on visuo-manual performance in a tracking task

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Movement precision and performance time were evaluated through a visuo-manual tracking task performed before and after 10-min hand vibration exposure. Constant displacement amplitude vibration of 0.2 and 0.3 mm peak to peak at 90, 150, 300 Hz were applied to the hand *z*-axis by a vertical handle. During exposure a grip force of 5% MVC was exerted for 5 s and then relaxed for 25 s while maintaining fingers-handle contact. The tracking task consisted in moving a ring (Ø = 9 mm) attached to a thin rod held between the index finger and thumb along a zig-zagged wire (Ø = 3.7 mm). Alterations of tracking errors (ring-wire contact) and tracking time were analysed as a function of the vibration parameters. The tasks were performed by ten healthy participants. Vibration induced a significant increase in tracking errors (ring-wire contact) and a significant decrease in tracking time. These impairments decayed with time after vibration exposure. The recovery period was > 5 min but < 10 min with the exception of 90 Hz vibration, for which recovery could be > 10 min. The number of tracking errors was neither influenced by vibration frequency nor by amplitude. The tracking time decreased as frequency increased and recovery was related to the displacement amplitude. The subjective rating of the performance on a visual analogue scale indicated that the subjects tended to perceive the task as being easier after vibration exposure. Vibration applied to the non-dominant hand while the participant performed the tracking task had no effect. These results show that vibration similar to hand – tool vibration affects precision and velocity control of visually guided hand movements. Furthermore, these performance decrements were not consciously perceived.

1. Introduction

Manipulating objects or controls under visual control of the hand are familiar and simple behavioural actions of everyday life. These activities require the coordination of complex sensory and motor processes involved in the control of the eye, head and hand. Visual and non-visual cues such as proprioceptive (Gauthier and Hofferer 1976, Gauthier *et al*. 1988, Vercher and Gauthier 1992) and exteroceptive (Akamatsu 1992) information do contribute to the coordinated control of eye and hand movements when they are simultaneously involved in a motor task (Gauthier *et al*. 1988). Furthermore, the combination of sensory information (auditory, visual, proprioceptive and tactile) about the arm position enhances hand tracking performances (Mather and Lackner 1980).

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Accuracy of limb movement is affected by hand and whole-body vibration (Lewis and Griffin 1976, 1979, Gauthier *et al*. 1981, Ribot *et al*. 1986, Martin *et al*. 1991). Furthermore, oculomanual coordination can also be affected by hand vibration (Martin *et al*. 1991). In the high frequency range ($F > 20$ Hz), the source of alteration was suggested to lie principally in the vibration-induced response of somesthetic receptors (Martin *et al*. 1980, 1991, Gauthier *et al*. 1981). Although visual cues may compensate to some extent for the vibration-induced alteration of sensory information, they may not be sufficient to counteract fully the deficit incurred by other sensory modalities (Martin *et al*. 1991). In addition, impairment of sensorimotor activities observed during vibration exposure frequently persist several minutes after cessation of the stimulus (Martin *et al*. 1980, Roll *et al*. 1980, Gauthier *et al*. 1981). Hence, motor control and more specifically visually guided activities can be significantly impaired during and immediately after vibration exposure and contribute to accidents involving falls, dropping objects and improper use of controls or tools. Finally, vibration-induced changes in the behaviour of sensorimotor systems such as spinal proprioceptive reflexes are frequency dependent (Martin *et al*. 1984, Park and Martin 1993). The 'frequency response' of the sensory receptors involved in these feedback systems has been suggested to shape the relationship between the motor responses and vibration frequency.

In an attempt to determine, first, the influence of vibration parameters, such as frequency and displacement amplitude in the impairment of visually guided tasks, second, to determine the duration of eventual post-effects and, third, to emphasize the often ignored role of movement errors in accidents occurring in vibratory environment, continuous manual control was analysed through the response of the visuo-manual system when the eye and the hand act together in a simple tracking task.

The present study describes changes in tracking error and tracking time after hand vibration exposure as a function of vibration frequency and displacement amplitude. The task was selected for its simplicity and ability to test manual dexterity (Guion 1965). Vibration parameters were selected to simulate small, powered hand tools. The results point out the role of proprioceptive and exteroceptive inputs in visuo-manual control. They also indicate a divergence between precision and velocity control which could lead to improper control of tools or controls in vibratory environments.

2. Methods

2.1. *Participants*

The experiment included ten healthy participants as paid volunteers. All participants were university students. Their age ranged from 20 to 32 years. All participants were free from any known neurological or musculoskeletal disorders. Prior to the experiment each participant read and signed an informed consent form.

2.2. *Experimental situation*

The participant was seated on an adjustable chair in front of a table with the arms unsupported. A metallic zig-zagged wire ($L = 600$ mm, $Ø = 3.7$ mm) fixed to an adjustable support was placed before the participant in a frontal plane (figure 1A). A ring ($Ø = 9$ mm) placed around the wire was attached to a thin rod ($Ø = 4.7$ mm), which was held between the index finger and thumb. Each end of the wire was equipped with a metallic contact insulated from the wire. These contact areas were

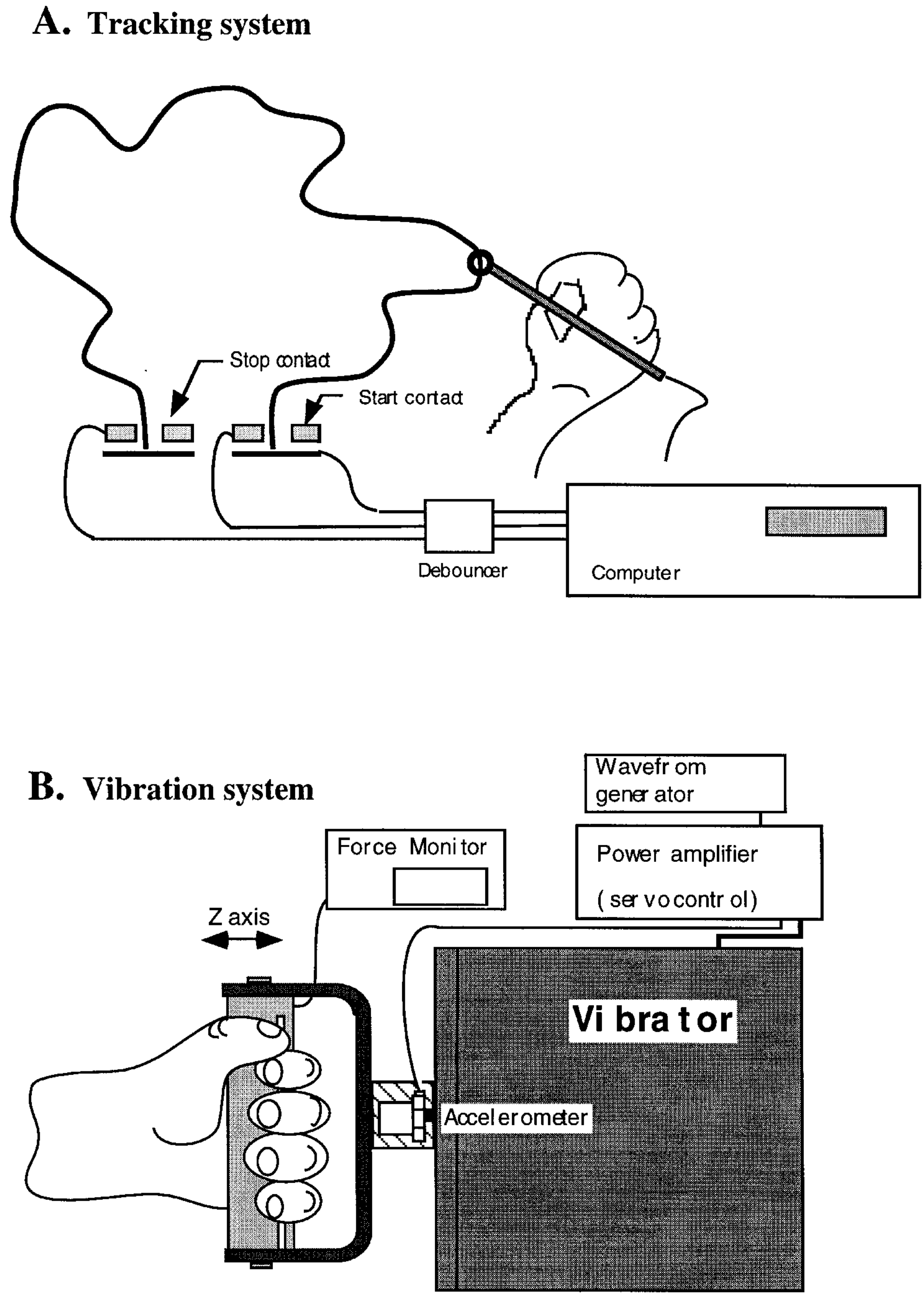

Figure 1. Tracking system (A): a ring is fixed to a thin rod held between the thumb and index finger. The ring is connected to a 4.5 V battery. Contacts between the ring, the wire, and start and stop washers are recorded by a computer via a three-channel debouncing circuit whose outputs are connected to printer port inputs. Vibration system (B): vibration is applied to the hand along the longitudinal axis of the forearm (*z*-axis). The vibration level is servo controlled by an accelerometer in the feedback loop. The force monitor provides a visual feedback of the grip force.

connected to the printer port of a computer via a debouncing circuit, and were used to start and stop a timer. The wire was also connected to a printer port input. The ring was connected to a 4.5 V battery. Software was developed to count the number of ring-wire contacts and compute the duration of the tracking task. The chair and device heights were adjusted to match each participant's anthropometry and height level preferences. The tracking task consisted of moving the ring along the wire while avoiding contact. The participant was instructed to perform the task as fast as possible with an emphasis on precision.

2.3. *Vibration*

Vibration was applied to the dominant hand along the longitudinal axis of the forearm (z-axis) by a vertical handle adapted on an electromagnetic vibrator placed on the table next to the tracking device (figure 1B). A padded arm rest fixed to the chair was adjusted to support the forearm horizontally, and aligned with the vibrator axis. The handle was equipped with a strain-gauge dynamometer to measure grip force. The dynamometer was connected to a digital voltmeter to provide feedback. Three sinusoidal vibrations of 90, 150, 300 Hz and two constant displacement amplitudes of 0.2 and 0.3 mm were used. The exposure duration was 10 min in each case.

2.4. *Procedure*

To avoid any learning effect during the experiment the participants were trained to perform the tracking task until their performance plateaued. Training ended when the participant achieved a similar performance for three consecutive trials (<15 errors, with a tracking time <35 s and variations limited to $\pm$ two errors and ± 2 s). This level of performance was reached in 20–40 min. The average performance over the last three trials was used as the baseline. Then, the tracking task was performed before, immediately after (t_0), and 5 (t_5) and 10 min (t_{10}) after vibration exposure; hence performance was tested in four conditions. The level of maximal voluntary contraction (MVC) of the grip was determined before the test session. During the vibration period the participant grasped the handle and exerted a grip force of 5% MVC during 5 s and relaxed for 25 s. This task, which simulated tool grasping, was paced by a brief auditory signal generated by computer. Data were collected for 21 trials for each participant ([three frequencies $\times$ two displacement amplitudes + one control] $\times$ three post-vibration conditions). The control condition was similar to the others, except that vibration was not applied to the handle. Owing to the practical limitations imposed by the setting of the vibration displacement amplitude, trials were randomized only across the frequencies. Half of the participants started with the 0.2 mm amplitude while the other half started with the 0.3 mm amplitude. The last test of each condition was also used as the pre-vibration test for the following condition; hence, two consecutive vibration periods were separated by a 12-min interval.

2.5. *Subjective evaluation*

The subjects were asked to rate the difficulty of the task after each trial on a 10-cm visual analogue scale. The scale was presented horizontally, the left and right anchor points were labelled to correspond to the least and most difficult task possible. The subjective rating was indicated by placing a vertical mark on the scale.

2.6. *Data analysis*

Repeated measures analysis of covariance (ANACOVA) treating the participant as a random blocking factor was performed on the tracking errors and tracking time to determine the effects of vibration on the visuo-manual task. Tracking time and tracking errors were used alternately as the added regressor. This type of analysis was also performed on the subjective rating of the task. Condition and frequency influences were further analysed using Tukey–Kramer multiple comparison test.

3. Results

Although a large interparticipant variability was observed, the tracking task was affected immediately after vibration exposure and the recovery time varied with vibration frequency. No changes in performance were observed in the control conditions (before each vibration exposure). The results of the ANACOVA performed on the number of errors, tracking time and subjective rating are presented in table 1. These data indicate, first, that vibration had a significant influence on precision and time, and, second, neither frequency nor displacement significantly affected the number of errors; however, these variables significantly influenced the time to complete the task in specific conditions as indicated by the significance of the interactions between frequency and conditions and displacement and condition. The subjective ratings appeared marginally affected by vibration exposure.

3.1. *Number of errors*

Figure 2 presents the averages of the number of tracking errors as a function of vibration frequency and time after vibration exposure. The grey dot on the left axis indicates the average baseline performance (12.4 ± 6) observed before vibration exposure. Immediately after vibration (t_0) the number of errors (averaged over amplitudes) increases with vibration frequency (15 ± 7.3 at 90 Hz, 16.6 ± 8.2 at 150 Hz, 17.5 ± 10.2 at 300 Hz); however, this tendency was not significant. This change in tracking performance (four errors) represents a 33% increase. The number of errors (averaged over frequencies and amplitude) decreases significantly ($p = 0.01$) with time (16.4 ± 8.6 at t_0, 14.1 ± 5.8 at t_5, 12.5 ± 6.2 at t_{10}). As shown on the graph, the number of errors 10 min after vibration exposure is similar to the baseline level.

Table 1. ANACOVA results for the tracking task parameters.

Effect	d.f.	*p* Errors	Tracking time	Rating
Frequency (*VF*)	2	0.11	0.83	0.94
Displacement (*D*)	1	0.79	0.052	0.63
Condition (*C*)	2	0.006*	0.000*	0.06
$VF \times C$	2	0.99	0.006*	0.85
D $\times C$	2	0.94	0.040*	0.85
Tracking time	1	0.02*	•	0.000*
Errors	1	•	0.02*	0.001*
Participant	9	0.000*	0.000*	0.000*

*Significant.

3.2. *Tracking time*

Figure 3 presents the averages of the tracking time as a function of vibration frequency and time after vibration exposure. The grey dot on the left axis indicates the average baseline performance (30.5 ± 5 s) observed before vibration exposure. The tracking time is significantly shorter (4.8 s, $p < 0.01$) immediately after vibration exposure. In this condition, the tracking time decreases as vibration frequency increases and is significantly shorter after 300 Hz (24.7 ± 4 s) than after 90 Hz vibration exposure (28.3 ± 3 s) for the 0.3 mm displacement amplitude. The tracking time increases significantly ($p = 0^+$) with time from 25.7 ± 4.3 s (t_0) to 29.7 ± 4.8 s (t_{10}), after 150 and 300 Hz vibration exposures; however, the differences in tracking time between t_5 and t_0, and t_5 and t_{10} were not significant. Furthermore, at t_{10} the statistical analysis indicates that the tracking time is (1) longer ($p < 0.05$) for the 0.2 than the 0.3 mm displacement amplitude (30.9 s for 0.2 mm, 28.0 s for 0.3 mm) and (2) shorter ($p = 0^+$) for the 90 Hz (27.5 s) than 150 and 300 Hz (30 and 29.4 s respectively) vibration. Finally, after the 90 Hz vibration, tracking time (mean across

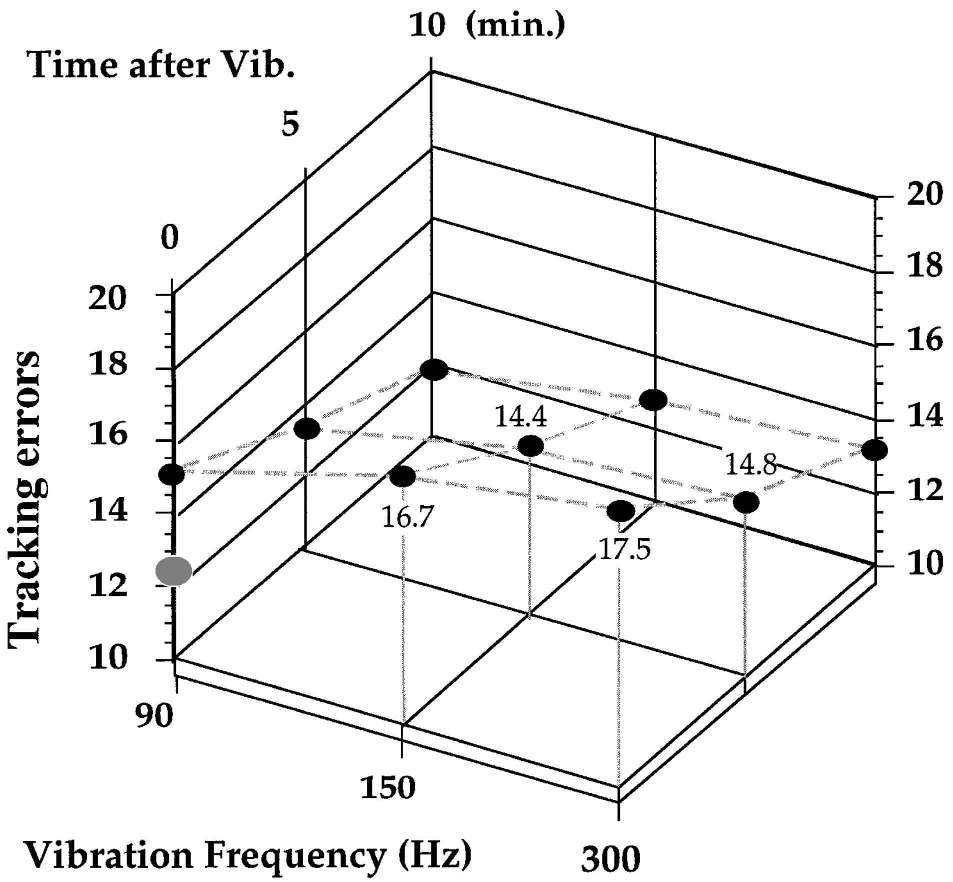

Figure 2. Number of tracking errors as a function of vibration frequency and time after vibration exposure. Tracking precision decreases immediately after vibration exposure (t_0). Ten min after vibration exposure (t_{10}) the number of errors is similar to the pre-vibration level.

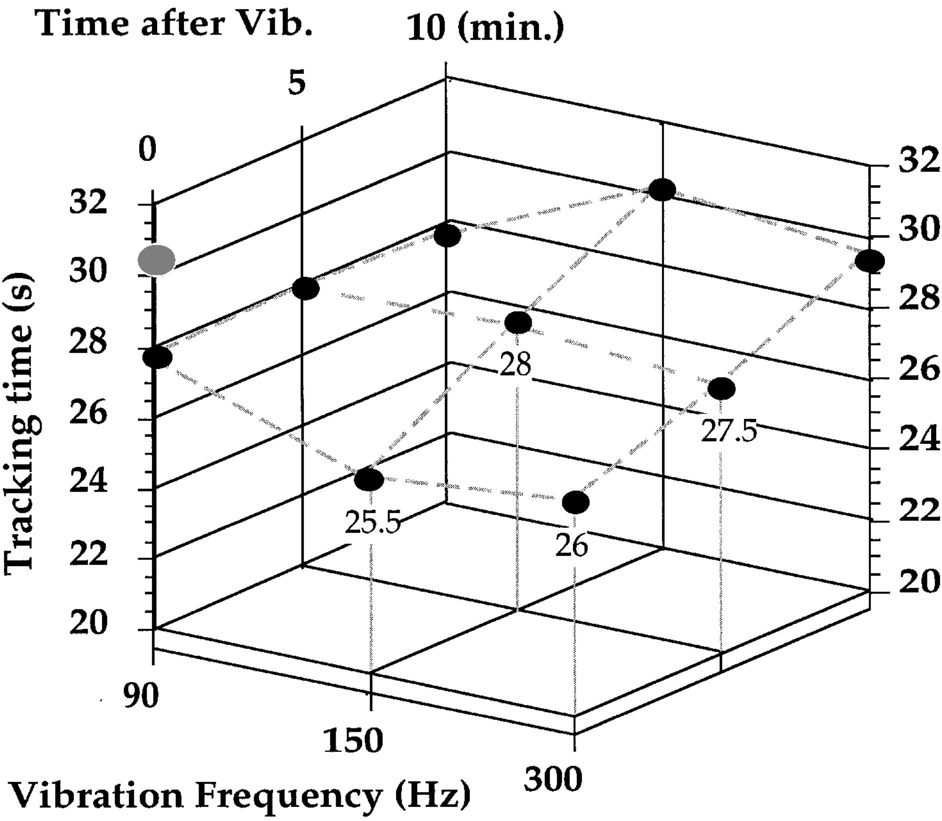

Figure 3. Tracking time as a function of vibration frequency and time after vibration exposure. Tracking time decreases immediately after vibration exposure. This increase in movement velocity is higher for 150 and 300 Hz than for 90 Hz vibration. The recovery of the pre-vibration level is also frequency-dependent.

conditions: 27.6 s) does not vary significantly ($p > 0.1$) with time during the post-vibration period tested. This suggests a recovery period > 10 min for the 90 Hz exposure.

3.3. *Perception of task difficulty*

The results of the ANACOVA performed on the subjective rating indicate that the perception of task difficulty is not directly affected by vibration exposure, despite a tendency ($p = 0.06$) to perceive the task as being more difficult immediately after vibration exposure. The graphs presented in figure 4 indicate that the subjective rating is correlated with tracking time ($r = 0.55$), while a weaker correlation is observed with the number of errors ($r = 0.30$). Furthermore, a multiple regression analysis shows that $SR = -4\ 25 + 0.226\ T_t + 0.076\ E_r$, where SR, T_t and E_r denote respectively subjective rating, tracking time and number of errors. However, this model explained only 37% of the variance. It is worth noting that eight subjects perceived the task to be less difficult immediately after vibration, while two subjects indicated the opposite. These latter showed an increase or no significant decrease in tracking time concomitant to an increase in tracking errors. These results indicate that perception of task difficulty, which increases as tracking time lengthens, is more particularly influenced by task duration than errors.

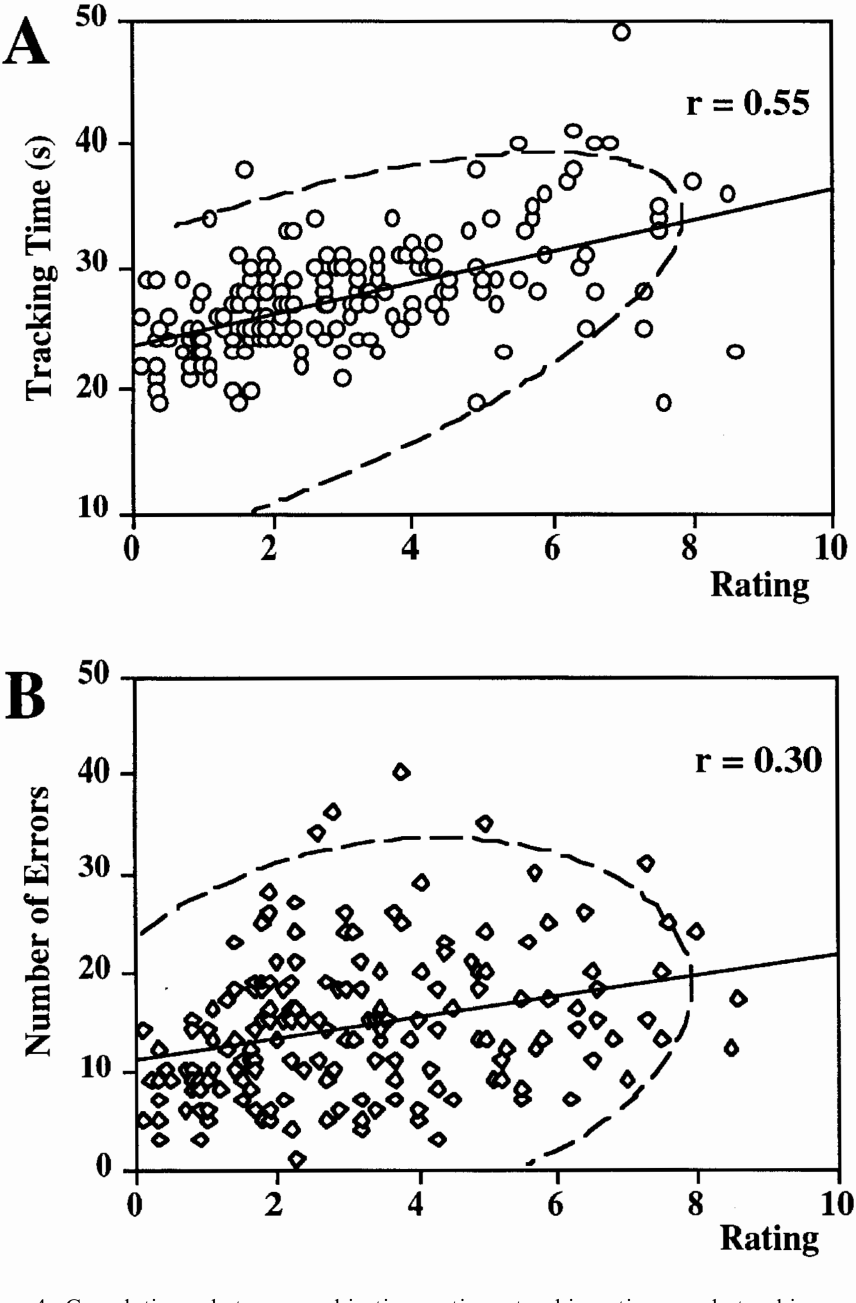

Figure 4. Correlations between subjective rating, tracking time and tracking errors. Perception of task difficulty increases with tracking time (A), while it is much less influenced by the number of errors (B). The dashed lines represent the 95% bivariate normal density ellipses.

4. Discussion

The present study investigated the effects of hand vibration characteristics on a simple visuo-manual tracking task. There were three major findings in this study. First, post-vibration impairment of visuo-manual tracking shows a long, frequency-dependent recovery time. Despite a moderate influence of the 90 Hz vibration on the tracking time, the recovery time for a ‘normal’ performance is longer for the 90 Hz than the 150 and 300 Hz vibration. This finding suggests that recovery is most likely related to the differential sensitivity to vibration frequency of the sensory systems (proprioceptive and tactile) involved in manual control. Second, the decrement in tracking precision appears to be related to an alteration of movement speed control which was significantly influenced by vibration frequency. Third, vibration exposure induced a divergence between the subjective perception of task difficulty and the objective measure of performance. This finding, which agrees with previous results, suggests that vibration-induced alteration of manual precision is not properly perceived, which may represent an additional risk during the manipulation of vibrating hand-tools.

4.1. *Mechanisms of post-vibration effects*

The results presented in figures 2 and 3 show long-lasting post-vibration effects. The graph in figure 4 indicates that the recovery is frequency dependent. Full recovery appears to take place only between 5 and 10 min after vibration exposure for the highest two frequencies (150 and 300 Hz) and may be > 10 min for the 90 Hz vibration. The time lag of the recovery and the influence of vibration frequency can be explained by the differential sensitivity of the sensory systems activated by the vibratory stimulus and the nature of the mechanisms involved in movement control.

Previous studies have shown that the alteration of continuous manual control resulting from vibration exposure can be attributed to the response of the somesthetic receptors to the vibratory stimulus (Gauthier *et al.* 1981, Ribot *et al.* 1986, Martin *et al.* 1991). These responses contribute to the alteration of the functioning of peripheral and central neurosensory mechanisms underlying motor control (Goodwin *et al.* 1972, Martin *et al.* 1984, 1991, Roll and Roll 1987). Primary muscle spindle receptors, known to provide position and velocity information, have a frequency response to vibration limited to ~ 100 Hz (Burke *et al.* 1976, Vedel *et al.* 1985, Roll *et al.* 1989), while tactile receptors, also involved in motor control processes, as discussed below, have a frequency response up to 250 – 300 Hz (Johansson and Vallbo 1983, Roll *et al.* 1989). Thus, effects of proprioceptive origin are more pronounced for frequencies < 100 Hz, while effects of tactile origin could be stronger for higher frequencies.

The very long time course of the recovery period seems to result from changes affecting peripheral and central mechanisms. First, peripheral mechanisms such as temporal depression of the sensitivity of tactile receptors (Lundström and Johansson 1986) and neural mechanisms suggested to include recurrent circuits (Rymer and Hasan 1981) have a short recovery time course (< 2 min) after vibration exposure. Thus, these mechanisms contribute only to immediate post-effects. Second, long lasting (> 5 min) post-vibration involuntary muscle contractions have been related to changes in central mechanisms (Gilhodes *et al.* 1992) triggered by the activity of the spindle receptors of the vibrated muscle. These post-effects are not elicited when symmetric vibrations are applied to antagonistic muscles. In addition, it has been hypothesized that intentional motor activity is subtended by a set of nonlinear oscillators constituting rhythm generators. Craske and Craske (1985, 1986) have suggested that the central structures including these oscillators might generate the so called post-contraction phenomena. Furthermore, tactile sensibility is known to be affected by vibration and the post-effects are related to the frequency, amplitude and duration of vibration exposure (Verillo and Gescheider 1977, Gescheider *et al*. 1979). The recovery time to perception threshold is about 5 min for a 10-min exposure duration, which is longer than the expected recovery time of the receptors themselves (Lundström and Johansson 1986). Overall, these hypotheses do not directly explain the present long duration post-vibration effects; however, they support the existence of central structures in which vibration-induced proprioceptive or tactile inputs, could trigger long-lasting phenomena that contribute to the duration of the post-vibratory effects. These phenomena would delay the recalibration of the sensorimotor systems.

The respective duration of the post-vibratory response of the mechanisms presented above suggest that the long time-course of tracking performance recovery has primarily a proprioceptive origin, which is strongly affected by the 90 Hz vibration. The tactile system may play a significant role in the first 5 min of the post-vibration period. This interaction is mainly acting at the highest two frequencies, for which we observed a slight increase in tracking error and a significant decrease in tracking time.

A significant amplitude effect is observed only 10 min after exposure (amplitude * condition interaction; table 1). This phenomenon may result from a possible saturation of the alterations already present for the lowest amplitude level. A desaturation could occur only after several minutes and allow the emergence of an amplitude effect. This result suggests that post-vibration effects on visuo-manual performance are already important at low vibration levels.

Finally, the contribution to post-vibration effects of mechanisms such as the depression of synaptic transmission (Nielsen and Hultborn 1993) and acute reduction of blood flow in the peripheral vessels (Welsh 1980) cannot be ruled out. However, their respective recovery times are not clearly described.

4.2. *Hand velocity and finger position control after vibration exposure*

Previous investigations have indicated that hand tracking can be performed using a velocity control mode based on prediction after training and acquisition of skills (McRuer and Jex 1967, Martin *et al*. 1991). In the present experiment, the movement trajectory, represented by the wire, is fully predictable. Although hand movement was not monitored in this study, we observed that the tracking strategy evolved from a step-by-step mode (position control) to a smoother and more continuous mode (velocity control) with training. After vibration exposure we observed a 33% increase in the number of tracking errors and a 14% decrease in tracking time. The decrease in tracking time represents a 20% increase in the average velocity of the hand. Hence, after vibration exposure, the considerable increase in movement velocity is likely to play an important role in performance decrement.

It seems counter-intuitive to observe an increase rather than a decrease in speed. One may expect a slow down in movement velocity in an attempt to minimize the influence of the vibration-induced alteration of movement precision. However, despite a required emphasis on precision, the deep alteration of velocity control cannot be compensated as it appears that velocity is not properly perceived by the subjects (see discussion below).

In the context of our experiment, hand movement velocity control seems primarily based on kinesthetic information issued from the hand tracking system. This hypothesis is supported by two set of arguments. First, the extent of the post-vibratory effects indicate that kinesthetic information eventually derived from the visual input is not used for hand velocity control or cannot compensate for the vibration-induced alteration of other sensory modalities cooperating to hand movement control (Gauthier *et al.* 1981, Ribot *et al.* 1986, Martin *et al.* 1991). As indicated above, the functioning of proprioceptive and tactile systems have been corrupted by their response to the vibratory stimulus. Hence, in the present context, visual detection of movement inaccuracy may not be sufficient to help a 'temporarily impaired hand controller'. Second, the effect illustrated in figure 3 shows that changes in tracking velocity are frequency dependent. This effect finds its origin in the differential sensitivity to vibration of the primary muscle spindles known to contribute to limb position and velocity control, and the tactile receptors, as described above. Furthermore, fast adapting tactile receptors, such as Pacinian corpuscles are most sensitive in the high frequency range (>80 Hz). In addition, these receptors are extremely responsive to dynamic events such as the movement of an object held between the fingers (Westling and Johansson 1987). They may provide appropriate trigger signals to change the motor output in specific movement phases (Westling and Johansson 1987) and have a proprioceptive response to finger movements (Hulliger *et al.* 1979). Because of these characteristics, Westling suggested their participation in motor control processes. Therefore, it can be suggested that as vibration frequency increases, the alteration of the muscle proprioceptive system decreases while the alteration of the tactile system increases. These phenomena are responsible for the slight increase in tracking error and the significant decrease in tracking time observed when vibration frequency increases.

As indicated above, the tactile information issued from the receptors located at the finger tips contributes to the control of finger movement and thus, to the control of the orientation of the ring (rotation about the horizontal axis). Hence, changes in tactile information of vibratory origin are not compensated by the visual detection of the position error. The impairment of this position control also contributes to the decrement of the tracking precision.

4.3. *Divergence between motor effects and perception*

Apparently the judgement on the task difficulty is mostly related to the tracking time. Faster trials are perceived as less difficult than slow trials despite the higher probability of a larger number of errors (figures 2 and 3). However, movement speed, per se, does not seem properly perceived after vibration since (1) velocity is not adequately controlled and (2) perception is not significantly differentiated between the experimental conditions. As indicated above, the vibration-induced alteration of sensory information does contribute to changes in the response of peripheral and central sensorimotor mechanisms involved in hand movement speed control. In addition, the kinesthetic information reaching the cortical areas is likely to be misinterpreted by 'decalibrated' central structures. Hence, the estimation of the overall tracking time seems to prevail over the velocity alteration of individual movements, which leads to a performance decrement in term of precision.

This observation is in agreement with previous results. Indeed, It has been shown that alteration of postural stability is not perceived during and after whole-body vibration (Martin *et al.* 1980). The subjects describe their posture as 'perfectly stable' while body sway increases. Furthermore, pain or discomfort induced by electrical stimulation of cutaneous nerves are attenuated by hand vibration (Martin *et al.* 1991), while motor activities usually correlated with pain perception are facilitated. Hence, all these results point at the divergence between perception and performance during or after vibration exposure.

5. Conclusions

Vibration frequency and displacement amplitude have a significant influence on the duration of post-vibratory effects. Recovery is faster for frequencies $\geqslant$150 Hz and the smaller displacement amplitude (0.2 mm). Dissociation between performance and perception of performance may have several consequences in workplaces where vibrating powered hand tools are extensively used. First, decrement in performance will contribute to quality problems. Second, as the alterations of movement control (faster and less precise movements) are not properly perceived, they represent a potential risk of accident since the user is not aware of and not prepared for possible tool control problems. For example, inadequate positioning of a tool may result in an abrupt motion of the tool that can either fall on or being pushed against a body part, or require excessive muscle force to stabilize the tool. In the context of the present experiment, the results show that even visual guidance is not sufficient to compensate for the vibration induced alteration of sensory modalities involved in hand and finger movement control.

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