KTH Engineering Sciences

Difficulties to Read and Write Under Lateral Vibration Exposure

Contextual studies of train passengers' ride comfort

Doctoral thesis

by

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Abstract

Many people use the train both as a daily means of transport as well as a working place to carry out activities such as reading or writing. There are, however, several important factors in this environment that will hamper good performance of such activities. Some of the main sources of disturbance, apart form other train passengers, are noise and vibrations generated from the train itself.

Although there are standards available for evaluation of ride comfort in vehicles none of them consider the effects that vibrations have on particular passengers' activities.

To address these issues, three different studies were conducted to investigate how low frequency lateral vibrations influence the passengers' ability to read and write onboard trains.

The first study was conducted on three types of Inter-Regional trains during normal service and included both a questionnaire survey and vibration measurements. Two proceeding laboratory studies were conducted in a train mock-up where the perceived difficulty of reading and writing was evaluated for different frequencies and amplitudes. To model and clarify how vibrations influence the processes of reading and writing the fundamentals of Human Activity Theory was used as a framework in this thesis.

In the field study about 80% of the passengers were found to be reading at some point during the journey, 25% were writing by hand, and 14% worked with portable computers. The passengers applied a wide range of seated postures for their different activities.

According to the standardised measurements, even the trains running on poor tracks showed acceptable levels of vibration. However, when the passengers performed a short written test, over 60 % reported to be disturbed or affected by vibrations and noise in the train.

In the laboratory studies it was found that the difficulty in reading and writing is strongly influenced by both vibration frequency and acceleration amplitude. The vibration spectra of real trains were found to correspond well to the frequency characteristics of the rated difficulty. It was also observed that moderate levels of difficulty begin at fairly low vibration levels. Contextual parameters like sitting posture and type of activity also showed strong influence on how vibrations cause difficulty.

Keywords:
lateral vibrations, passenger activities, reading, writing, sitting posture, frequency weighting, rated difficulty, field study, laboratory study, transient vibrations, stationary vibrations.

List of publications

Paper I.
Khan, S., M. and Sundström, J.
Effects of vibrations on sedentary activities in passenger trains.
Submitted to: Journal of Low Frequency Noise, Vibration and Active Control, August 2005.

Paper II.
Sundström, J. and Khan, S., M.
Influence of stationary lateral vibrations on train passengers' ability to read and write.
Submitted to: Applied Ergonomics, April 2006.

Paper III.
Sundström, J. and Khan, S., M.
Train passengers' ability to read and write during lateral vibration transients.
13:th International Congress on Sound and Vibration, 2-6 July 2006, Vienna. Austria.

Contents

1 Introduction

1.1 Background

Since the historic day of the *5th* of *June* in 1856 it has been possible to travel or to transport goods by train in Sweden. Due to the growing industrialisation during the last one and a half centuries the need for transports has increased dramatically. Thanks to its capacity to carry heavy loads across the country trains have become one of the most fundamental infrastructural transportation system throughout the decades. In addition, the technical features and designs of passenger trains have gone through a major development over the years. Since the old and fundamental railway technology has been continuously refined and modernised, today, travelling speeds above 300 km/h can be reached on several international railways. Technologies like tilting car bodies and advanced bogie suspensions are commonly used to provide passenger comfort on high-speed trains. However, in many cases passenger trains share tracks with heavy freight traffic, hence rides are often on somewhat deteriorated and imperfect tracks.

Availability, capacity, speed and comfort are some of the reasons why passenger rail transport has become a competitive alternative on intermediate distances, *i.e.* 3-4 hours of travel. Many people choose the train so as to accomplish office work while travelling. Despite the technical developments in recent years, a new set of problems have arisen with the advanced technologies and high travelling speed observing that humans still have roughly the same prerequisites as in 1856. Some trains and lines cause too high levels of vibration and noise to facilitate good working conditions for the passengers. Therefore contractors and operators already demand rail vehicles to be certified in accordance with a number of standardised tests, *e.g.* tests to certify safety as well as good ride quality and comfort onboard.

There is, however, a remarkable difference between the level at which we can perceive vibratory motion and the level at which we actually get disturbed (Mansfield, 2005). Today's standards for assessment of whole body vibration exposure are mainly based on studies of level differences between different vibration signals. These perception-studies of level differences have been made in a laboratory environment where the test subjects were requested to compare different vibrations and judge whether a signal is more intense than another. The most important requirement for such tests is that the participants have to be focused on the intensity of the vibration to make aware judgements (Jones *and* Saunders, 1974). Such focused and aware judgements are, however, very different from the normal state of mind that most train passengers are in when travelling by train. Often, passengers are occupied with different activities like reading, writing or even sleeping (Westberg, 2000). Still, it is with physical intensity judgements as a base that the ride comfort is certified in our trains today (ENV 12299, 1999; ISO 2631-4, 2001; Jones *and* Saunders, 1974).

The reason for the difference between the levels of perception and disturbance of vibrations can be found within the context of travel and the passenger's awareness. In order to handle and explain the influence of vibrations on reading and writing a contextual model with three dimensions has been derived from the fundamentals of Human Activity Theory (Sundström, 2003). The definition of the context that is used in this thesis is based on "the conditions and present situation during which the activity is occurring". To be able to understand the interaction between the working passenger and the used artefacts (*e.g.* paper, pen, body and seat) the properties of the artefact s must be thoroughly studied or known. These properties can, however, only be accessed or become aware to the passenger when the working process brakes down due to a disturbance or interference in the environment.

1.2 Vibrations in trains

Due to irregularities in the track geometry the rails are usually far from smooth and plane. In general there are four kinds of track irregularities, *vertical misalignment*, *lateral misalignment*, *cant irregularity*, and *gauge irregularity* (Andersson *et.al.*, 2005). When the wheels of the train run over these irregularities vibrations are induced in the carbody. The different directions of the irregularities will mainly give rise to carbody vibrations in four axes of direction, *i.e.* (x-) *longitudinal*, (y-) *lateral*, (z-) *vertical*, and (about x) *roll*. Since the wavelength of the irregularity is more or less fixed, higher travelling speeds will cause higher frequency contents in the induced vibration.

The structural dynamics of a passenger railcar usually gives rise to several resonance peaks in the frequency range 0.5 to 20 Hz (Andersson *et.al.*, 2005). The directions of these vibrations are also coupled together which causes a complex dependence of the different motions in the train. The fundamental resonance frequencies are usually derived from the separate structures and suspension characteristics of the rail car, *e.g.* wheel sets, bogie frame, and different structural modes of the car body.

To evaluate this complex blend of vibration directions and frequencies, current ISO- and CEN-Standards have incorporated a variety of filters for frequency weighting of the motion. Each filter represents the human sensitivity to vibration in a specified direction. The measured acceleration signals (in m/s^2 r.m.s.) are then run through the filters and finally integrated to comfort-indexes for a desired track section or time interval.

1.3 Standards and earlier studies

There has been several studies on the different effects that vibrating motions have on humans, ranging from barely perceivable levels, through uncomfortable, and up to hazardous levels as in some off-road vehicles (Griffin, 2003; Mansfield, 2005; Marjanen, 2005). However, the most common type of studies on vibration comfort with seated subjects are actually instrumental vibration measurements of accelerations that are transformed into frequency weighted comfort-indexes (ISO 2631-4, 2001; ENV 12299, 1999), see Figure 1-1.

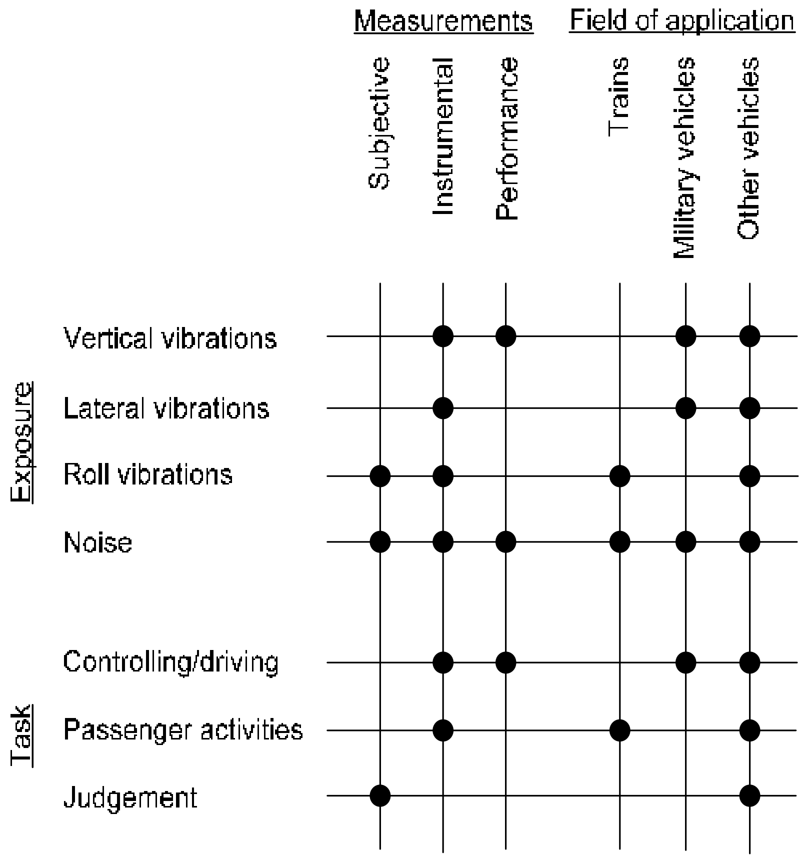

Figure 1-1 Principal schema of the most common applications of human-vibration studies.

Studies on vibration influence on different control tasks have mainly focused on objective assessment of performance of tracking tasks (Lewis *and* Griffin, 1978; McLeod *and* Griffin, 1989). However, only a few studies have been made on activities like reading, writing or drinking (Corbridge *and* Griffin, 1991; Griffin *and* Hayward, 1994; Huddleston, 1964). Performance of reading tasks has been evaluated with measures of reading errors (Griffin *and* Lewis, 1978). In a review by Wollström (2000) a considerable amount of vibration studies were found to have military applications. A large amount of laboratory studies can also be found on seat evaluation tests or field measurements with applications for example; road vehicles, agricultural or forestry machines. Lateral vibrations are, however, seldom given much attention since it is often the vertical vibrations that reach the highest levels in military and off-road vehicles. There are a number of studies on the effects of horizontal (x, y) vibrations (Holmlund *and* Lundström, 1998; Mansfield *and* Lundström, 1999) but none of them have been performed on trains.

Vibration measurements on Swedish trains in normal running conditions are rarely found in the literature. A few vibration studies, however, have been conducted in Great Britain and Japan (Howarth, 2004; Corbridge *et.al.*, 1989; Suzuki *et.al.*, 2000). Train passengers exposure of noise has been studied with the focus on masking different sources of sound (Khan, 2003). General subjective preferences and opinions on the comfort of interior and train travelling has been studied by (Kottenhoff, 1999). Monetary evaluations of disturbances from onboard vibrations has also been studied (Förstberg *et.al.*, 2004).

Lateral vibrations in the low frequency range (0.5 - 20 Hz) have been investigated by few (Corbridge *and* Griffin, 1986), however, only sparsely in railway applications. Suzuki (1998) studied the effect of transient lateral vibrations on the subjective comfort of standing subway travellers. Vibration reports can, however, be found on rail vehicle dynamics and the effect of different design parameters in bogie design, car body suspension, and track alignment (Carlbom, 2000; Kufver, 2000).

Comfort studies on trains have been mainly limited to the range 0.2 to 1.0 Hz to investigate the effects of nausea (motion sickness) in tilting trains (Förstberg, 2000). In recent laboratory studies nauseagenic effects have also been found in frontal and pitch motions (Butler, 2005; Joseph, 2005). Studies in this low-frequency range have normally focused on roll motions and subjective ratings of nausea/illness (Thorslund *and* Persson, 2005). In the 1980s a series of field tests were made on lateral low frequency vibrations (0.1 - 1.0 Hz) influence on comfort, and reading and writing (ORE, 1986). There is one field study by Harborough (1986), who studied train passengers' dissatisfaction during curving. The ride quality has also been studied in terms of thermal comfort by Parsons *and* Griffin (1993).

The sound environent is also a crucial factor when designing trains since the structural vibrations usually give rise to noise both inside and outside the train. Howarth *and* Griffin (1990) found complex cross-modal effects for noise and vibrations in buildings nearby railways.

In a review by Wollström (2000) it was concluded that earlier studies on reading ability were not conducted under conditions that made them so relevant for railway applications. For writing conditions, only two railway-relevant studies were found (Corbridge *and* Griffin, 1991; Griffin *and* Hayward, 1994). In a study by Westberg (2000) it was concluded that the frequency weighting stated in the international standard for assessment of whole body vibration was somewhat different from when activities like reading and writing were performed under vibration exposure. This discrepancy in frequency dependence indicates that the frequencies that are most harmful for reading and writing will be underestimated by the present standards. Westberg (2000) also showed that reading and writing are two of the most common activities among train passengers on intermediate to long travels within Sweden.

1.4 Aims and scope of the thesis

There is clearly a lack of knowledge on how train passengers activities are influenced by vibrations (both stationary and transient). Specifically the effect of lateral vibrations have been neglected for a long time. Thus, the objective of this thesis is to investigate how the ability to read and write while travelling is influenced by low frequency vibrations in the lateral direction, see Figure 1-2.

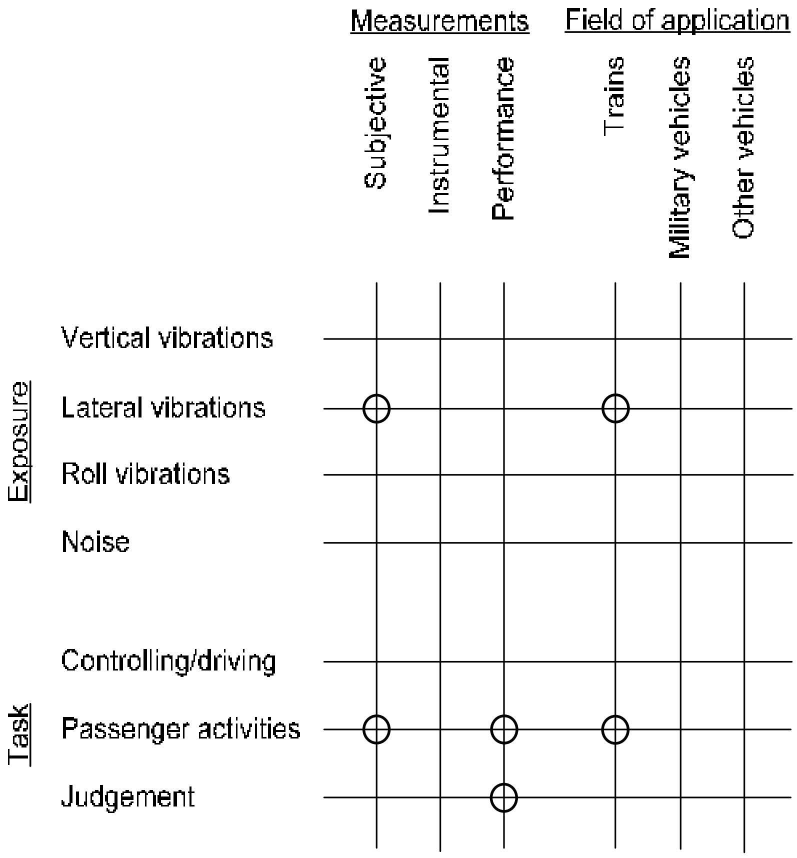

Figure 1-2 Illustration of the principal applications of this thesis

This thesis is based on three different studies. The first study was conducted in trains during normal service and comprised of both a questionnaire survey and vibration measurements. The second and third studies were both conducted in a train mock-up where the difficulty to read and write was evaluated for various vibration frequencies and amplitudes.

The thesis will not investigate physiological vibration effects like motion sickness/nausea and musculoskeletal discomfort. Nor will any effects of sub-threshold exposures from vibration or noise be treated here. Cross-modal effects of noise and vibrations will also not be studied.
To avoid any elaborate discussions on the concept of *comfort* the term is used throughout this thesis as:

"The subjective state of well-being. The comfort experience is influenced by physical factors (dynamic, ambient and spatial), as well as social and situational factors." (cf. Alm, 1989).

1.5 Thesis contributions

This thesis has approached the implication of vibrations in rail vehicles from a Human-Factors point of view. By utilising a multi-disciplinary approach a more complete set of aspects of passengers' activities has been put forward.

This thesis is believed to give contributions by its original research in the following aspects:

- By using the fundamental terminology of Human Activity Theory it has become possible to clarify the dependence of context for the studied activities reading and writing.

- Through the combination of adapted methods in laboratory- and field studies.

- Presented principal frequency weigthing curves for two common activities.

- The field study has given contributions in the form of Swedish vibration data for passenger trains. Measurements were made at additional points on tables and armrests. Passengers activities, seated postures and disturbances were also surveyed.

- In the first laboratory study the effect of stationary lateral vibrations were studied. The etiology of the participants was studied in form of athropometry age and gender. Perceived task difficulty for reading and writing was studied for two different sitting postures.

- In the second laboratory study the effects of lateral vibrations transients were studied. The anthropometry of the participants were controlled/delimited. Perceived task difficulty was measured with a rating scale (Borg CR-100) for reading. An additional test of the principal threshold was made for reading disturbance.

2 Human activity and posture in context

Reading and writing are two of the most essential skills that we learn in school. By mastering these two skills we can communicate and share information, which is something that most people do several times a day. For some people, reading and writing are the main working activities, and being able to perform them well is taken for granted in many situations. Writing reports, letters and e-mails; reading road signs, instructions, memos, journals and newspapers are just some examples of such situations. Since both reading and writing are acquired abilities they continuously have to be practiced and nurtured to be maintained (Erikssson-Gustavsson, 1998). Reading is a typically activity as we are waiting at the bus stop, for example, we read signs, timetables advertisements, papers or magazines. But for several, mainly obvious reasons, essays are seldom written at the bus-stop or in the subway.

Reading can be managed more or less independently of body position, whereas writing demands a supporting surface to hold the writing material. In environments where whole-body vibration exposure is common the seated posture is by far the most common body position. Generally a seated posture is applied to increase the stability and thereby the possibility to perform tasks that demand high precision. There is good agreement that whole-body vibrations below 20 Hz will decrease performance due to the transmission of vibrations, especially to the head but also to the limbs, according to Lewis *and* Griffin (1978). The strongest influence on performance occurs when the direction of motion coincides with the sensitive direction associated with of the system to be controlled. Several researchers have concluded that these control-effects are due to a combination of involuntary hand movements and impaired visual acuity due to the vibrations (cf. Lewis *and* Griffin, 1978) In some environments we do not even attempt reading or writing, since the working process is severely hampered or influenced by interruptions from noisy passengers and excessive vibrations.

To understand the ability of reading and writing in the presence of vibrations, the actual working processes requires a detailed study. This section is concerned with the fundamental knowledge and theories behind activities like reading and writing and the influence of vibrations on the performance. The aim of this section is to give an outline of the fashion in which vibrations can cause disturbance in the operation of reading and writing. To enlighten the importance of context and awareness of the working processes the principles and terminology of Human Activity Theory will be used as a theoretical framework in this thesis.

2.1 Human activity theory

We perform several different activities in our ordinary daily lives and the principles behind most activities can be successfully outlined by Human Activity Theory (A-T). Several authors have used and described the most fundamental aspects of Activity Theory (Bødker, 1989, 1990, 1996; Hydén, 1981; Karlsson, 1996).

This section presents the theory as it is interpreted and used in previous work (Sundström, 2003). Here the theory serves as a framework for understanding, and a basis for explaining and discussing the process of reading and writing under vibration exposure.

2.1.1 Fundamental activity theory

In Activity Theory, the term "activity" is defined as a human process directed towards an object. In Figure 2-1, the term *object/goal* describes the motive, goal, problem or person that the activity is directed towards (*e.g.* to have a clean and shiny car). The *subject* describes who is performing the activity (*e.g.* the owner, driver, passenger, or the researcher) and the *mediator* is the tool or artefact with which the activity is performed (*e.g.* water, shampoo and sponge).

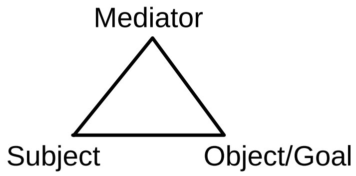

Figure 2-1 The three terms describing human activity (Sundström, 2003)

The vast number of *situations* in real life creates a web of activities with a number of goals or objectives (Bødker, 1996). It is usual to find that what is the objective for one individual (subject) is just a mediator or tool for another individual within the same activity web. For instance, a train or traffic operator needs a driver and a train as *mediators* to transport goods or people from A to B, *i.e.* the operator’s object or goal. Meanwhile, the driver is the *subject* in the action of driving, where the train and the railway are *mediators* for the *objective* of taking the train from A to B in time. This means that the two different subjects, *i.e.* the operator and the driver, both incorporate the train in their activity but in different activity systems. This difference of use between the activity systems of two different subjects can easily cause conflicts due to differences in demands on the mediator. The driver might, for instance, suffer from low-back pain due to long and static work periods in ill-fitted seats, whereas, the operator might claim not to afford a more expensive and appropriate seat in order to cut the costs.

The three level hierarchical structure of the activity in Figure 2-2 represents different structural sets into which human activity can be organised or described.

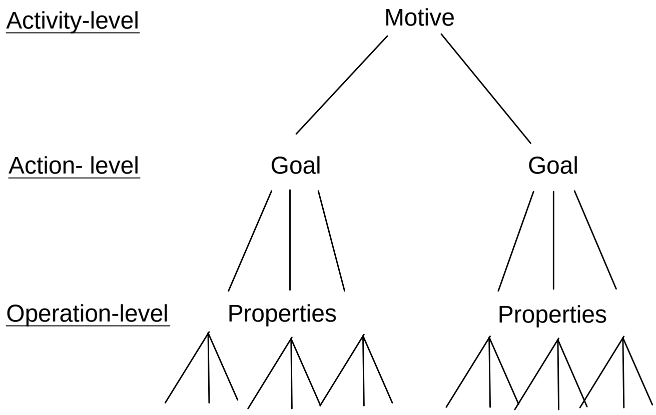

Figure 2-2 The hierarchical activity structure (Sundström, 2003)

Activity level

At the *activity level,* the activity is described in general terms (*e.g.* build a house, or wash my car). An activity is ruled by a generally described motive (*e.g.* my car lasts longer if it is clean). This motive can be both aware and unaware to the subject in question. The activity can be performed by a collective of individuals or by a single individual (*e.g.* building a house can be performed by a construction worker at a huge building site, or by the solo hobby carpenter).

Action level

At the *action level*, several different actions form an activity (*e.g.* washing a car typically involves a series of actions such as rinsing, shampooing, drying and waxing). Actions can be alternative, sequential, or even parallel but they are all ruled by mentally aware goals (*e.g.* rinse to remove gross particles from spoilers and chassis of the car). The action is performed by an individual or by a user of a mediator/tool.

Operational level

At the *operational level,* several sequential, parallel or alternative operations form an action. A specific operation can occur within several different actions (*e.g.* rinsing can occur both within the action of removing dirt or in removing shampoo from the car). The distinction between the operational and the other levels is that operations are determined by the properties of the object (*i.e.* the interaction between subject-mediator and the object). Note that the individual/user is always mentally unaware of this interaction. This also means that the mediator, the tool, is not something that the user consciously reflects upon (*i.e.* the hammerer becomes "one" with the hammer) (cf. Heidegger 1992, Karlsson 1996).

Transformation between levels

Within the three-level hierarchy, as shown in Figure 2-2, transformations between levels occur. What used to be an activity may become an action and what used to be an action can suddenly become an *operation*. As we learn and develop a new skill, the changes between the operational and action levels are very frequent until the *action* is fully *operationalised* through learning and experience. The changes from operation to action, on the other hand, are usually triggered by a *breakdown* or a *focus shift, e.g.* when a scratch in the paint is found while the sponge is rubbed over the car, or when the sponge needs more shampoo.

At the operational level, where "things actually happen", the performance can be disturbed or interrupted due to poor *transparency* of the artefact. The transparency tells us how well the mediator lets the subject interact with the properties of the object. A mediator with poor transparency easily causes the operation to break down, *i.e.* the operation becomes an action. Changing the level also means changing the object of the action. In this change, the mediating tool can become present and something which we consciously reflect upon. The term breakdown is borrowed from Heidegger (1992). In Heidegger's terms, the driver uses the throttle to set the speed of the train but, to the person doing the throttling, the throttle does not exist as an object. It belongs to the background of '*readiness-to-hand*' and is taken for granted without explicit recognition or identification as an object. The throttle is part of the throttler’s world but is not present any more than are the tendons of the throttler's arm. The throttle itself exists as a throttle only when it is not doing the work, or is not there, then it becomes *'present-at-hand'*. This process of change, from '*readiness-to-hand*' to *'present-at-hand'*, is referred to as a *breakdown*. The emergence of the throttle exists if the throttle breaks or if there is a changed speed limit to be taken and the throttle does not respond as intended.

A *focus shift* is when the subject self causes a change of activity level either of his/her own will or due to the nature of the activity itself, *i.e.* regardless of the mediator or the object. These *breakdowns* and *focus shifts* are normal events occurring in all kinds of activities and situations, usually to the extent that we tend not to reflect on them.

2.2 Activity Theory and train passengers' activities

In previous research it has been shown that the fundamentals of human activity theory could be successfully applied to study how truck drivers' sit during driving (Sundström, 2003). In analysis of video films taken in the driver cabin, activities on operational level could be identified and a majority of the postural changes could be explained by typical activities of truck drivers while driving (Sundström, 2003). As mentioned in the previous section, train passengers occupy themselves with a variety of activities during travel. Usually the passengers also have aware goals of their activities, *e.g.* to read or write a memo for a business meeting or just make time fly by reading a novel. When it comes to assessing the vibrations in a train running at full travel speed, traditional standards like (ISO2631-4, 2001) and (EN12299, 1999) do not consider the passengers activities. As mentioned, these standards are based on focused subjective judgement of the intensity of vibrations. While comparing the activities and goals of the working passenger and the focused test subject in Figure 2-3 the differences become clear.

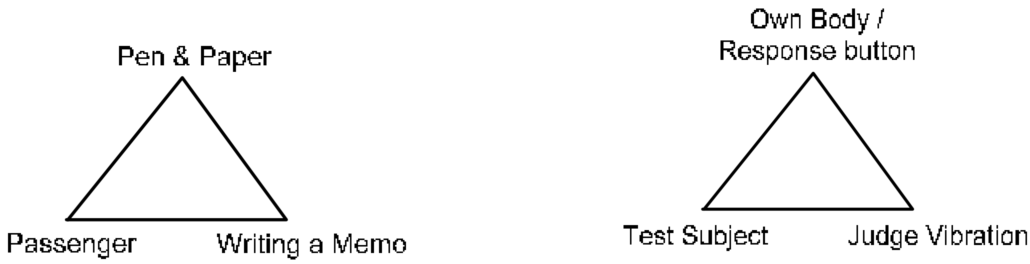

Figure 2-3 Comparison of a working and an assessment situation

Even if both situations occur under the same vibration exposure, each has different artefacts and goals giving the passenger and the test subject different prerequisites for assessing vibrations. As the awareness of a test subject is focused on the goal to judge the intensity of the vibrations, similarly the passenger's awareness is focused on the goal to produce a written memo, for instance.

By applying the terminology and fundamental theories of human activity to the issue of sitting in the context of reading and writing in trains, a few assumptions can be made. One of the most basic assumptions is that the sitting process is automated, *i.e.* operational and thereby unaware to the passenger (Sundström, 2003). Among several factors, it is the performance of the work that makes the passenger unaware of the process of sitting. Another reason for this unawareness is the nervous system's ability to adapt to steady temperature and pressure, when distributed over the body (Atkinson *et.al.*, 1990). Under normal circumstances the neural signals from receptors in muscles and skin (the somato-sensory area) never reach our consciousness. So, these processes will remain unaware unless factors like noise and vibration exposure exceed the limit of perception. The sitting (the seated posture) should, thus, primarily be regarded as means to facilitate a certain task. Just as different artefacts, such as the paper, pen, and table can be regarded as means or tools for writing, the posture is used by the passenger to reach and provide a proper body alignment for reading and writing. The human body is, thus, one of our tools/mediators in the action of reading or writing. This tool is, however, alive, active, and to some extent autonomous, since it is constructed for mobility and variation.

To gain deeper understanding of the process of reading and writing, the principles from earlier work is utilised in this thesis (Sundström (2003). Whether the reading or writing is considered to be actions or operations does not matter, because the seat and table themselves are not "active" mediators in the working process (*i.e.* they are passive, but fundamental like the gravity of earth). Instead, the interaction with, or the use of, the seat and table as mediators should be seen as parallel activities to the activity of reading or writing. This implies that the seat and table are used in direct association with other mediators that are more "active" in the actual working. Thus, the seat, table and working tools have to be regarded as an artefact system, which is used in different contexts. In order to obtain relevant information about the passenger-work interaction within this system, the context of use has to be considered and taken into consideration throughout the investigation.

According to Karlsson (1996), we need to study how artefacts mediate use in order to understand them. Studying the passenger-work interaction in the context of a vibrating train journey, the assumption of reading or writing as an operationalised action can be shown in a detailed example, given in Table 2-1.

Table 2-1 A detailed example of working during train travelling, table modified from Karlsson (1996)

Goal/ Consequence	**Activity**	**User**	**Artefact**	**Environment**
Motive: Satisfy customer needs (objective) / earn wages (subjective)	Activity: Transporting employee and work	Drivers/operators /employer	Technical system	Global environment: System of railways
Goal: Correct time and place of delivery	Action: Working on the train	Passenger/ employee	Artefact: Pen, paper, text, computer, table, seat	Local environment: The rail/track, the traffic situation
Fits/Misfits: Poor interaction, passenger unable to read/write	Operation: Reading/writing	Passenger's anthropometry, muscles, brain etc.	Properties of the artefact: Hard seat/ small text/ sharp pen, table & seat heights	Properties of the environment: Uneven track, noisy passengers, WBV

Zooming in on the passenger's interaction with the artefacts for reading/writing we must incorporate the conditions under which the working takes place, since the artefact can not be studied in isolation, see Figure 2-4.

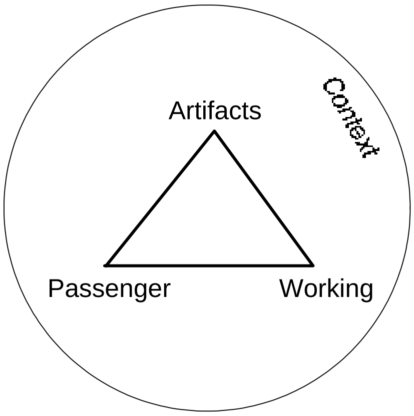

Figure 2-4 Cf. Archer in Karlsson (1996)

The continuous process of reading or writing onboard a train is affected by a large number of conditions, *e.g.* track standard, train suspension, vibration properties of seats and tables, type of work, reading or writing skills and interference from other passengers. One of the greatest endeavours is, thus, to handle the contextual influence from all these conditions. From Karlsson (1996) it's possible to treat all these conditions in the environment-dimension, see Table 2-1. Out of the five dimensions in her proposed framework, it is in the *environment* column that actions and operations take place.

In a previous work Sundström (2003), three out of the five dimensions in Table 2-1 were extracted to handle and explain the various contexts of truck driving. In this thesis however, the same three dimensions are used to outline the different contexts of reading and writing onboard trains:

1. The action of reading or writing
   goals: gain/spread information, obtain comprehension, and produce legible text
2. The artefacts
   pen, paper, text, computer, seat, table, own body
3. The environment
   train compartment, temperature, illumination, other passengers, noise and vibrations

These three contextual dimensions provide a more delimited and comprehensive view of train passengers' activities. In subsequent sections the interactions between the three dimensions are explained more in detail. In order to describe and explain the properties of train passengers' reading and writing abilities the fundamental knowledge about the involved processes have to be investigated and the role of the seated posture has to be identified.

2.3 Vision and reading

According to Griffin and Lewis (1978), good vision is:

> *'... to see sharp images and judge the location of objects in space.'* pp. 384

The visual acuity is thus the most fundamental aspect of good vision. Under static conditions, the visual acuity is created by three entities of the eye, *i.e.* the cornea, the lens and the receptors of the fovea. The lens acts to project the image of an object on the receptors of the fovea (cones), see Figure 2-5. The fovea is the centre of the eye fixation system and has only a small region of 1° that can perceive details (Kroemer *and* Grandjean, 2000). When the observer or the viewed object is moving, the eye has to engage movements to compensate for the moving image on the retina.

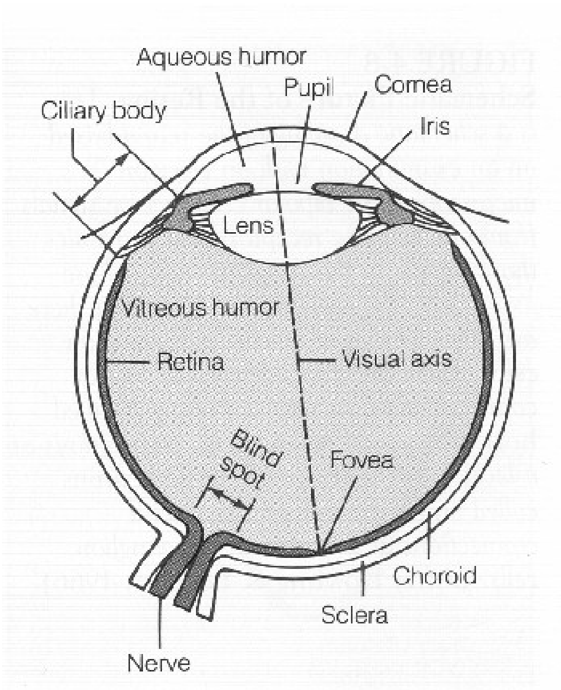

Figure 2-5 The anatomy of the eye (Atkinson, 1990)

2.3.1 Eye movements

The eye has six external muscles that can direct the eye towards the point of interest. These muscles jointly give the eye three different abilities to create a sharp image of a moving object, *i.e.* holding the object *fixated* on the fovea; following the moving object; and to compensate for the unsteady image of the moving object.

A f*ixation* occurs when an object is focused on the fovea of the eye, typically for 150-600 ms (Duchowski, 2003). There are three types of small non-voluntary fixation movements of the eye: *microsaccades*, *tremor*, and *drift*. *Microsaccades* are fast, step-like, random changes of eye position that lasts ~25 ms. With an amplitude of 0.1° they help to maintain the image fixated on the fovea. *Tremors* are very small and high frequent oscillations at 30-80 Hz that occur during a fixation. *Drift* is a continuous, slow, arc shaped movement of the eye. All of these non-voluntary movements help to avoid the light receptors of the fovea to be tranquilized by the image.

Larger movements of the eye can either be in form of reflexes or in form of *saccades* that are both voluntarily or involuntary. The voluntary movements are used to enable the eye to *fixate* on a target/object that is of aware interest. *Saccades* are capable to move the eye from a start- to a target-coordinate with a duration of 10-100 ms. Once the *saccade* has started it can not change target since the individual is virtually blind during the motion. The motion can be very fast (800 °/s) and have either a straight, curved or even sawtooth trajectory. The control of the saccades is approximate to a zero-order (position) control system (Wickens, 1992). This implies that the *saccadic* motion is compensatory and directly proportional to the discrepancy between the fixated point and the target object. Head motions are employed when saccades need to be greater than 30°.

An object can also be followed by the eye in form of involuntary smooth *Pursuit* motions. This reflex only manages to maintain a target of constant speed fixed on the fovea, and is activated when an object is moving on the retina (Wickens, 1992). The actual motion is performed as *microsaccades* that give the trajectory a small step-wise appearance. The *pursuit* motion has a latency of 120 ms for initiation or speed change. The *saccadic* and *pursuit* motions act both independently of each other and in parallel. Just like the saccades, the *pursuit* motion is limited to 30° while the head is still.

There are also two basic unaware reflexes, *vestibular-ocular* and *opto-kinetic,* that enable a clear and stable image in the retina even though the viewed object or the observer is moving. The *Opto-Kinetic Reflex* (OKR) is engaged when the retinal image is moving across the fovea and is based on the retinal information for control. The OKR is a slow reflex that is very efficient below 0.1 Hz but less effective at frequencies above 1 Hz.

The *Vestibular Ocular-Reflex* (VOR) is the main image stabilizing reflex. It is employed when the head moves in any direction and keeps a static object fixated. VOR is a fast reflex with poor compensation at low frequencies (0.05 Hz). The semi circular canals are the major signal source for the reflex which gives a good compensation between 1 and 7 Hz.

2.3.2 The reading process

The knowledge and definition of the reading process in detail is still under debate and research. Adams (1994) impose a model with four sub-processes, in Figure 2-6. A number of researchers have, however, identified the two most prominent sub-processes of reading as; *decoding* and *comprehension* (Eriksson-Gustavsson, 1998), seen as dashed grey lines in Figure 2-6.

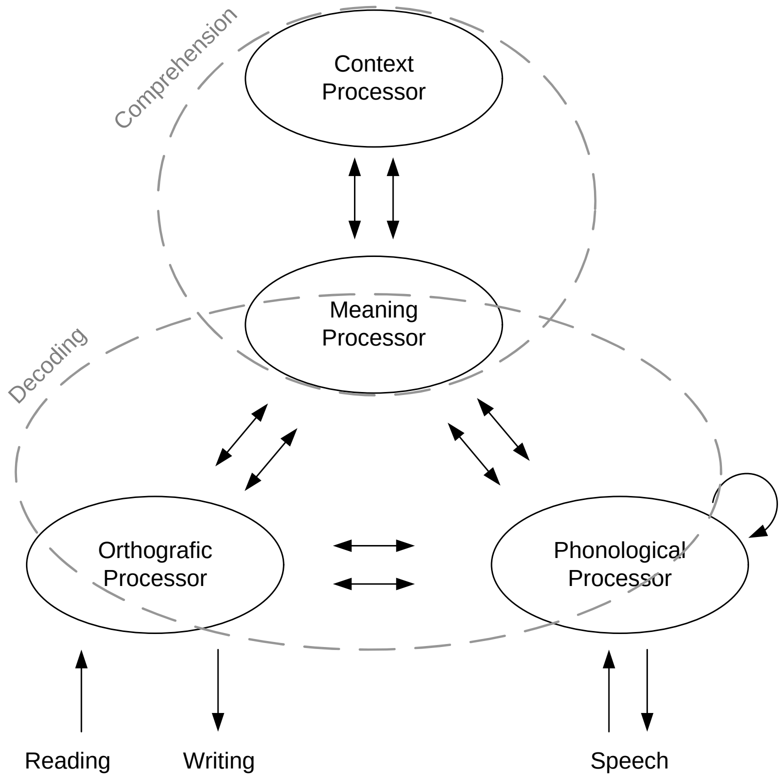

Figure 2-6 The sub processes of reading modified from Adams (1994)

Decoding is regarded as the fundamental and primary process of reading (Eriksson-Gustavsson, 1998; Johansson, 1999). Without successful decoding of the separate letters or words of text there is no possibility to understand or comprehend the contents of the text. Decoding itself is the share perception, analysis and identification of the graphical features that constitutes a letter or a word (Wickens, 1992). According to Adams (1994), decoding is a part of the orthographic process that in turn couples the words with the phonetics of speech and the representation of meaning. In this manner, both decoding and phonetic analysis are affected by the reader's vocabulary, strategic ability and knowledge of the world (cf. Lundberg, 1984). When decoding has become an automatic skill it can free mental resources for the process of comprehension.

Comprehension is the part of the reading process when meaning and understanding of the text is created. Comprehension is an active and creative cognitive process in the interaction between text and reader. During the comprehension the reader infers and couples the contents of the text with conditions in real life and broadens the message of the text. In this part of the reading process intelligence and general cognitive abilities are required for successful understanding of the written words. The context has a major influence in supporting the comprehension since it provides a strategic base for the reading (Eriksson-Gustafsson, 1998).

Eye movements during reading

The eye typically performs three different types of saccades during reading, *rightward reading saccades*, *correction saccades* and *leftward line saccades*. Rightward reading saccades last 30 ms and cover 4 - 12 letters in each jump along the text line. The *correction saccades* are occasional small leftward saccades, whereas the *leftward line saccades* occur just before the end of each line and move the gaze down to the next line, 120 ms (cf. Duboi-Poulsen, 1967).

During normal reading the eye typically makes four fixations per second, (Kroemer *and* Grandjean, 2000). Experienced readers do not fixate one word and then neatly jump to the next. Short words are often skipped and longer words are typically fixated more than once (Sereno, 1992). It is well established that readers look longer at *low-frequency words*[1] than on *high-frequency words*[2] (Morris, 1992). For words that are highly predictable due to the context of the text, fixations are shorter. Accordingly, difficult texts do give longer fixation durations and shorter saccade length.

2.4 Manual control and hand writing

The complete process of writing is somewhat more complex than reading. Writing consists of cognitive and manual processes that demand feedback and continuously shifts between different aware and unaware phases. (Moreti *et. al.*, 2003). The whole progress of writing also demands more of our cognitive abilities than reading. When writing essays or creating stories, three main cognitive processes are employed in order to form a readable text, *i.e.* planning, translating and reviewing (Hayes *and* Flower, 1980). This section will, however, only address the principle aspects of the manual control in hand writing.

2.4.1 Hand-arm movements

The human hand-arm system is a complex biomechanical system with a redundant number of muscles and sensors for accurate control (Hepp-Reymond *et. al.*, 1996). The hand and wrist consists of some 27 bones and 39 muscles to move the wrist and fingers. Through this complexity the hand-arm system becomes 'over-specified', providing a large variability and adaptation but also demands an extraordinary control system. During a pencil tracing task Hyldgaard (2000) identified nine different movements of the fingers, hand, and arm.

To describe the skill of manual performance two different views are typically used, *i.e. open-loop* and *closed-loop* (Wickens, 1992). These views are borrowed from fundamental control theory and define the effectiveness and need for feedback. The *closed-loop* system is controlled by a difference, or error, between the target and the actual position. This error is continuously looped back as feedback for the process to act upon. The *open-loop* is, on the contrary, not depending on feedback from the process, but rather based on anticipation (feed-forward) of where the target will be positioned in the near future.

The spatial accuracy of hand movements shows a non-linear dependence of speed. Hyldgaard (2000) conducted experiments with a pencil-tracing task and found that the relation between speed and accuracy was exponential. These findings correspond well to accuracy as described by *Fitts's law*. Fitts's law describes the trade-off between the time to reach a target area and the accuracy in positioning (Wickens, 1992).

[1] L*ow-frequency words* are words that are rarely used in the written language
[2] *High-frequency words* are words that are frequently used in the written language

Wickens (1992) concluded that the two general characteristics of a well-learned motor skill are that; *1)* they are mainly performed as open-loop processes, but; *2)* they can very well benefit from feedback from muscles and joints. These *open-loop* skills can only be created by intensive practice and when they are established they demand very low attention to perform. So, to execute the response only a single cognitive selection/initiation is required to create a consistent outcome, *e.g.* like writing a signature.

2.4.2 The writing process

The physical act of handwriting is, thus, an ability that we learn and develop to a skilled level. As we learn to write the control of the pen becomes gradually autonomous until the performance develops to unaware *proprioceptive muscle operations* (neuro muscular control loops). These muscle operations, often called *motor schema*, are verified through feedback of muscle spindle receptors in the hand-arm complex (Griffin and Lewis, 1978, II) and sometimes through visual feedback. The motor schema is however not a schema that controls the muscle in an exact pattern, but rather a motion-programme that guides the movements of a centrally stored 'template' (Wickens, 1992). Since the schemas are not coded as position-patterns, the outcome is reproducible under different occasions and prerequisites.

2.5 Importance of the seated posture

Reading and writing typically requires a stable and relaxed sitting posture, in order to obtain a comfortable and efficient working process. In a vibrating environment, the posture becomes even more important in suppressing and compensating the motions to limit their effect on the performance of the work. The posture has, thus, a vital role in transmitting vibrations to the different body segments, as well as to the working material.

The direction of the vibrating motion is defined by an orthogonal co-ordinate system in the standard ISO 2631-1. The common terms for the translational directions are: *frontal* (x-axis) back to front, *lateral* (y-axis) right to left, and *vertical* (z-axis) foot to head. Exposures of whole-body vibrations are most common to humans in seated postures. The movements can occur in any axis of direction and the responses and effects display large individual variation (Mansfield, 2005). As previously mentioned, most studies on seated postures and vibration have been conducted in the vertical direction, usually with an upright posture on a rigid seat without backrest, but sometimes with slightly inclined backrest and even with a harness.

Whole-body vibrations are usually defined by its most sensitive range 1 - 20 Hz (Mansfield, 2005). Largely due to the resonance phenomena in the human body, vertical motions are most easily perceived at 5 Hz, whereas horizontal motions are most easily detected below 2 Hz. Horizontal vibration frequencies below 1 Hz will cause the body to sway, and in the range 1 - 3 Hz it becomes difficult to stabilize the upper parts of the body (Griffin, 2003). As the frequency increases, the lateral vibrations are less well transmitted to the upper body, and above 10 Hz the vibrations are mostly felt near the contact point with the seat.

Seating conditions can interact considerably with the effects of vibration on reading performance. Lewis *and* Griffin (1980) studied the effects of vibrations on reading performance for two different seating conditions: leaning back in a helicopter seat and upright on a flat seat. They concluded that vibrations in the lateral (y-axis) only give little motion transmitted to the head. However, their results indicated that it is possible to predict the relationship between seat motion and decrements in reading performance. Rotational head motions could be used as a performance measurement, provided that the vibration transmissibility from seat to head is known. Kitazaki *and* Griffin (1997) used a rigid seat without backrest and three postures under vertical vibrations. To some degree, the effect of the body posture could be explained by changes in the body-seat interface, but effects on the forces in the spine are also likely to be affected by the posture. In a reaching task Kerr *and* Eng (2002) investigated the postural stability and displacement of the centre of pressure under the buttocks. Both the direction of movement and the degree of foot support were found to affect the postural stability.

It is important to note that the influence from the seat properties should not be neglected. The seat itself can greatly increase or decrease the motion depending on the frequency content of the vibration. According to Griffin (2003) the backrest can help to reduce the instability at low frequencies. On the contrary, the backrest can cause vibrations to transmit to the upperbody at high frequencies. Below 1 - 2 Hz the dynamics of the seat only have little influence in the vertical direction. However, in the region of 4 Hz the seat resonance greatly amplifies the vibrations. The frequencies above 10 Hz are attenuated in most seats. When it comes to the influence of armrest very few studies are available.

Lundström *et. al.* (1998) studied vertical energy absorption while seated in two different postures on a rigid seat without backrest. The study concluded that the posture has a pronounced effect on vibration transmissibility in the body. For both the erect and relaxed upper body, the absorbed power was found to be proportional to the square of the acceleration. A relaxed posture will, however, result in a softening of the biomechanical system, which reduces the resonance frequency of the body. As the muscles relax the body-stiffness reduces and the damping increases. It was found further that females absorb a lager amount of power than males, which may be due to differences in body constitution.

How will the vibrations and the posture interact with the processes of reading and writing? Since vibrations are a part of the context they can act in connection to any of the contextual dimensions previously described. It is therefore interesting to study the interactions between the separate contextual dimensions. If we are involved in an action on operational level the effects of vibrations can be regarded as fits or misfits in the interaction according to Karlsson (1996).

2.6 Misfits due to vibrations

It is not easy to understand what happens in the mind of the writer or reader when a shift in focus occurs. According to A-T, a *breakdown* will cause a shift in mental focus. This shift may cause the person to look up and wonder what is happening. But if the focus shift is caused by a *breakdown* in the operation, it most likely causes the person to become aware of the more detailed goals of the operation. As previously stated, we are unaware of the detailed goals or the control of the hand when we form a specific letter under normal and automatic handwriting. When this operation is shifted into aware actions we actually return to the same struggle we once had at the early stages of learning to write, as shown in Figure 2-7.

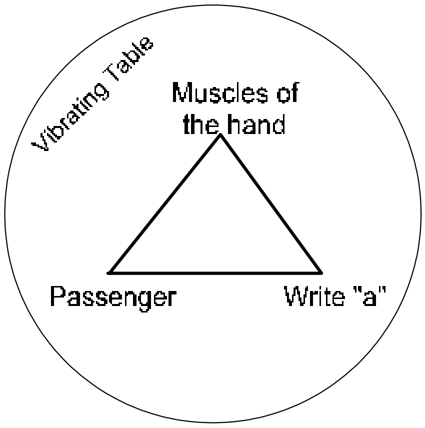

Figure 2-7 When writing has become an aware action

Misfits are common in most everyday interactions. Even though we are accustomed to most of the frequent misfits they will affect the performance of an operation and even increase the difficulty of the action.

2.6.1 Interactions during reading

A misfit or breakdown in the reading process can be caused by many factors, *e.g.* misspelled words, poor grammar, physiological body reactions (sneeze, cough, tiredness), but also from the environment in form of disturbing passengers, poor illumination, draught, as well as noise and vibration in the railway car. The major interest of this thesis is the breakdowns caused by vibrations. The properties or *transparency* of the reading process can be described in terms such as visual acuity, word decoding and comprehension, but it is the interactions between the contextual dimensions in Figure 2-8 that reveals where there are misfits in the process. To avoid deep discussions regarding the cognitive process of comprehension only visual acuity and word decoding will be discussed here.

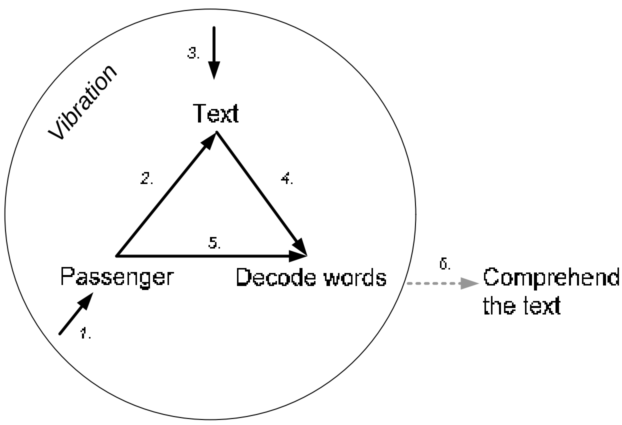

Figure 2-8 Interactions while reading under vibration exposure

From Figure 2-8 six different interactions can be identified. These interactions will help in revealing where the interesting breakdowns occur during vibration exposure.

1. The passenger is exposed to whole-body vibrations through supporting surfaces (*e.g.* seat)
2. The passenger causes the text to vibrate (*e.g.* hands, arms, and knees)
3. The text itself is vibrating through supporting surfaces (*e.g.* table)
4. The vibrating text affects the reading process
5. The vibrating passenger affects the reading process (*e.g.* the eyes)
6. The reading process affects the passenger's motive to comprehend the text

As stated previously, the fundamental parts of the reading process is word decoding and visual acuity. Since the comprehension is exclusively dependent on a proper decoding of the text, any misfit among the interactions 4 or 5, in Figure 2-8, will hamper the decoding or even cause the passenger to shift focus. Such a shift in focus may force the passenger to consciously gaze at each letter and word in order to identify their meaning. With this shift the passenger has also changed the initial motive from comprehension of the text to identification of individual letters and words.

2.6.2 Interactions during writing

Misfits or breakdowns in the writing process can be caused by a range of conditions, *e.g.* poor support for the hand and arm, malfunction of the pen/pencil, hand sweat, cold fingers and wrists, poor illumination, vibrations, both mental and physical disturbances from the environment, such as talking passengers that may distract the formation of a written story, *i.e.* creates a lack of words to write, or even physical contact that will affect the handwriting. The properties or *transparency* of this interaction can thus be described in terms of manual precision, legibility and cognitive processing of the story, but it is the interactions between the contextual dimensions in Figure 2-9 that reveals where the misfits occur. The cognitive part of the writing is also left out in the discussion since there are few stringent methods for assessing individual parts of a cognitive process in the human mind.

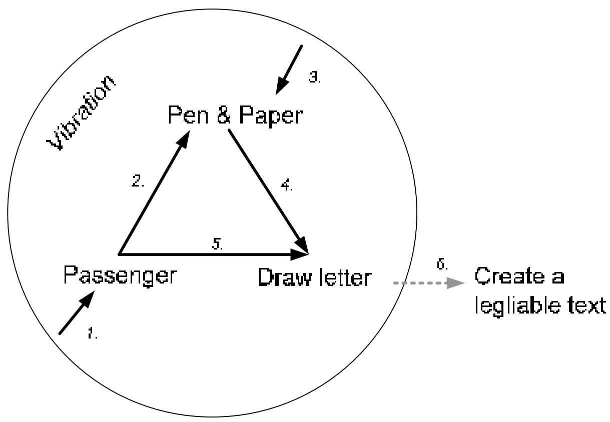

Figure 2-9 Interactions while writing under vibration exposure

From Figure 2-9 six different interactions can be identified. These interactions will help to reveal where the interesting breakdowns will occur due to vibration exposure.

1. The passenger is exposed to whole-body vibrations through supporting surfaces (*e.g.* seat)
2. The passenger causes the pen to vibrate (*i.e.* hand-arm vibration)
3. The paper itself is vibrating through supporting surfaces (*e.g.* table or knees)
4. The vibrating pen and paper affects the writing process
5. The vibrating passenger affects the writing process (*e.g.* the eyes)
6. The writing process affects the passengers motive create a legible text

As stated previously, the *manual control* is the fundamental part of the writing process. Since the manual precision is exclusively dependent on a proper *proprioceptive* control, any misfit among the interactions 4 or 5, in Figure 2-9, will hamper the handwriting or even cause the passenger to shift focus. Such a shift in focus may force the passenger to draw larger letters to be able to maintain legibility, for example. With this shift the passenger has thereby also changed the initial motive from creating an overall legible text to making each individual letter legible.

2.6.3 Properties of the operation

To make use of Activity Theory for evaluation and development of more comfortable railway cars, the properties of the interaction between the passenger and artefacts must be understood or at least known. These properties can only be accessed, or become aware to the passenger when there is a *breakdown* in the interaction, since *operations* can not be predicted. Regarding operations Bødker (1989) claims that; "*The person will not know what these are until they are done;"*, *i.e.* they are not triggered by any quantifiably predetermined set of conditions. According to this conservative view it becomes very complicated to assess the properties of an operation. What can be done, of course, is to study the outcome of the different processes during different contexts of artefact use in order to gain access to the operational properties.

3 Methods

The aim of the present thesis was as previously stated:
"to investigate how the ability to read and write while travelling is influenced by low frequency vibrations in the lateral direction"

To put the problem of passengers' activities in perspective the most appropriate method be the study of passengers and their activities in the proper environment *i.e.* on board an ordinary train. The type of reading and writing activities and how often they are performed must be established first. Further vibrations in the train must be measured and evaluated according to eventual disturbances. Then it is possible to delimit the research question into more detailed studies.

On a systematic level the following three main issues are thus of special interest:

1. Passenger survey (to list the passengers' activities and train travelling experiences)
2. Vibration survey (to survey the vibrations on contemporary trains and lines)
3. Laboratory studies on sedentary work (to find how different vibrations disturb the passengers' activities)

In accordance with these three issues a study plan with two parts was arranged. The first part was designed as a field study to investigate passengers and vibrations on ordinary trains during normal service. The second part was planned as two separate laboratory studies to investigate how different frequencies, amplitudes of vibrations and seated postures affects the ability to read and write. The first laboratory study focused on stationary lateral vibrations, whereas the second laboratory study investigated the effect of occasional transient lateral vibrations. Since the main purpose of the field study was to survey both the passengers and the vibrations standard questionnaire and vibration assessment methods were used. In the following laboratory studies, however, the methodology was adapted to facilitate proper conditions and results.

Ethical considerations
In all the parts of the studies the test subjects participated on a voluntary basis. They were informed that they could leave the experiment at any time and in the passenger survey the participants were completely anonymous. In the laboratory studies all subjects gave their informed consent and the personal data were coded for confidentiality. Under the lab studies the participants were never exposed to any vibration levels above normal doses in daily life. Neither were they exposed to physical treatment nor faced with any situations that could cause ill health or physical discomfort. An appropriate level of high safety was considered in equipment design, with emergency stop and motion feedback etc. At all times during the experimental sessions educated trained personnel were surveying the running machines and controls.

3.1 The field study

To the best of the author's knowledge, there are few public studies on the vibrations in contemporary Swedish regional or intercity trains (over intermediate to long distances). Great Britain and Japan have a few examples of studies for vibration research (Howard, 2004; Suzuki *et.al.*, 2000). Generally, it is the manufacturers who undertake vibration studies on behalf of the train operator who ordered the train, before it is put into service. Due to the lack of Swedish data a broad approach was chosen for the field study, see also ***Paper I***. The filed study was thus decided to include both a questionnaire survey and onboard vibration measurements. To obtain a representative distribution of vehicle dynamics in the study three technically different trains were selected for the field study (InterRegio, Kustpilen, and Regina). The trains also represent a variety of the most commonly used vehicles that departs from Stockholm central station.

The Swedish high speed train X2000 was not included in this field study due to its tilting-car technology which is known to cause motion sickness (nausea) among some individuals (Förstberg, 2000). Since nausea strongly influences the passengers' comfort as well as the ability to read and write only non-tilting trains were included in the tests.

The lines where chosen to give a representative distribution of track standard; from newly laid or maintained, fairly straight, good tracks to tightly curved, old, poorer tracks. The selection was based on knowledge of the maintainance schedule of the tracks as well as subjective experience from travelling on the different lines.

The field test was run over three consecutive days in April 2003. On each of the studied trains ordinary paying passengers were randomly recruited to volunteer in the survey.

3.1.1 Passenger survey

As has been discussed by Kjellberg *et.al.* (1993), Rebiffé (1980), Richards (1980), and Sundström (2003) the context has a major influence on how a specific situation is experienced. It is also known that the seated posture plays a vital role both in the performance of work (Gireco, 1986) but also in attenuating and absorbing vibrations that are exposed to the body (Gunston, 2003; Holmlund *and* Lundström, 1998; Kitazaki *and* Griffin, 1997; Lundström *et. al.*, 1998).

The fundamental objective of the survey was to gain knowledge regarding the activities and seated postures that train passengers normally apply while travelling. It was also vital to gain understanding of the passengers' experience from disturbances and evaluation of noise and vibrations onboard the train. It was further considered valuable to verify the results of a previous passenger survey (Westberg, 2000).

This passenger survey was used as a problem detection study where a printed questionnaire was considered the most economical and most effective method to obtain information from a large number of passengers onboard the trains. There are, of course, several alternative data-gathering techniques to distribute questionnaires to the passengers onboard the train. The questionnaires could have been sent by ordinary mail to a random number of citizens. Two major drawbacks with postal questionnaires are the low response rate and the memory bias due to the difficulty to recall experiences from a previous train journey. The most important issue is, on the other hand, the absence of context and vibrations that are necessary to undertake adequate performance tests. Another alternative would have been in-depth interviews with the passengers. Interviews are however very time consuming. So, although a large quantity of information was generated, only a limited number of persons can be involved. Similar drawbacks apply for observational studies of seated posture and activity using video technique. Although the collected data might provide extensive information and advanced analysis, observation techniques only allow a limited number of subjects. A limited number of subjects will further form a poor base for generalization and over all representation.

In order to obtain a broad and representative base for the data the questionnaires were handed out to more than 300 randomly selected passengers on the trains. The participants were informed that they had the right to withdraw from the study at any time and that no information could be traced to them as an individual. The respondents were not paid for their participation but were informed that their results could help to improve the noise and vibration environment in future trains.

Data analysis

In previous train passenger surveys Kottenhoff, (1999) found that passengers value their train ride differently due to the context and price of the travel. In particular travellers with long travelling times and more expensive tickets were found to be more susceptible to disturbances in overall comfort. This particular group of passengers were also noted for their will to pay for better comfort. Hence the responses of the current survey were analysed appropriately to find individual parameters that correlate with the disturbance or perceived difficulty. Some of the expected parameters are: age, gender, level of education, ticket price, purpose of journey, experience of train travelling and the length of journey.

3.1.2 Vibration survey

The main objective of the vibration measurements was to investigate the vibration levels and frequencies that are present in contemporary passenger trains in Swedish Inter-City traffic. Acceleration magnitudes were measured and assessed as comfort-values according to the present standards ISO 2631-4 and Wz Index. The requirements for the whole body vibration measurements that are specified in ISO 2631-4 involve tri-axial (x,y,z) acceleration measurements at three interface points between the seated human body and the supporting surfaces (backrest, seatpan, and floor). In a previous passenger survey Westberg (2000) showed that many passengers use the table and armrests while writing and reading. Therefore, the present study used two additional triaxial accelerometers in the measurement set-up, one on the table and one on the armrest.

The specific aims of the vibration measurements were as follows:

1. Compare and rank the measured directions of vibration (x, y, z) for each track.

2. Compare and rank the five positions: Floor, Seat-pan, Seat-back, Armrest, and Table.

3. Compare two train types run on the same track

The interest was not only in the study the direction and level of the vibrating motions. Since three different trains were used in the measurement study they would most likely also differ in frequency spectra due to their dynamic properties.

Standardized methods

ISO 2631-4 (2001) prescribes how to measure and evaluate the vibration transmitted to the body through the supporting surfaces. The standard does not provide vibration exposure time limits but quantifies the vibration in response to human health and comfort as well as for the probability of vibration perception and the incidence of motion sickness. The acceleration signals are evaluated using frequency weighted r.m.s. method defined by:

$$a_w(t_0) = \left[\frac{1}{\tau} \int_{t_0-\tau}^{t_0} [a_w(t)^2] dt \right]^{\frac{1}{2}} \qquad (3\text{-}1)$$

where, $a_w(t)$ is the instantaneous frequency-weighted acceleration; t is the integration time for running averaging; t is the time (integration variable); t_0 is the time of observation (instantaneous time). Weighting functions for the different directions are shown i Figure 3-1.

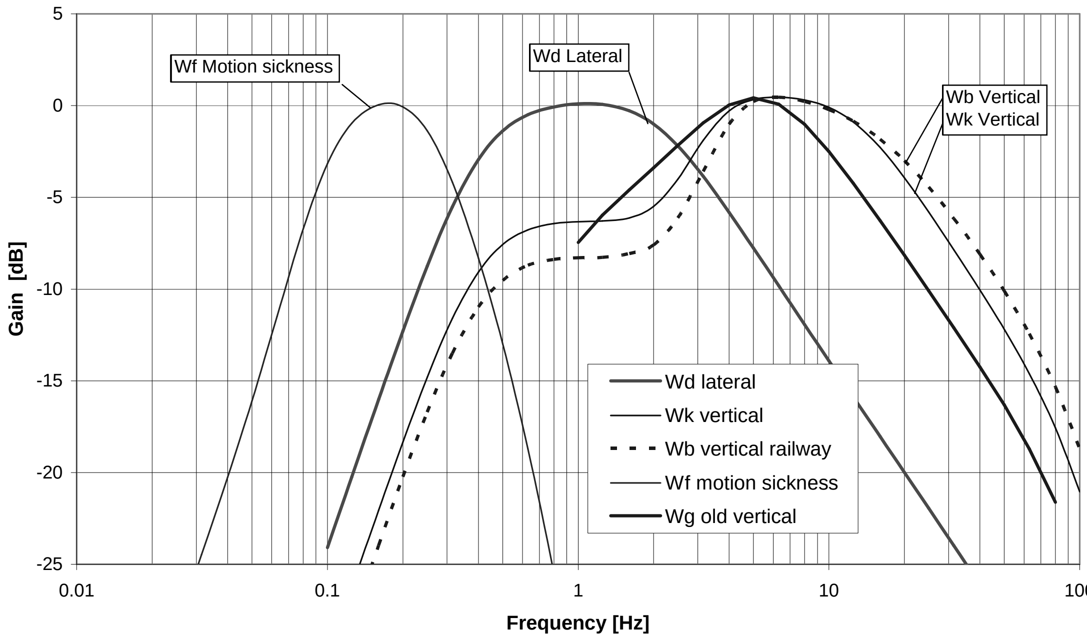

Figure 3-1 Frequency weighting functions for the different directions (ISO 2631-4, 2001).

The frequency weighting of accelerations w_d is used for longitudinal and lateral accelerations whereas w_k is used for vertical acceleration. The r.m.s method is recommended for motions with a crest factor less than or equal to 9. The crest factor is defined as the modulus of the ratio of maximum instantaneous peak value of the frequency-weighted acceleration to its overall frequency-weighted root-mean-square acceleration. Since the standard does not include multiplying-factors for armrest and table the weighting factor for the floor was used here. The ISO-standard defines the total vibration value of weighted r.m.s. acceleration for all directions in respective position.

Wz Index (Sperling *and* Betzhold, 1957) is sometimes used for measuring passenger discomfort for railway trains. This index has been frequently used in Swedish rail industry since the 1960:s. The method originated in the 1940:s and was recognised by ERRI[1] (ORE) in 1977. Wz is a frequency weighted root mean square (r.m.s.) value of accelerations. It is evaluated over a defined time interval or over a defined track section. For an arbitrary acceleration signal that is not necessarily a harmonic signal the frequency weighted root mean square (r.m.s.) value of accelerations is used.

[1] ERRI - European Railway Research Institute (formerly ORE - Office for Research and Experiments)

The index is calculated as follows:

$$Wz = 4.42(a^{wrms})^{0.3} \qquad (3\text{-}2)$$

where, $a^{wr.m.s.}$ is the r.m.s.-value of the frequency weighted acceleration $a^{w}(t)$ (m/s^2) according to Figure 3-2.

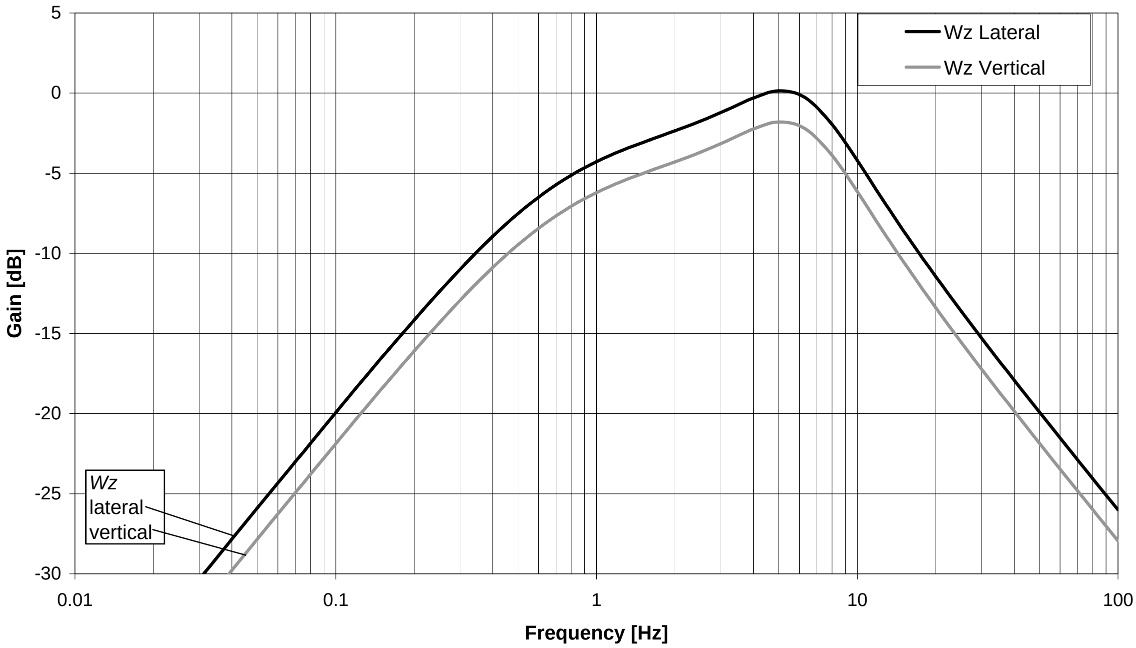

Figure 3-2 Frequency weighting functions for Wz (Sperling and Betzhold, 1957).

Wz value of 2.5 is often compared to ISO-weighted r.m.s. acceleration value of 0.25 m/s^2. These limits are often considered as acceptable for ride comfort on trains with respect to motions.

3.2 Laboratory studies

An ideal study would have consisted of reading and writing tests onboard real trains during normal running conditions with paying passengers as volunteers. Such experimental conditions would however offer very low or no control over the frequency content or the vibration levels in the rail car. To obtain a reliable and repeatable control of the presented parameters the experiments were set-up in a laboratory environment. As described in previous sections the vibrations in real trains consists of motions in several directions. To gain control over the effects from one single direction the lab studies were limited to only involve lateral (y-) motions with one discrete sinusoidal frequency at a time.

3.2.1 Aims of the experimental studies

Primarily both laboratory studies I and II shared the same fundamental aim to study the ability to read and write under lateral low frequency vibration exposure. Secondary aims of the laboratory studies were to verify the previous tests made by Westberg (2000) and to further develop the method.

The Specific aims of Lab study I were as follows:

1. To investigate how different parameters (frequencies and acceleration amplitudes) of stationary lateral vibrations influence the ability to read and write.

2. To investigate how the seated posture modifies this influence

3. To study the effects of age, gender and some anthropometric parameters.

The Specific aims of Lab study II were as follows:

1. To investigate how different frequencies and transient lateral acceleration amplitudes influence the ability to read and write.

2. To investigate what extent the process of reading is disturbed by transient lateral vibrations.

As stated in the previous section, can the properties of the interactions between the passenger and artefacts not be easily isolated or parameterized. This was the greatest challenge in the experimental design to ascertain measures that were valid but still free from confounding factors. The three contextual dimensions described in the previous section (action, artefacts, environment) were therefore considered in the experimental design. In the laboratory studies there was the context defined by the task, posture, exposures and in the environmental parameters of the carbody interior.

3.2.2 Vibration parameters

Kjellberg *and* Wikström (1985) pointed out five parameters that characterise the vibration response: intensity, its variation with time, frequency, direction, and duration. In the field study, see ***Paper I***, large variations could be seen among all these parameters. To gain control over the possible interactions between the parameters a limited range of (discrete) sinusoidal vibration frequencies were selected for the laboratory study. The harmonic vibrations were presented at different amplitudes in the lateral direction both as stationary vibrations and as occasional transients. As previously stated have vertical vibrations been the main direction of vibration investigation for several years. Eventhough lateral stationary sinusoidal vibrations are not very representative for real conditions, they form a good beginning for further study (Griffin, 2003; Mansfield, 2005).

Whole-body vibrations are mainly studied in the frequency range 0 - 20 Hz. The most sensitive frequencies for activities like reading and drinking have been found in the lower end of the range near 2 Hz (Corbridge *and* Griffin, 1991). In the present laboratory studies the intention was to avoid influences of motion sickness (nausea), the vibration stimuli therefore had to exceed 0.5 Hz. For an upper frequency limit Westberg (2000) used 10 Hz in his studies. Since vibrations over 10 Hz are known to only cause minimal response effects (Griffin, 2003; Mansfield, 2005) this was considered an appropriate limit for the present laboratory studies.

The acceleration amplitudes should correspond to what are commonly occurring in trains, though not too high to be unrealistic or harmful and on the other hand not too low to prevent any effects at all. Average levels of vibration in trains should typically stay below 0.25 m/s^2 r.m.s. Westberg (2000) used 1.0 m/s^2 in his studies, which were considered a bit too high.

3.2.3 Postural conditions

The chosen postures were derived from the results of the passenger survey described in section 3.1.1. By combining all the possible alignments of the human body segments a vast number of seated postures arise. The purpose was therefore to find a limited number of postures that were as different as possible but yet adequately representing the postures that were reported by the train passengers in the field study. After removing the extreme postures and postures involving armrests two principal features of support remained, *i.e.* support of the upper body and support of the working material. These two features were combined in the two sitting postures seen in Figure 3-3, *a)* with backrest and material on the lap and *b)* without backrest and material on the table.

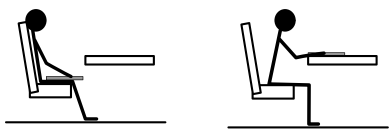

Figure 3-3 The two sitting postures

3.2.4 Tasks and measurement design

There is a major difference in goal or objective between a task performed in the field under the context of ordinary work and a task that is performed in a laboratory experiment. Although the physical context with a seat, task and vibrations is more or less equal to what the train passengers feel in the field the goals and motives will differ. On board the train passengers have personal goals, whereas in an experiment the test subject is given a predetermined goal by the experimenter. This difference in goal should not be underestimated as it may lead to shortcomings as described by Rexfelt (2005). Gaining control over the goals and motives of the test subjects is crucial for obtaining an ecological validity that is good enough to reflect and describe the real situation of use.

From Figures 2-8 and 2-9 it can be noted that it is all too easy to cause a change of the goal or motive of an operation if proper care is not taken. Therefore were the fundamental operations of the reading and writing processes considered the most valid to study, *i.e.* word decoding and manual control. Fundamentally, the tasks themselves did not have to provide an exact measurable quantitative output themselves. The tasks should rather be means to occupy the test subjects with something resembling a reading or a writing task. To be valid the tasks should only have limited influences from other processes, *e.g.* comprehension and visual feedback. In other words, the actual output from the reading or writing task must not necessarily be an objective measure of ability or performance of reading or writing. The aim was to create tasks that reflects the core process of reading (text decoding) and writing (hand writing) respectively. These tasks should be possible to perform for a short period of time, *i.e.* less than 1 min, with as constant a level of absolute difficulty as possible. The tasks should further be possible for the subjects to consciously reflect upon, and of course be influenced by the vibration exposure.

Reading task

The term *reading-ability* does by its definition represent more than just decoding or quickly stumble through a complicated text. Reading-ability is normally regarded as the whole process from decoding to understanding and reflecting over the contents of the text. The complete process that forms the reading-ability has been found to be influenced by parameters like age and educational level (Eriksson-Gustavsson, 1998). Since this thesis is more concerned with the physical word-decoding of the reading process the term *ability* will be used in a more narrow sense.

To find or develop a reading task that was neutral and not driven by the motive to comprehend was a complicated issue. Just giving the subjects a plain text to read, *e.g.* from a newspaper or a novel would have given poor control of the actual progress of decoding. Further, the context and style of such texts would have affected people differently. A text whose context is familiar and enjoyed by the reader will most likely be enjoyed even if a few words are missed, since the 'context processor' and the 'meaning processor' will help the reader to fill the gaps that is missed by the 'orthographic processor', *i.e.* in the decoding. This problem could partly be overcome by letting the subjects read the text aloud, but, in order to run more than one subject at a time the reading task had to be silent.

Johansson (1999) has developed a method called 'Word chains' for assessment of school children's reading capabilities. The test is a word-decoding test and has proven to give a reliable and valid assessment of the reading performance among students. Originally there are two types of word chains in the test: one with words that are semantically unrelated (part A), and one with semantically related words (part B). To limit the influence of semantic skills *part A* was chosen as reading task in both laboratory studies. During the laboratory studies the word chains were randomly ordered to avoid any temporal effects of difficulty throughout the task. The word chains are more thoroughly described in ***Paper II*** and ***Paper III***.

Writing task

Hyldgaard (2000) used a pencil tracing task test to measure pure manual performance in children. To construct a tracing task that resembled the fine control of hand writing was regarded too awkward and was abandoned in favour of a more handwriting-like task. In the field study, described in ***Paper I***, the passengers were given a writing test consisting of a simple text paragraph to be copied by hand. Such a task will however be confounded with the ability to read the text to be copied. To write compositions would on the other hand be strongly influenced by the individuals' cognitive and linguistic abilities to create a story (Hayes and Flower's, 1980). Dictation was finally considered to be a task that was least dependent of cognitive abilities. The text was selected from a reading comprehension part of the *Swedish Scholastic Assessment Test* (Lyxell, 2002) and was recorded on tape. The text did not contain too many complicated words or number series. To allow individual setting of pace and loudness each test subject was given a dictating machine with a volume control and a foot switch.

Response variable

It has been the goal of several researchers to objectify subjective experiences or even feelings (Jones *and* Saunders, 1974; Strandemar, 2005). Usually the motive is to obtain a quantitative measure of the human response that is both valid and repeatable under a variety of different conditions. Measures or judgements of task performance could however come to reflect people's skill or general capabilities, which was not the intention of the present studies.

The ability to perform an action on an operational level can be evaluated in several ways. In Sundström (2003) truck drivers' sitting was analysed with video recordings of different contexts of driving with an Activity theory approach. A method was developed to transcribe and map different situations (why, what, how). The method further made it possible to identify and describe breakdowns and focus shifts over time. Bødker (1989) used a similar mapping technique to study the use of different software applications. Intelligible data-matrixes could be rendered to describe the chronological changes in focus and awareness. However, this kind of mapping/transcription techniques is too slow and inaccurate to study such dynamic and complex operations as reading or writing under vibration exposure.

Studies on reading performance under vibration exposure have identified valid measures of objective task performance. Griffin *and* Lewis (1978) reviewed several studies that used reading error and reading speed as measures of performance under vertical vibration exposure. Reading speed or writing speed are however time based measures that are highly individual, and cause large variations in the response data. Time is a very conservative measure of performance and not a true or good measure of ability. In fact will slow readers manage and even perform well in complicated reading tasks if only given adequate time (cf. Nation, 2005) The variation in the number of words read will consequently be due mainly to the differences in reading skill rather than a measure of vibration effect.

Multiple choice questions were initially considered for testing of reading comprehension in the planned lab studies. Such methods are common in educational tests (Philips, 1989) but carries many confounding problems and are time consuming. The difficulty of the reading task could easily be affected by the schemata, style or topic of the text, since the context has a strong influence on both decoding and comprehension of the text.

Read-aloud protocols have for several years been used as one of the most fundamental methods to study the different phases of composition writing. To let the subjects in present laboratory studies give verbal, aloud, reports about their reading or writing progress would drastically decrease the efficiency of the experiment as it would be too noisy with more than one subject at a time.

Huddleston (1967) successfully used the character size of handwritten text to analyse the effects of large vertical vibrations (1.6 m/s^2). Due to the relatively small acceleration amplitudes that were used in present experiments, the variation in character size was expected to be too small to constitute a reliable measure.

In a laboratory study Westberg (2000) used a 4-point rating scale to evaluate the difficulty to read and write under vibration exposure. The scale was graded from *not at all difficult* to *very difficult*. In a verification test Johansson (1999) found poor correlations between students self judgement of difficulty and the number of correct responses of the word chain test. It is reasonable to believe that self rated difficulty is partly based on a reflection of how we live up to our own demands to perform well. Subjective rating of difficulty can however be valid since the experience of performing a certain task under vibration exposure is matched to the goals and motives of that particular task. This demand-dependence is inevitable since it is the goals and motives that drives the operation of the task, see theory section.

Originally the frequency weighting filters in the standards ISO 2631-4 and ENV 12299 are derived from subjective ratings that have been converted into frequency weighting curves to enable objective vibration assessment. In order to obtain the same baseline to evaluate the results a subjective response method was chosen for the present laboratory studies. There are several studies on whole-body vibration that have reported good consistency of subjective judgement of acceleration intensity according to Stevens' power law (Jones and Saunders, 1974; Howarth *and* Griffin, 1988). The power law states that the relation between the vibration stimuli and the psychophysical response can be predicted by the following exponential function:

$$R = cS^n \tag{3-3}$$

where R is the magnitude of the response, c is a measurement constant, S is the physical intensity of the stimuli, and n is the exponent of growth (Borg *and* Borg, 2001).

A verbal rating scale that has its origin in the same psychophysical expression is the Borg CR-100 scale. Since the Borg-scale is based on the same exponential function as the power law it was regarded to be well suited for subjective vibration judgements in the present laboratory studies. The Borg-scale originated in the 1970s for purposes of assessment of physical work load, and has been developed in several steps, from RPE, to CR-10, and now CR-100 (Borg *and* Borg, 2001). The CR-100 scale is in its principal a verbally level anchored rating scale for judgement of perceived intensity, see Figure 3-4. It has proven to be very successful and has also been used for evaluation of difficulty of cognitive mathematic tasks (Borg *et. al.*, 1971). The drawback of the Borg scale lie mainly in the preparations that require thorough introduction, calibration and practice. On the other hand, once these steps are overcome it is a very sensitive and adaptable instrument that is providing reliable *between* and *within-subject* ratings of simple sensory perceptions.

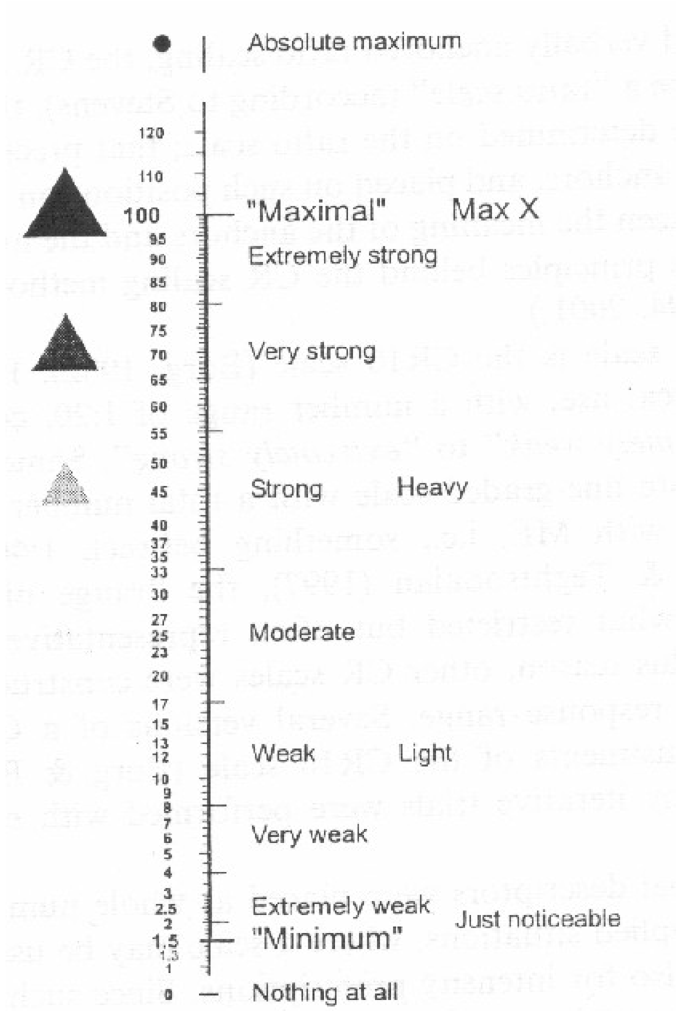

Figure 3-4 English version of the Borg CR-100 scale (Borg and Borg, 2001)

Instructions

The subjects might not be aware of the motives for choosing to participate in an experiment, *i.e.* on an activity level. It is of course impossible to be absolutely sure of each subject's personal goal of participation. Their reasons could be anything from earning money, contributing to research, or to perform well in the tasks (Rexfelt, 2005). The individual motives must, therefore, be separated from the goal of the experimental task in order to give the subjects the possibility to make correct and valid assessments. The motives of the research and the goals of the experimental tasks were therefore thoroughly explained to all subjects, and the same instructions and objective were given to all participants. Two short extractions of the instructions are shown below.

Instructions for the writing task:
You are about to copy a dictation text so that it becomes legible for someone else. Imagine yourself that you are to write down a recorded voice memo form a friend or a colleague.

Instructions for the reading task:
You are about to read word chains. You shall mark with your pen where the words should be separated. Imagine yourself that you are to proof-read a text for a friend or a colleague.

In order to give correct responses the participants had to know what was expected of them. In both laboratory studies the subjects were therefore instructed that there was no predetermined right or true answer to what is experienced as difficult. The importance of a good rating was emphasised since it was their own feelings that were the instruments in the research. To limit confusion and learning effects the subjects were also given time to get acquainted with and practice each of the sequences of the experiment during the introduction of the experiment. To gain control of any learning effects reference tests of reading and writing were made immediately before and after the experiment. A short questionnaire was filled out directly after the experiment, to evaluate whether the subjects felt that the tasks had been irrelevant or natural.

Experimental equipment
The two laboratory studies were set up and performed in the Marcus Wallenberg Laboratory at the Royal Institute of Technology (KTH) during the spring of 2004 and winter 2005. A train mock-up with lateral motion was used in both experiments. The mock-up consisted of a 3.5 *m* section of a (Bombardier C20) subway carbody that was equipped with tables, seats, ventilation and lighting, see Figure 3-5.

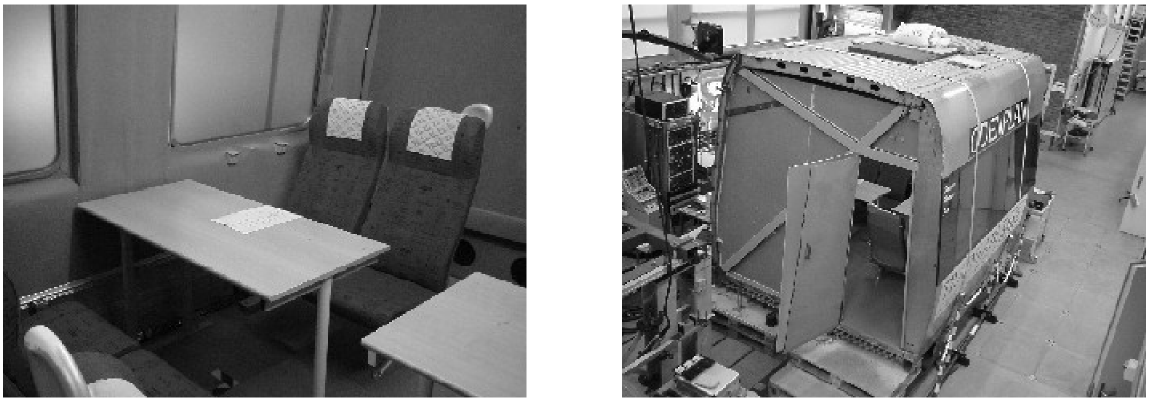

Figure 3-5 Interior and exterior view of the train mock-up

The internal environment of the train mock-up is further described in ***Paper II*** and ***Paper III***. In both experiments all subjects were provided with the same set of *artefacts* for the tasks, *i.e.* a ball-point pen, tasks printed on white A4 paper, dictation machine, head phones and a foot switch. A printed version of the Borg CR-100 scale was taped on the table surface to give the subjects instant access to the correct verbal anchors during the rating.

Control system design
The carbody was mounted on a wagon frame with four steel wheels running on two steel rails, see Figure 3-6. A position controlled hydraulic cylinder was used to create the desired lateral motion. The capacity of the hydraulic cylinder was 50 kN and the stroke length was ±75 mm. For simplicity and safety reasons the internal positioning gauge of the cylinder was continuously used for motion feedback. The vibrations were generated by a Dynamic Signal Analyzer, SigLab® 20-42, controlled via a Matlab®-application. To avoid sampling-ripple the signal was first LP-filtered and finally white noise was added (50-100 Hz, 0.25 mm peak) to increase realism to the stimuli.

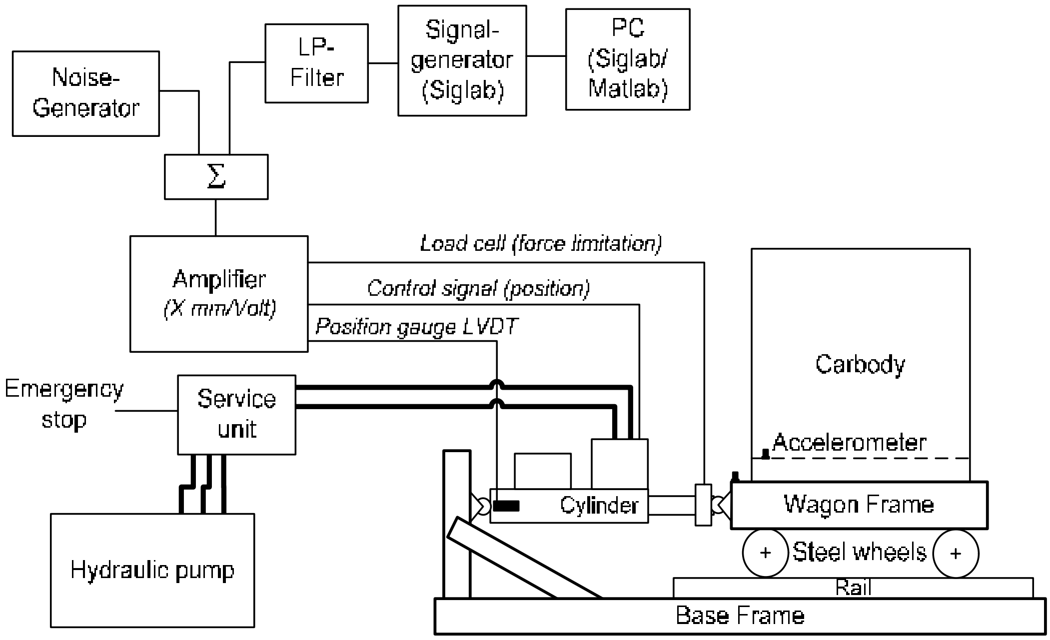

Figure 3-6 The control system of the mock-up

Accelerometers were positioned at the hydraulic mount on the wagon and on the floor inside the cabin for the purpose of documentation. The acceleration channels and the input signal and internal positioning gauge were all recorded on a DAT recorder (SONY PC 216 AX) at a sampling rate of 6500 Hz during all experimental sessions.

3.2.5 Response data analysis

All response data was coded into a *Microsoft Excel*® spread sheet and was further processed and analysed in the statistical software *SPSS*®. Analysis of variance (ANOVA) was used for both *between*, and *within-subject* differences according to a *Repeated measures General linear model*. The anthropometric data were examined in a *Factorial Principal Component Analysis* where regression coefficients were derived for an anthropometric model. Details of the statistical analysis are further described in ***Paper II***.

3.2.6. Laboratory study I (*Paper II)*

Test variables

A previous study had found maximum ratings of difficulty in the range 2 - 4 *Hz* (Westberg, 2000). In a review by Lewis *and* Griffin (1978) it was concluded that the x- and y-axes have their greatest effect on performance in the range 1 - 3 *Hz*. So, in order to obtain higher representation among the lower frequencies in the 1/3-octave band and to limit the total time of the experiment the frequency 6.3 *Hz* was excluded. Due to physical limitations in stroke length of the hydraulic cylinder the lower frequency was set to 0.8 *Hz*. Whereas the upper frequency was limited to 8.0 *Hz* due to the influence from higher resonance frequencies in the structure of the carbody itself, *i.e.* the roof, walls and the windows. The selected frequencies for the vibration stimuli in the laboratory study I is shown in Table 3-3.

In a laboratory study that used a stationary amplitude of 0.3 m/s^2 (peak) only minor ratings of difficulty were obtained for the studied frequencies (Westberg, 2000). It was therefore necessary to use higher amplitudes, however, not above 1.0 m/s^2 in peak. The amplitude 0.4 m/s^2 was determined from pilot tests to be fairly low but still causing some degree of difficulty. The amplitude 0.8 m/s^2 was determined to be somewhat high but does occur occasionally in regular trains.

Table 3-3 Vibration amplitudes and frequencies used in laboratory study I

Amplitudes (m/s^2)	0.4, 0.8
Frequencies (Hz)	0.8 1.25 1.6 2.0 2.5 3.15 4.0 5.0 8.0

To avoid fatigue and to limit the total time of the experiment the durations of the exposures must be kept short. The intervals should offer reasonably long pauses to avoid over-hearing of exposures and give enough time for the subjects to make their ratings. A short exposure time would prevent the subjects from attenuating their posture or to adapt to the effects of the vibration but also to prevent them from adopting optimum working strategies. Westberg (2000) previously used both 25 and 60 *s* and found 60 *s* to be slightly more difficult. To avoid effects of fatigue but still have comparable experiments 25 *s* was therefore used for all exposures in laboratory study I.

The postures and tasks were combined in four sets A, B, C and D, according to Table 3-4.

Table 3-4 The four sets of combined task and posture

	Material on Lap	Material on Table
Writing	A.	B.
Reading	C.	D.

To avoid learning and order effects, the experiment was divided into four balanced groups according to a randomized 4x4 Latin Square (Kirk, 2003), see Table 3-5.

Table 3-5 Sequence order for the four sets of lab study I

I.	B	A	D	C
II.	A	D	C	B
III.	D	B	C	A
IV.	C	D	B	A

Test subjects

Through the years several laboratory studies on human vibration response have been limited to involve only male test subjects and sometimes preferably students. But, since Swedish train passengers were found to have an even distribution between the sexes and representing a wide range of ages and occupations the issue of selection bias had to be tested. The present laboratory study therefore aimed to obtain a 50-50% distribution between female and male participants. In an international adult literacy survey (IALS) it was found that the reading ability was related to age independent of education level (older generally lower ability) (Eriksson-Gustavsson, 1998). To control for age the test subjects were recruited according to three age-categories: students 20-25, mid-aged 40-45, and older 60-65. All of the subjects were necessarily either studying or working at least half-time, *i.e.* not retired. The subjects were recruited by advertising posters and handed out 'leaflet' to commuters at one of the major local transport junctions 'Östra Station' close to the Royal Institute of Technology in Stockholm. Submission and booking for joining the test was made via an internet form on an official homepage at VTI.

The participants had to be healthy and perform normal or effortless reading and writing of the Swedish language. In connection to the study a background survey was used to gather information on each participant's individual background, *i.e.* fitness, experience of vibration exposure, musculoskeletal disorders (Kuorinka *et.al.*, 1987), and reading and writing habits. Three anthropometric measures were also obtained from each subject, *i.e.* seated height, arm length, and leg length according to definitions by Pheasant (1999). A digital photograph was taken of each participant against a calibrated background grid, as shown in Figure 3-7. After the picture had been calibrated to a proportionate scale the anthropometric measures were taken in the picture. Each test person's weight was taken in a relaxed seated posture leaned against the backrest. The weight was taken with a digital bathroom scale that was placed in a train seat.

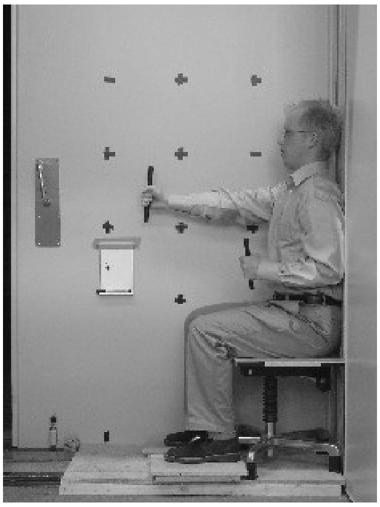

Figure 3-7 Example of digital photograph for extraction of anthropometric measures.

Experimental procedures
Throughout the experiment the subjects were informed which posture and task to attain. For each posture and task the frequencies and amplitudes were presented randomly for the 18 stimuli. After each stimulus (sinusoidal signal) had been presented for 25 *s* the vibrations faded out and the subjects rated the difficulty to read or write according to the Borg CR-100 scale. The subjects were instructed not to see the tasks as a competition but to find a nice comfortable working pace that they could maintain for one hour, and to do their best.

3.2.7. Laboratory study II (*Paper III)*

Test variables
Three different tasks were assigned in this experiment, A*)* reading, B*)* writing, and C*)* judgement of disturbance. The reading and writing tasks were the same to those used in the

first laboratory study. Part A and B also involved the Borg CR-100 scale for rating of difficulty.

In the disturbance test (part C) the subjects were equipped with a push button and a plain text. The subjects were instructed to read the text and when they were disturbed by a vibration transient they should immediately press the button. In this way it would be possible to obtain an indicator of a *breakdown* or a *shift* in *focus* since the subjects have to become aware of the reading disturbance to press the button.

In laboratory study II only one posture was used, *i.e.* sitting leaned against the backrest with the work material on the lap. This was done to obtain a design which included more amplitude levels than in the previous study and to limit the total time of the experiment. This leaned-back posture was chosen to avoid having too extreme levels of difficulty due to transient signals since it was previously proven to cause less difficulty in the first laboratory study.

In an experiment with standing subjects Suzuki (1998) used a frequency of 2 *Hz*, based on the insight that lateral vibration transients in subway cars are common in this low frequency range. In the present study the intention was however to study several different frequencies. Suzuki (1998) designed a transient vibration pulse based on one sinusoidal frequency, with a sudden amplification over one period, see Figure 3-8.

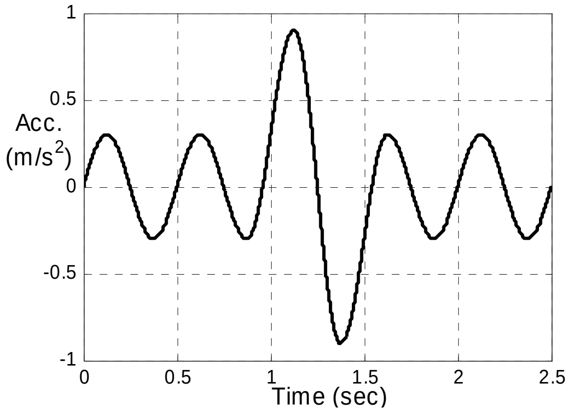

Figure 3-8 The principal acceleration pulse used in laboratory study II

To create a train-like motion with minor influence from the stationary component of the vibration signal the stationary amplitude was set to 0.3 m/s^2 (peak) in the current study.

For the reading and writing tasks (A and B) the duration of each frequency were set to 25 *s*. During this time three transient pulses of the same amplitude were randomly presented to ensure the subjects did not miss an acceleration peak. Three different amplitude levels were used to analyse whether the amplitude dependence was linear. The frequencies and amplitudes are shown in Table 3-6.

Table 3-6 Amplitude peaks and frequencies for the Reading and Writing tasks

Amplitudes (m/s^2)	0.7, 1.0, 1.4
Frequencies (Hz)	1.25, 2.0, 2.5, 3.15, 4.0, 5.0

For the reading-disturbance tasks (part C) only three discrete frequencies were chosen in order to include more amplitude levels in the experimental design. The primary interest of the disturbance test was to investigate the presence of a disturbance magnitude threshold for the transient vibrations. Each frequency was given a duration of 3 *min*. During this time nine shocks of different amplitudes were randomly presented twice to ascertain that the subjects would not miss the acceleration peak. The frequencies and amplitudes are shown in Table 3-7.

Table 3-7 Amplitude peaks and frequencies for the Reading-disturbance task

Amplitudes (m/s^2)	0.43, 0.47, 0.50, 0.53, 0.57, 0.60, 0.63, 0.67, 0.70
Frequencies (Hz)	1.25, 2.0, 4.0

Each of the parts (A, B, and C) formed a set in the experimental design of this second laboratory study, see Table 3-8.

Table 3-8 The three sets of task and posture

	Material on Lap
Writing	A.
Reading	B.
Disturbance	C.

To avoid learning and order effects, the experiment was counter balanced according to Table 3-9. Since *part C* was considered an exploratory part that differed from the other two it was always run last in the experiment.

Table 3-9 Sequence order for the three sets of lab study II

I.	A	B	C
II.	B	A	C

Test subjects

Since gender, age and anthropometric effects were studied in the first laboratory study the underlying aim for study II was to control for the variation in the anthropometric data. Therefore, 21 test subjects were recruited according to predefined body measures and seated weight. By simply combining the 50-%ile of the anthropometric measures from the previous laboratory study none of the former subjects qualified for the present laboratory study. Therefore, the inclusion-measures had to be adjusted and given within a span according to Table 3-10.

Table 3-10 Required anthropometric measures and obtained results

	Seated Height [cm]	**Seated Weight** [kg]	**Arm Length** [cm]	**Low. Leg Length** [cm]
Target	***95-100***	***40-50***	***70-75***	***55-60***
Mean	95.0	49.3	73.0	54.0
Median	95.2	47.2	72.2	53.5
SD	2.2	5.5	3.4	1.7

The subjects were recruited during a campaign in the entrance hall of the library at the Royal University of Technology (KTH). Age and gender was noted for each subject but was not part of the inclusion criteria. The background survey questionnaire from the previous laboratory study was also used in this second laboratory study.

Experimental procedures

In general the same procedures were used as in laboratory study I. The Borg CR-100 scale was used for rating the difficulty of reading and writing. The major difference was the vibration stimuli and the disturbance test with push-buttons.

4 Summary of paper resuls

In each of the appended papers results are presented form the three consecutive studies. The main results from the passenger questionnaire and the vibration measurements of the field study are presented in paper I. The main results of each laboratory study are presented separately in Papers II and III. The section here has two main aims. The first is to give a joint view of the three included studies and their respective results. The second aim is to present a more detailed view of the results and to enlighten some more specific characteristics of the obtained data.

4.1 Results of the field study (Paper I)

The field study was conducted onboard three different types of trains during normal service. One interest was to obtain the passengers' views with respect to their experience of the noise and vibrations in the context of a normal train journey. The passengers' activities and postures were also studied since they represent the fundamental components of the onboard-travelling-context. In relation to the subjective questionnaire data the actual vibration levels were established in order to survey and understand the vibration exposures onboard. Therefore, one part of the study consisted of a passenger questionnaire survey and the other part consisted of vibration measurements on contemporary trains and lines.

4.1.1 Passenger survey

In total 330 passengers participated in the onboard questionnaire survey with a share of 52% female and 48% male travellers. The general background of the survey participants shows that all kinds of people travel by train; young, old, big, small, male, female, students, professionals and unemployed. Age distribution of passengers followed closely the variation for the Swedish population.

Background information about the present journey revealed that the major purpose of travelling was related to either study or work. Even though 85% of the respondents were seated in the 2nd class compartment the type of class did not show any significant effects. Neither were there any significant differences in responses between passengers due to type of train ($p > 0.05$).

On average the passengers reported a travelling time of 72 minutes. Reading was the activity that was undertaken by most passengers for the longest time of the journey. Thereafter came eating or drinking, at some point during the journey, but only for less than one third of the time, *i.e.* 20 min. A high number of travellers also reported to perform no definite activity at all, *e.g.* being devoted to their own thoughts or just looking out the window. Writing by hand came in fourth place but was only performed for less than one third of the time, or about 20 min. writing or working with computer was reported by 14 %. The obtained results correspond well to a similar study by Westberg (2000).

During analysis of the postural positions for each of the reported activities associations were found between posture and activity. To sit leaning forward with the material on the table was more common for writing against reading. On the other hand, to sit leaned against a tilted backrest with the material on the lap, was a more common posture for reading. About 40 % of the passengers reported to sit with their legs crossed, either while they were reading or writing.

When asked about their experience of disturbances from noise, vibrations or shocks in the train about 27 % of the passengers did not consider motions to be the worst source of disturbance. A similar number of passengers however reported that the worst source of disturbance was either vibrations, shocks, or noise in the train. The judgement of these disturbances did not show any significant differences due to gender, age, travelling experience, class, or type of train. The purpose of the journey did however have significant influence on the rated disturbance for vibrations of the table and general vibrations in the train ($p < 0.05$).
A short written test was made to measure the difficulties of handwriting while the train was running. The passengers rated how they managed the handwriting task, from *no difficulties* to *impossible*. A ratio of 48% of the passengers experienced the handwriting to be more than moderately difficult. A strong correlation was found between the rated difficulty of handwriting and the perceived difficulty they thought the vibrations caused ($r^2 = 0.87$). The momentary vibration conditions of the trains would most likely have affected the participants while doing the written test. However, it was not possible to correlate the subjective responses to the vibration measurement with appropriate accuracy, since the time of the responses were not synchronised with the vibration measurement.

4.1.2 Vibration survey

The vibrations were measured with tri-axial accelerometers that were placed on the floor, seatpan, backrest, armrest and table. All the acceleration signals (x,y,x) of the five positions were weighted according to the ISO 2631-4 and *Wz* filters. From the *Wz* evaluation the highest discomfort-values were found in the vertical (z) direction, except at the backrest where the highest level occured in the longitudinal (x) direction. In general the lowest *Wz* values were found in the longitudinal (x) direction in all trains but at different locations. This pattern is consistent for all the measured trains and tracks, see Table 4-1.

Table 4-1 Vibration discomfort indexes according to Wz and ISO 2631-4

Train Types / Lines	**Wz** Highest	**Wz** Lowest	**ISO** (rms) Highest	**ISO** (rms) Lowest
X50 on Poor Track	2.79 (seat)	2.42 (floor)	0.33 (seat)	0.08 (floor)
X50 on Good Track	2.75 (seat)	1.89 (floor)	0.28 (seat)	0.07 (floor)
Y2 on Poor Track	2.95 (seat)	2.07 (floor)	0.41 (seat)	0.16 (floor)
IR on Good Track	2.68 (seat)	1.73 (floor)	0.24 (seat)	0.06 (floor)

Surprisingly, the highest mean *ISO*-values were found at the seatpan, followed by the backrest, table and the armrest. Furthermore, the vibration levels at the floor were generally found to be the lowest in all five positions.

The phase differences between the floor and the occupied seat were found to be negligible in the range 1 - 10 Hz, which indicates that the seat was almost rigidly connected to the floor.

For the two trains that were run on the same (good) track, similar distributions of discomfort indexes were found for all the measured positions and directions. This comparison showed that the overall differences in *ISO*- and *Wz* values were insignificant. The newer *Regina* train (X50) showed slightly higher values than the *IR* train possibly due to its higher travel speed.

Although the three studied train types show individual vibration frequency spectra, they all present their highest magnitudes in the lower frequency range 1-3 Hz. Above 10 Hz the vibration magnitude generally decreased with increasing frequency for all the trains and positions.

4.2 Results of laboratory study I (Paper II)

Two laboratory studies were made to thoroughly investigate the effects of vibrations on two types of sedentary activities. The first laboratory study was concerned with stationary lateral vibrations and their influence on the seated participants' ability to read and write in terms of perceived difficulty. During the design and preparations of the study, results from the field study were used as a base. Amongst several different features the demographic factors had to be considered since the population of normal train travellers represented a broad variety of attributes, *i.e.* young, old, big, small, male, female, students, professionals and unemployed. Valid postures and activities were extracted from the field study to represent a controlled set of contexts for sedentary work in a train. The writing test from the field study was developed to obtain more restricted and refined results.

4.2.1 Demographic data

A total of 48 healthy subjects participated in the study, consisting equally of 50% women and 50% men. To investigate the influence of age the subjects were recruited according to strict age criteria, *i.e.* three age groups with five-year intervals. In earlier publications (Sundström 2004) significant correlations were identified among several of the demographic variables. Variables like gender and anthropometry were found to be strongly and significantly correlated with each other. To handle these complex relations between the anthropometric measures a *Principal Component Analysis* (PCA) was undertaken (Chatfield *and* Collins, 1980). To obtain a variable that accounts for most of the variations in the anthropometric data a new un-correlated variable was created from a linear combination of the four anthropometric measures.

In the Repeated measures test of *between-subject effects* no significant effects ($p > 0.05$) were found on the rated difficulty due to the anthropometric variable, gender, or age. The mean level of education was high, with 80% of the participants having passed or was involved in university studies. None of the participants reported to have any previous experiences of whole-body vibrations from occupational or leisure activities.

The number of *fitness* activities per week had no significant effect on the rated difficulty. However, the number of *fitness* activities did have significant interaction effects with both posture and vibration amplitude. Non-significant effects were found for all the studied parameters of physical health, *i.e.* musculoskeletal disorders, medication/treatment, use of tobacco, or need of visual correction.

How often the subjects normally write by hand or on a computer showed no significant effect on the perceived difficulty ($p > 0.05$). The type of writing tasks that normally occupy the subjects showed no significant effects. Nor were there any significant main-effects on reading-difficulty due to the variety of different literature read by the subjects. This further suggest that the reading task (word-chains) was unaffected by the subjects' reading skills/habits. The fore and after test revealed some learning effects in the reading task, measured in the number of decoded word-chains. It is however likely to believe that the subjects learned this particular decoding task very quickly, and that the effects of the learning were minimal.

4.2.2 Effects on reading and writing

Out of totally 3456 required responses there were only 10 cases of missing data. In each case the missing responses were replaced with group means. To summarize the correlations and standard deviations for all the levels of the within-subject effect *Mauchly's Test of Sphericity* was applied on the whole material. The test revealed a significant homogeneity ($p < 0.000$) for the frequency-variable, *i.e.* the only variable having more than 2 levels. Women generally gave lower ratings of difficulty for the reading task than the men although these gender differences were non-significant. The students also gave slightly lower ratings than the other two groups, in both reading and writing.

Remarkable significances were found for the influence of all the control variables (Frequency, Amplitude, Posture, and Task) both independently and in interaction up to third level. However, the interaction on the fourth level (F*A*P*T) did not have significant effect on the perceived difficulty which however could be an effect of chance.

Effect of amplitude
The effect of vibration amplitude shows a strong and proportional relation with difficulty in both tasks, *i.e.* 0.8 m/s^2 giving double difficulty compared to 0.4 m/s^2. The mean level of rated difficulty for all conditions at 0.4 m/s^2 was just above 20 on a scale from 0 to 100. It should however be kept in mind that a difficulty-response of 25 actually corresponds to a 'Moderate' experience of difficulty on the CR-100 scale. A subjective response of 45 corresponds to 'Strong' whereas a score of 70 corresponds to a 'Very strong' perception of difficulty.

Effect of context
Both posture and task showed significant effects on the rated difficulty ($p < 0.001$). According to the A-T models described in the theory section the influence of context can be studied by comparing the tasks and the postures. Considering the differences between reading and writing, where the biggest influence from the two postures were observed for the reading task.

Effect of task
Reading and writing show the same principal frequency dependence. The main difference between the two tasks was that reading was generally rated less difficult than writing. "Total means of the rated difficulty are plotted as a function of frequency for reading and writing with material placed on the lap, in Figure 4-1. The two amplitude levels are presented in 95 % confidence intervals for each task and posture.

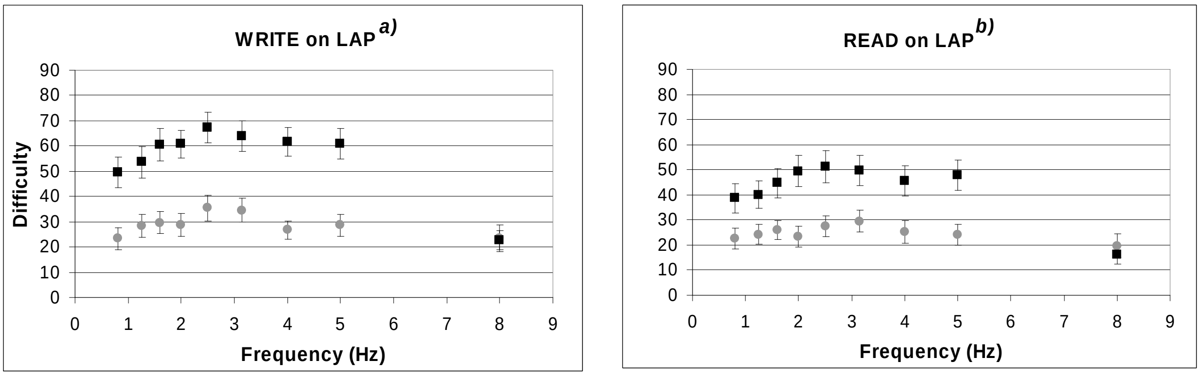

Figure 4-1 Frequency characteristics for perceived difficulty of Writing(a) and Reading(b)

Effect of posture

The seated posture showed to have a significant effect on judged difficulty. The effects of posture also seem to differ between the age groups and the two tasks. The difference in characteristic is clearly seen when comparing the responses for the two postures in Figure 4-2. The results reveal that the difficulty is rated lower when the work is performed on the lap, *i.e.* when sitting leaned against the seatback. It was not possible to control the exact body alignment of each test subject during the vibration exposure. So, even though the two postures were more or less different their two distinguishing features made it very difficult to identify the causes of the response. the support or lack of support of the upper body, or the actual damping of the work material that gave rise to the postural effects.

Comparing the two postures at the frequencies *2.0, 2.5* and *8.0* Hz only small discrepancies were found. The differences mainly occured at the mid frequencies (3.15 -5.0 Hz) and the lower frequencies (0.8-1.6 Hz), see Figure 4-2.

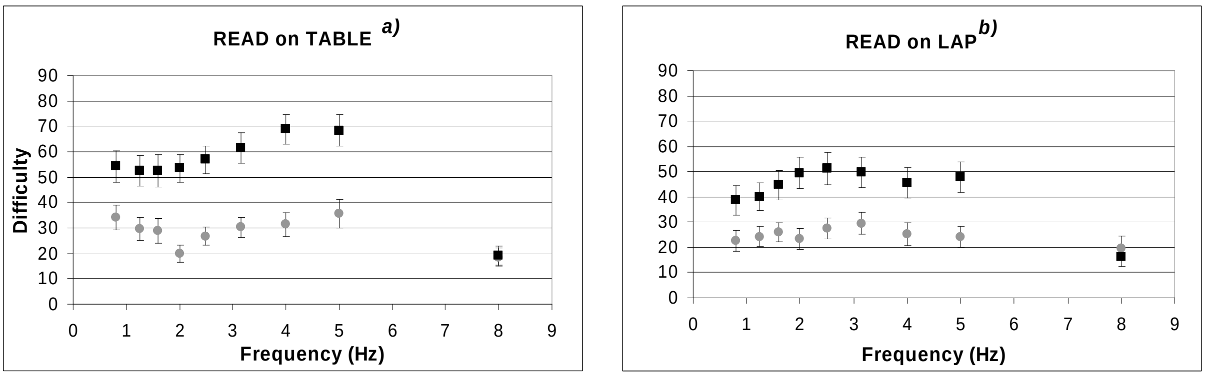

Figure 4-2 Frequency characteristics for perceived difficulty of Reading on the Table(a) and on the Lap(b)

Effect of frequency

The frequency shows very strong and non-linear effects on perceived difficulty. The obtained results are difficult to interpret even with a biomechanical approach since the human body has several vibration modes in the studied range. Besides, there are individual differences in how vibrations affect us. In general the frequency characteristics were found to be consistent with the responses found in the laboratory study by Westberg (2000). Westberg also noticed *"a more pronounced frequency dependence while reading compared to writing"*. He also found response peaks at 2.0 Hz for reading and 4.0 Hz for writing with generally higher responses in difficulty for writing against reading. Outside the work carried out here, there are only a limited number of studies available to compare the obtained results.

To explore the obtained frequency dependence further four intervals within the studied range will bedescribed and commented upon; < 2Hz, 2-4Hz, 4-5 Hz, and 5-8 Hz. Below 2 Hz an increase in difficulty is shown for the leaned back posture as the frequency increases to this lower limit. While seated leaning over the table (without backrest) the effect is roughly constant over the frequency range. In this range others have found swaying motion of the upper body (Griffin, 2003).

Gunston (2003) studied lateral vibration transmissibility in terms of *apparent mass*[1] of subjects seated on a rigid seat without backrest and noticed an almost flat response in the range 0.2-2.0 Hz. Holmlund *and* Lundström (1998) studied the mechanical impedance of subjects in relaxed and sitting erect on a rigid seat without backrest. They found two principal peaks in the lateral impedance at 2 and 6 Hz. Up to the first peak in the range 2-5 Hz they noted a general increase in impedance with frequency. The second peak was found in the range 5-7 Hz for most subjects while seated in the relaxed posture.

The frequency responses are somewhat similar to *apparent mass* responses found in vertical (Mansfield *and* Griffin, 2000) and in the lateral direction (Fairley *and* Griffin, 1990). Three general resonance peaks were found at 0.7, 2.0, and 5.0 Hz. Apparent mass responses are however difficult to interpret since the peaks behave in a non-linear fashion. Another possible explaination to the obtained frequency responses is that parts of the frequency characteristics comes from different eye-movement reflexes, as described in Section 2.3.1.

Howarth and Griffin (1988) studied the effects of frequency, magnitude and direction of building vibrations. From the determined weighting functions of the lateral vibrations they obtained a similar decrease between 4 and 8 Hz. For frequencies greater than 5 Hz they also noted vertical motions to cause more annoyance than horizontal motions. The same major decrease was also noted by Westberg (2000) in the range from 4 to 10 Hz. This decrease in difficulty with increasing frequency is not so surprising, since the displacement of a vibrating motion rapidly decreases with increasing frequency.

4.3 Results of laboratory study II (Paper III)

The second laboratory study was concerned with transient lateral vibrations and their influence on the seated participants' ability to read and write in terms of perceived difficulty. In this study the results and experiences from the two previous studies were implemented in the design. To investigate at what level acceleration peaks will disturb normal reading an additional third judgement part was included in the study, *i.e.* part C.

The two previous studies showed insignificant differences in responses due to gender, age and anthropometry. Therefore the participants were recruited according to limited ranges in anthropometry and age to see if the reliability in responses could be further improved in this

[1] *The apparent mass is the calculated quotient between the applied force and the obtained acceleration.*

study. The hypothesis was that higher levels of difficulty should be expected in this study. To avoid too high resonance effects and difficulty ratings only one posture was chosen. To sit leaned against the backrest with the material on the lap was thought to provide more support for the seated subject and to be a simple but yet a common posture.

4.3.1 Demographic data

In total 21 subjects participated in the study, whereof 6 were female and 15 were male. The age parameter was omitted in the analysis since the participants were all relatively young. Also the level of education was disregarded, since all subjects were working or studying at the university the variation was minimal. In previous publications (Sundström 2005) significant correlations were presented among several of the demographic variables. It must be pointed out that even though most of the correlations are significant it does not imply that they have a significant influence on the perceived difficulty.

With comparison to the first laboratory study the participants here showed fewer correlations between the anthropometric measures. This may be an effect of the smaller variation in anthropometric data, which was due to the more restricted inclusion criteria in this second study. Due to these inbound correlations in the anthropometric data the same *Principal Component Analysis* (PCA) and regression method was also applied in this laboratory study. The regression method that was utilized in this PCA gave somewhat different estimations of the factor score coefficients $m_1 – m_4$ against the first laboratory study.

In the Repeated measures test of *between-subject effects* showed no significant effects (p > 0.05) in rated difficulty due to the anthropometric variable or gender. Only a few participants reported to have previous experiences of whole-body vibrations from occupational or leisure activities.

The number of *fitness* activities per week had no significant effect on the rated difficulty, what so ever. Non-significant effects were found for any of the studied parameters of physical health, *i.e.* musculoskeletal disorders, medication/treatment, use of tobacco, or need of visual correction.

70% of the participants write by hand or on a computer for at least 10 min every day. Only 10% reported that they never write by hand for longer than 10 min periods. The subjects' normal type of writing tasks did not show any significant effects. The subjects every day reading habits were mainly focused on letters, notes, messages, articles, and technical reports. About 80 % also read newspapers and magazines every day. Whereas only 38% read novels more than two times per week. No significant main-effects were however found in reading-difficulty due to what type of literature the subjects usually read. Once again it seems as if the reading task (word-chains) was unaffected by the subjects' reading skills/habits.

4.3.2 Effects on reading and writing (part A&B)

In these two parts of the study, only 4 responses were missing out of a total of 756 responses. The responses show homogenous variations ($p < 0.05$) for both vibration frequency and amplitude.

Effect of amplitude

The vibration amplitude showed significantly strong and linear effects (p < 0.001) on the perceived difficulty. For the writing task the effect of amplitude is more pronounced than for reading. On average the differences in mean rated difficulty was only minor between the three amplitude levels. At the amplitude 0.7 m/s^2 the mean difficulty is about 20 for each frequency.

Effect of context

Since only one posture was used the contextual effect was studied through comparison of the two tasks. The writing task was rated as slightly more difficult than the reading task, which is consistent with the findings from the previous laboratory study on stationary vibrations. These differences however proved to be not significant (*p=0.142*) and also showed low power. On comparing the responses of difficulty against those obtained under stationary vibrations it becomes clear that the transient vibrations cause generally lower levels of difficulty. This lower level could be one of the main reasons to the insignificant observed differences between the reading and writing responses.

Effect of frequency

The vibration frequency showed a strong and non-linear effect (p < 0.001). The most distinct characteristics of the frequency are the general decrease in difficulty as frequency increases. The maximum values for both tasks were found at 1.25 Hz whereas the influence is less at 5.0 Hz. A smaller variation in responses at 5 Hz indicates a higher degree of agreement. Further characteristics are shown by the local peaks in difficulty at 2.5 Hz for the reading task and at 3.15 Hz for the writing task. The obtained results also show general consistency with the previous results by Westberg (2000). Westberg used vibration transients of three frequencies (1, 2 and 4 Hz), at three amplitude levels (0.5, 1.0 and 2.0 m/s^2). With increasing frequency he found almost linear, but similar, decrease in difficulty-response for all amplitudes.

To get a more diverse picture of how the amplitude and frequency affect the perceived difficulty amplitude measures other than acceleration (m/s^2) were considered. From the stationary background vibration with the un-weighted peak amplitude of 0.30 m/s^2 (*i.e.* 0.21 m/s^2 r.m.s) the crest factors for the three amplitude peaks (0.7, 1.0, 1.4 m/s^2) can be calculated according to the ISO-Standard (ISO 2631-4, 2001). None of the three calculated crest factors (3.33; 4.76; 6.67) exceeds the critical limit value 9. In the ISO-Standard two different vibration dose values are stated, *i.e.* the *VDV* and the estimated vibration dose value (*eVDV*). For sinusoidal vibrations with low crest factor, as in this case, a simpler *Root-Mean-Quad* (r.m.q) value can be used according to Equation 4-1 (Griffin, 1993).

$$r.m.q = a_w \cdot (3/8)^{1/4} = a_{cc} \cdot W_d \cdot 0.7825 \qquad (4\text{-}1)$$

With the calculated r.m.q-value, all responses can be compared according to the same scale despite each stimulus having a different amplitude and frequency. The total mean difficulties for all frequencies and amplitudes are plotted in Figure 4-3 as a function of frequency weighted *r.m.q*.

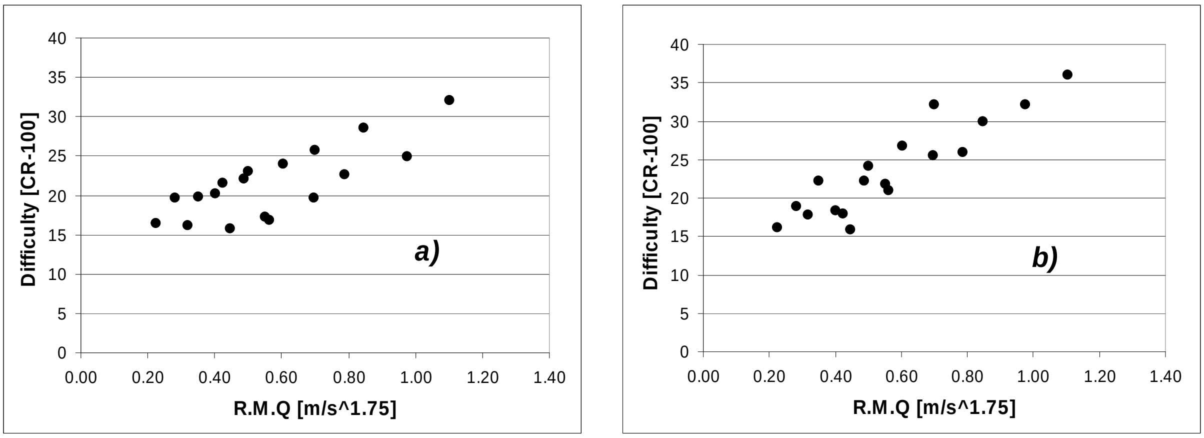

Figure 4-3 Mean difficulty plotted for Reading (a) and Writing (b) as a function of R.M.Q.

A linear relation appears between the *r.m.q* and the rated difficulty, for all the frequencies and amplitudes. High *Pearson correlations* were obtained both for writing (r^2 = 0.82) and for reading (r^2 = 0.62).

4.3.3 Disturbance test while reading (part C)

In the disturbance test the subjects marked their disturbance while reading by pressing a button. The amount of disturbance marks were calculated for each transient vibration stimulus. At 1.25 Hz the highest amplitude (0.7 m/s^2) only gave a 33 % amount of disturbance marks. For 2.0 Hz and 4.0 Hz the same amplitude gave 29 and 24 % amount of disturbance respectively.

The principal results of reaction times of the button pressing is presented in Table 4-2 for each frequency and respective amplitude.

Table 4-2 Mean values and standard deviations of reaction times for reading disturbances.

	1.25 Hz		**2 Hz**		**4 Hz**	
m/s^2	*Mean (s)*	*SD*	*Mean (s)*	*SD*	*Mean (s)*	*SD*
0.433	-	-	0.90	0.43	7.36	0.56
0.466	1.60	0.50	3.61	2.88	3.29	3.15
0.500	1.17	0.49	1.08	0.23	0.89	0.18
0.533	2.22	1.10	2.22	2.02	3.55	4.69
0.566	1.67	0.65	1.19	0.46	3.38	2.58
0.600	1.77	0.61	1.81	1.11	1.71	1.22
0.633	2.24	0.58	1.60	0.78	1.94	1.15
0.666	1.70	0.98	1.85	2.10	1.07	0.37
0.700	1.45	0.55	2.36	2.66	1.19	0.56
	N=78		N=76		N=48	

Out of 1134 possible occations of button pressings as few as 203 reaction times could be calculated. This limited number is mainly due to the low reliability of these exploratory data. Typical values from tests involving focused reaction tests usually obtain reaction times close to 0.3 sec at best. Normal values for brake-reaction-times while driving are typically around 1.0 sec. It is thus reasonable to assume that the subjects' were deeply involved in the reading task, since several of the obtained reaction times exceeded 2.0 sec.

5 Discussion

5.1 Responses of rated difficulty

The fundamental aim of the laboratory studies reported here was to measure the passengers ability to read and write. As stated in the method section the term *ability* is confounded with a number of personal prerequisites, *e.g.* education, age, reading habits, and inteligense. To measure the subjects ability in terms of disturbance was also abandoned due to the risk of getting confused with rating of the actual vibration exposure. Difficulty was finally found to be the most neutral and performance-based measure. To use any of the Borg scales the ratings had to be expressed in terms of intesity. The reasons for using the Borg CR-100 scale was driven by the need to represent the responses on a higher scaling than just ordinal. In this sence the CR-100 scale is very sophisticated and demands thorough introduction and callibration, but it is well worth the effort, since it proved reliable data. Even though the scale is verbaly level anchored, and as close to a ratio-scale level, subjects will perceive a presented stimulus differently. Infact were there very few subjects that rated their perceived difficulty accoring to the same pattern as the total mean. However during construction of trains, or other vehicles, only little attention can be given to each individual's needs. Nevertheless care must be taken to allow as wide distribution of the passengers' requirements as possible (Pheasant, 1999).

The CR-100 scale can be seen as a filter that transforms verbal expressions to a numerical representation of a perceived magnitude. This filter assumes a skewed distribution with more words describing low or moderate intensity. This distribution is then numerically transformed to magnitude estimates with an exponential expression. While using this filter it is reasonable to believe that its inbound characteristics will be reflected in the response-distribution. The results form the first laboratory study are however very consistent with the frequency characteristics what were found in a similar study by Westberg (2000). Further were the individual variations in rated difficulty fairly small, proving the reliability of the scale.

In the second laboratory study, on transient vibrations, the lowest amplitude caused almost equal mean levels of difficulty at all frequencies. Similar levels of difficulty were observed for the lowest ratings in the first laboratory study. It is thus tempting to believe that a base-line excists in the percieved difficulty, from which all ratings are based. Eventhough the means in rated difficulty only show minor differences between the frequencies the variation indicates that the subjects make some sort of judgement or actually feel some kind of difference. The presence of an eventual base-line was however not possible to establish by measuring the difficulty for static conditions since the ratings were referred to "*the difficulty due to the vibrating motion*".

The responses in the second laboratory study showed large individual variations which could be caused by a generally low level of difficulty (too low acceleration amplitudes). Another reason might be that the subjects were focused on the tasks and therefore unaware of the occasional vibrations. Due to lack in preparation for the last part of the second laboratory study the amplitude peaks were slightly lower than planned.

5.2 The experimental situation

Generally it is understood that laboratory experiments can never be expected to represent exactly the same contextual prerequisites present in the real field. The aim should of course be to create an ecological validity that in an efficient way simulates the real situation. In both laboratory studies reported in this thesis the subjects gave high and consistent ratings of fidelity for the mock-up's vibrating motions. A few subjects further commented that if the worst vibration exposed in the experiement would have occurred in a real train they would have stopped working. This indicates that for vibrations with an amplitude of 0.8 m/s^2 some frequencies would produce intolerable conditions for reading and writing. A small group of subjects also admitted that they experienced slight dizziness, or light nausea, but that it quickly disappeared during the half time break. These effects may be due to the confined environment of the mock-up combined with the undivided mental focus on the tasks.

A reading task that consists of word-chains can not be said to be very representative for fluent reading of a text. As outlined in the method section (3.2.4) are however the word-chains valid for the decoding process (Johansson, 1999), which is a crucial part of the reading process. One of the complications of using word-chains under vibration exposure is the risk of confusion between the difficulty of decoding the separate words and the difficulty of making a precise pencil mark.

A writing task involving dictation can neither be regarded as representative for most situations of writing. Although, there are several situations and writing tasks that involve mere transcription or copying of spoken or written language. Since this thesis was not concerned with the cognitive processes in writing, dictation was considered valid for extracting the manual hand writing.

Since it was noted that the train passengers in the fieldstudy applied different postures for different tasks this dependence had to be considered in the laboratory. To obtain a reasonable number of postures in the experimental design and yet represent the variation in postures, a combination of postures were used. The two postures that were chosen in the experiements had two characteristics that differed, *i.e.* the support of the back and the support of the working material. This combination unfortunately made it impossible to identify the actual cause to the difference in responses between the two postures.

To be able to generalise the results, these have to be interpreted according to the differences between the laboratory and the real use situation in a running train (cf. Rexfelt, 2005). This is essential since the primary task for the experimenter is not the primary task for the writer (Piolat *et.al.*, 2001). The purpose of the instructions was therefore to give all subjects in the laboratory studies equal goals and motives. Nevertheless, a more thorough investigation of the subjects' individual motives could have given a better understanding of their individual responses. There is a risk that the subjects rated their writing difficulties in actual terms of how legible their own handwriting was. This fact may however also reflect the writing difficulty indirect. The number of word chains in the reading task were arranged so that no one should be able to manage them all. There is thus an obvious risk that the ambitious subjects experienced frustration when they could not complete all the words within time. Such a frustration or disappointment might also influence the rating of difficulty (Johansson, 1999). In other words, there is a danger that the rated difficulty is confounded with aspects of how well the subject's fulfils his/her personal goals/motives, *i.e.* how many words they expected to read/write. The opposite could of course apply if the subjects did not find the task important, or necessary. One possible approach to control for this would have been to use parts of a questionnaire that Kjellberg *and* Wadman (2002) developed to evaluate psychological stress in terms of importance, realism, energy, involvement, and frustration. Another but less likely source of error is that some subjects may have judged the intensity of the vibration instead of the actual diffculty.

5.3 Control measures

In both laboratory studies the control variables were mainly focused on age, gender and anthropometry. Physiological measures could have been used to gain control of the test subjects sensation of distress during the experiment. According to deWaard (1996); heart rate, blood pressure, or eye movement are some of the most reliable physiological measures of arousal and operator state. The major disadvantages with such measures are however their interference with both the test subject and the situation. Physiological probes are generally sensitive to noise and often demand complicated and time consuming routines for application and calibration. As an indicator of the physiological state of the participants they were asked to rate their physical well-being at the end of each laboratory study. However, the rated level of well-being did not have any significant effect on perceived difficulty.

The individual differences in general reading and writing skills were disregarded since each individual was used as their own reference. Accordingly, no tests were devised to establish reading or writing skills. However, when analysing the subjects reading and writing habits no significant effects were found for the rating of difficulty. Neihter were there any effects of use of correction like contact lenses or glasses in any of the laboratory studies. Although the subjects visual acuity or need of correction were not tested in the experiments, any effects would have been properly considered in the *repeated measures* design.

Significant effects due to the order of the experimental conditions were found for the first laboratory study. Since these temporal effects were anticipated they were compensated by balancing the experimental design.

5.4 Objective measures of performance

As described in the method section, the reading and writing tasks were not designed to render a quantitative or objective output. The number of correctly decoded words and the number of written words could of course be counted and used as measures of performance or efficiency. However, these numbers would be vague measures since the variation in the data would most likely be insufficient. There are three main reasons for the limited variation; the exposure time, pace of work, and the level of education. Since the exposure/working time was only 25 s long the subject could not manage to read or write so many words. Short exposure times were traded against avoiding temporal effects like fatigue and habituation but also to limit the total time of the experiment. The variation in work pace was intentionally limited by instructing the subjects to find an even and comfortable pace of work throughout the experiment. All subjects were also instructed to do their best since Hyldgaard (2000) pointed out that adult subjects normally prioritize quality in performance before speed of performance. Lastly was the educational level among the participants very high on average, with few exceptions. Thus will objective measures that are based on reading and writing speed be inadequate measures of performance. Further, not all subjects ceased writing exactly on time, probably because they were eager to finish the piece on the tape.

5.5 Context and awareness

The importance of context and awareness has been pointed out in the theory section. In the theoretical modelling the contextual dimensions have been defined as *1)* the action of reading or writing, *2)* the artefacts and *3)* the environment. These contextual dimensions have been incorporated in the two laboratory studies by controlling the tasks and postures (*i.e.* actions and artefacts) as well as through the vibrations and restricted mock-up interior (*i.e.* the environment). Through this interwoven design it has been possible to study the importance of the context.

Awareness has been used more or less as an indicator of whether an activity is on *action level* (aware) or on *operational level* (unaware). In the laboratory studies, the most interesting causes of a shift in awareness have been the breakdowns caused by vibrations. Perhaps this thesis cannot provide all the answers to what actually happens when a vibrating motion (misfit) causes a breakdown. However, vibrations can indeed cause shifts in focus and thereby cause disturbances that increase the feeling of difficulty. If a vibrating motion of the passenger's body is near the most sensitive frequencies or actual resonance frequencies of an organ or bodypart it is easy to understand that the performance will be affected. When skills like reading and writing are developed the detailed processes and goals of the operations become unaware to us. But when a breakdown occurs the reader/writer will go from being unaware of the goals of the process to being aware of the automatic operation and maybe also its goals. From having the goal to read and comprehend a text the focus will be shifted to identifying the separate letters and decoding each word. Respectively, moving away from fluent forming of words on the paper to concentrating on drawing one legible letter at a time when there is a focus shift in writing.

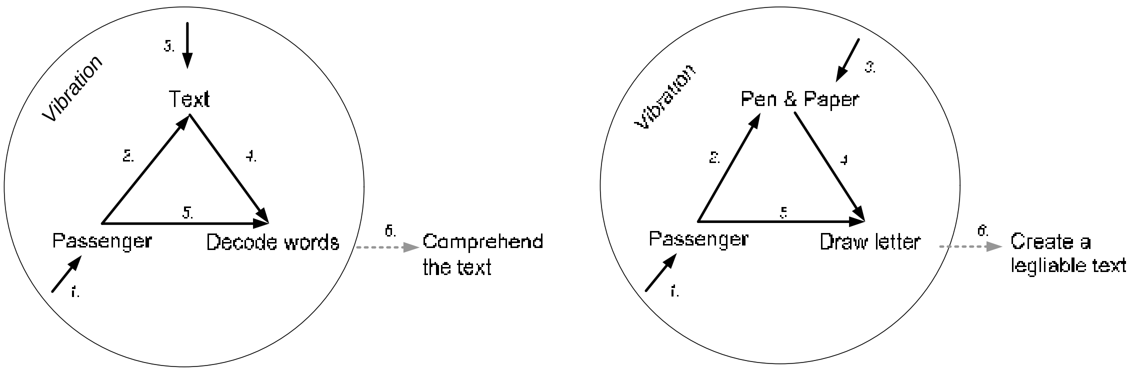

Figure 5-1 Interactions while Reading under vibration exposure

To understand how the awareness is affected by breakdowns in the reading and writing processes the interactions in each process has to be investigated. The models in Figure 5-1 help to identify where the most crucial breakdowns will occur. In the theory section the most beneficial interaction to study was identified between the vibrating artefacts (text and paper) and the objective (word decoding and forming of words). The answer lies thus in the different parts of the visual acuity and manual performance that can or will be disturbed by vibrations.

The importance of awareness in the actions of reading and writing are discussed separately in the following subsections.

5.5.1 Reading

It is clear that when the text vibrates due to excitation from the hands or from the working surface the visual acuity and word decoding will be affected. Griffin and Lewis (1978) declared that "displacements less than +/-1' of arc in any direction are unlikely to affect visual acuity". On typical reading distances (0.4 - 0.75 m) at 8 Hz this corresponds to a displacement of 0.1 - 0.2 mm or accelerations of 0.3 - 0.5 m/s^2 respectively. Even if these values should not be seen as absolute thresholds it is clear that the acceleration levels 0.4 and 0.8 m/s^2 are likely to have affected the visual acuity. According to Moseley *and* Griffin (1986) it is known that at frequencies above 2 Hz, pursuit eye movements are not efficient.

During reading the saccades and fixations usually show a complicated pattern. For instance, a skilled reader very seldom fixate each word in a sentence. An individual who learns to read or reads a very difficult text does however tend to fixate some words more than once (Rayner, 1998). Eye movements could therefore be a successful indicatfor detecting a breakdown in the reading activity.

To approach the effect of breakdowns the judgement of reading disturbance was studied in the second laboratory study. The subjects were instructed to press a push-button to mark when they were disturbed in their reading. These disturbance marks were logged over time and were thought to indicate the occurrence of breakdowns in the reading. When analysing reaction times of these push-button marks it became clear that it is far from obvious when a vibration transient will cause a breakdown in the reading process. Nor could it be established whether the subjects actually became aware of the vibrations when they had a breakdown in their reading. The subjects may very well have been so accustomed to breakdowns that they did not push the button each time this occurred. Interestingly a few subjects asked the experimenter if they could bring the text home to read it to the end. This kind of enthusiasm and engagement clearly shows that the subjects were deeply involved in reading the text.

Other plausible explanations for shifts in the frequency characteristic (at least for vertical vibrations) are the ocular and vestibular reflexes of the eye, OKR and VOR. The OKR is as mentioned very efficient below 0.1 Hz but less effective at frequencies above 1 Hz. Whereas the VOR provides good compensation between 1 and 7 Hz. The semi circular canals are the major signal source for the reflex which results in poor compensation at low frequencies (0.05 Hz). According to Griffin & Lewis (1978) there is good evidence for a critical frequency around 6 Hz where the saccades will compensate for the vibrations. At frequencies higher than ~7 Hz performance improves. Above the critical frequency the vestibular-ocular reflex induces compensatory eye movements that stabilises the line of sight when the head is making a pitch motion due to vertical vibration. This compensation only applies for rotational head motions and not for translational motions. For this effect to occur under lateral vibration exposures the frequency must be high enough to excite the rotational mode of the head.

5.5.2 Hand writing

When paper and pen are excited either by the hand or the working surface the way words are formed are clearly effected. The limitations in the manual performance thus lies with the fine sensory-motor control of the hand and arm. Vibrations would not cause any problem if they could be fully compensated for, *e.g.* by letting the hand vibrate in phase with the table. In such a case the operation would only consist of a small overlaid tracking motion. One reason why compensation of manual operations does not work in this manner is the lack of anticipation and predictability of the vibrations in our environment. The maximum bandwidth in manual tracking of a random signal is normally 0.5 to 1.0 Hz. Predictable signals can, however, be tracked up to 2.0 - 3.0 Hz (Wickens, 1992). Eventhough the seated posture also influences the frequency dependence this is somewhat similar to the findings in the first laboratory study on stationary vibrations.

When a skilled manual operation like handwriting is performed the movements of the pen can be regarded as an open-loop process. Since the proprioceptive muscle activities demand very little feedback, the activity becomes an unaware process and can be better regarded as an operation. Since open-loop processes are based on feed-forward control the operation is very delicate and can only handle minor disturbances before they demand feedback or breaks down. When the open-loop behaviour no longer functions it is not able to perform at a skilled automatic and unaware level. Instead we will become dependent on feedback to establish a compensatory control of the movements. The manual operation has thus degraded from an *open-loop* to a *closed-loop* performance.

When it comes to more detailed knowledge on the proprioceptive (open-loop) processes and their capabilities very few explanations are available. According to Jones (1996) relatively little is known about the relation between proprioception and motor skills.

5.6 Weighting of vibrations

The frequency weighting filters in the standards ISO 2631 and Wz are used for producing an amplitude measure that better represent the vibrations as experienced by a seated person, *i.e.* amplifying the frequencies which are the most sensitive. The characteristics of the ISO weighting curve can however not be compared with all types of frequency responses. A frequency weighting is actually an inversion of an equal response curve (Mansfield, 2005). To illustrate how comparisons of weighting filters should be made an example is given with frequency characteristics obtained in the first laboratory study. If it is assumed that the amplitude-difficulty relation is linear, according to Equations 5-1 and 5-2, interpolation between data points from the two measured amplitude levels 0.4 and 0.8 m/s^2, see Figure 5-2 is possible.

$$\text{Difficulty} = \text{Amplitude}\cdot k + m_0 \qquad (5\text{-}1)$$

$$H(\omega)=Out(\omega)/In(\omega) = Diff/Amp = (Amp\cdot k + m_0)/Amp \qquad (5\text{-}2)$$

From these extrapolated data it becomes possible to group frequencies and amplitudes with equal difficulty, see Figure 5-3.

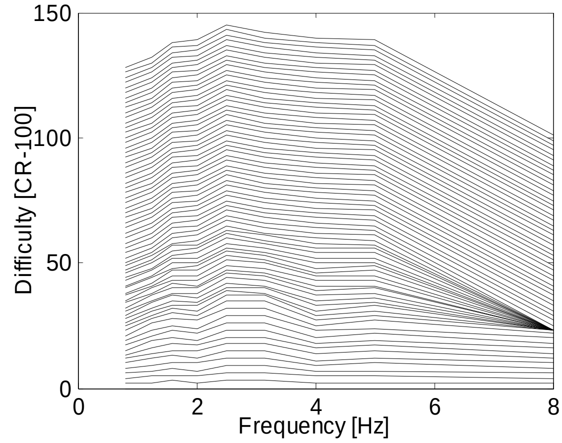

Figure 5-2 Extrapolated mean difficulty

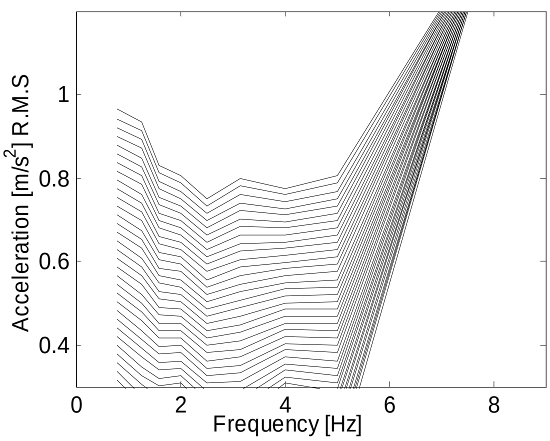

Figure 5-3 Equal difficulty

By finally inverting the values for each group, Figure 5-4, it becomes possible to compare them to the weighting curves of ISO 2631-4 and *Wz*, see Figure 5-5.

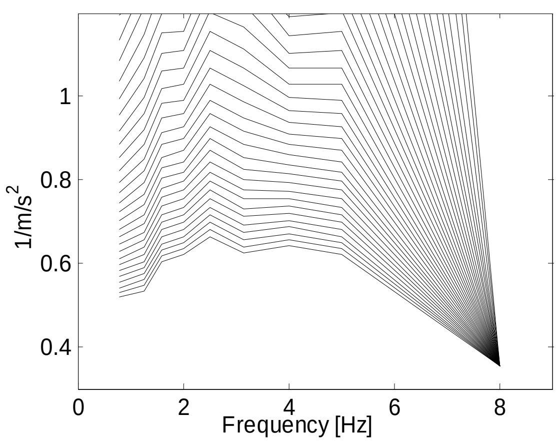

Figure 5-4 Inverted difficulty

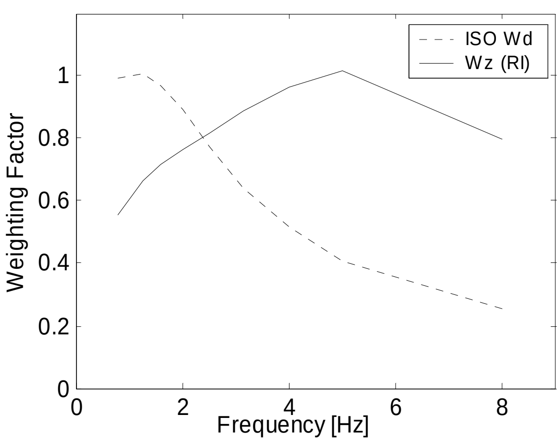

Figure 5-5 Standard weighting functions (ISO2631-4, 2001; Andersson et.al., 2005)

However, since the acceleration was constant for all frequencies the inversion of the equal difficult contour gives the same shape as the equal acceleration curve. The similarity in shape is clearly seen on comparison of Figures 5.4 and 5.6. The corresponding transfer function for writing on the table is shown for comparison in Figure 5-7.

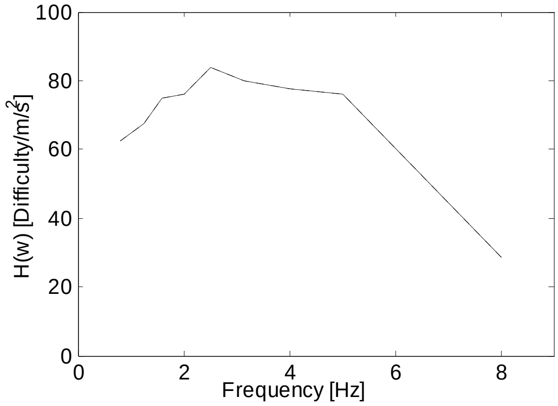

Figure 5-6 Transfer function for Read on Lap

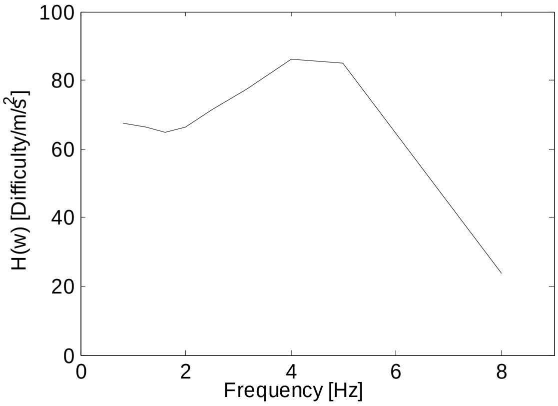

Figure 5-7 Transfer function Write on Table

Similar comparisons were made by Howarth and Griffin (1988) who reported good matching between lateral frequency weighting and *Wd* (iso-acc). However, when comparing the obtained contours of equal acceleration with the frequency weightings of ISO 2631 and Wz it can be concluded that the best fit is obtained by the Wz filter. Although the fit is far from perfect it resembles the findings by Westberg (2000). The best fit seems to be a combination of the two filters. The ISO filter is well in accordance with the theory that lateral motions are most easily perceived below 2 Hz. However, as stated by Mansfield (2005) the relation to equal sensory perception is one of the major limitations of the present weighting filters. Creating a new weighting filter is not one of the aims in this thesis. Nevertheless more accurate weighting functions could have been developed by incorporating additional acceleration levels in the experimental design.

5.7 Evaluation of Activity Theory

To outline how vibrations can cause disturbances of activities like reading and writing the fundamentals of the Human Activity Theory (A-T) has been used throughout this thesis. There are of course alternative theories and models for human behaviour and activity. Since the aim of this thesis was not to evaluate the A-T other theories were not investigated.

The separate parts of the reading and writing process could of course be discussed independently from each other, but those could not have been treated in relation to their goals and awareness during performance. Neither could the relations between the different interactions in the working process been handled stringently nor be modelled in a holistic way. The shifts in awareness due to breakdowns caused by vibrations would further have been difficult to explain with emphasis. The theoretical modelling would rather be rather thin without this model since it brings structure and transparent relations to the problem. Activity theory provides terminology and framework to handle and explain the different issues involved with train passengers' activities under vibration exposure.

Further, A-T can clarify what effects different goals or motives have on performance of the activity quite simply. The difference in awareness/focus is the central issue to explaining why the frequency weightings in ISO 2631-4 are not suited for assessment of vibration discomfort for working passengers. Since an individual with an activity focus will not be aware of the vibrations in the same way as an individual focused on vibration.

What can be concluded from A-T is that vibrations may very well cause breakdowns in the working process. We are however fairly used to have breakdowns or interruptions that cause a shift in focus in our every day activities. But being exposed to frequent focus shifts in the activity becomes extremely annoying and demands more effort. Thus, an increase in efforts to to perform a certain task will, with time, cause it to be perceived as more difficult and tiring (Eysenck *and* Keane, 1993). As we suffer form a breakdown we actually become aware of the detailed goals of the process. We are usually liberated from these goals since we develop the operations to a skilled, automated, and unaware level.

Something that the A-T does not explain with convincing strength are the mechanisms that cause breakdowns and focus shifts. To find such explanations the properties of the physical operations have to be identified in detail (*e.g.* movements and reflexes of the eye, and neural motor schema of the hand during normal working conditions). This is however something that has to be considered in future studies.

5.8 Implications of train vibrations

To put things in perspective it must be noted that there are several other issues that train passengers value more than ride comfort and low levels of vibrations. For the ordinary train passenger, vibrations is not the first issue that is brought up in the discussion (Förstberg *et.al.*, 2005). This priority was partly confirmed in the control questions used in the laboratory studies. Matters like punctuality of the train, room for luggage and overcoats, and distrubances from other passengers were generally given higher priorities than noise and vibrations. However, when passengers are given the appropriate context they rate noise and vibrations as a major source of disturbance.

According to the findings in the field study the vibration levels are '*comfortable*' according to ISO 2631-4 and Wz. In other words, the actual *comfort* is not the issue since the ride comfort is acceptable. The fundamental issue should thus be the activity-comfort, *i.e.* the ability to perform activity without being disturbed by vibrations.

6 Conclusions

The objective of this thesis has been to investigate how the ability to read and write is influenced by low-frequency vibrations in the lateral direction. This influence was investigated through one field study and two succeeding laboratory studies.

To illustrate the importance of context and awareness and how vibrations can interfere with activities like reading and writing two simple models were devised from fundamental Human Activity Theory (A-T). This theoretical modelling emphasises the importance of having an understanding of the goals and motives that an activity is ruled by.

In the field study it was found that a majority of the train passengers used their travelling time to do office work. About 80% of the passengers were reading some time during the journey, 25% were writing by hand, and 14% worked with portable computers. While reading most subjects sat leaning against the seat backrest resting their book or paper on the lap. While writing, it was equally common to sit leaning over a table as to have the material on their lap.

None of the standardized routines that the train manufacturers use in their certifying vibration tests, *e.g.* ISO2631-4 or ENV12299, concern disturbance or annoyance of the passengers' activities. Nor do these standards compensate for variations of the passengers' seated posture.

The field study revealed that even the trains that were run on poor tracks showed acceptable vibration levels according to the present standards. However, when the passengers were asked to perform a short writing-test, over 60 % reported to be disturbed or affected by vibrations and noise in the train. It can be concluded here that even low levels of vibration can affect the performance of sedentary activities like writing.

Among the five measurement points, *i.e.* on floor, seat, backrest, armrest and table, the seat and the table were found to have nearly the same vibration levels as the floor. On comparing the frequency spectra, each train type showed somewhat individual characteristics but in the lateral direction all trains had their vibration peaks in the range 1-2 Hz.

Vibration frequency and acceleration amplitude was found to have a strong influence on the difficulty to read and write in the experimental studies. The acceleration amplitude of the vibration proved to be the strongest variable. It could also be concluded that the seated posture is an equally important parameter as the frequency of vibration. The posture was further noted to have greater importance than the task itself.

Passengers are not always disturbed by, or even aware of, the exposed vibrations. In fact as few as 35 % of the studied vibration shocks were noted to disturb reading.

Stationary vibrations were found to cause higher levels of difficulty for the tasks than transient vibrations, although the stationary acceleration amplitudes were lower.

The main conclusion is that present frequency weighting filter for evaluation of lateral vibrations in ISO 2631-4 and ENV 12299, underestimates the effects for vibrations in the frequency range between 2.0 - 5.0 Hz. A more appropriate evaluation of the passengers' *activity-comfort* would easily be achieved by modifying the present lateral filter to give more weight for frequencies around 3.0 Hz.

7 Future work

To put the present thesis in perspective and to make the best use of obtained results and knowledge the following issues are recommended for further research.

- Study how activities like drinking and working with a notebook computer are influenced by lateral vibrations.

- Investigate how activities are influenced by more realistic motion patterns and vibrations in more than one direction.

- Establish applicable weighting filters for different postures and activities.

- Create analytical models that handle the individual differences in responses in order to describe the most appropriate frequency function of the obtained data.

- Investigate the physiological phenomena that lies behind the characteristics of the frequency weighting curves, *e.g.* the vibration modes of different sitting postures.

- Investigate the potential of using eye movements as an indicator of task difficulty for reading under vibration exposure.

- Undertake more detailed studies of the limits of the manual (proprioceptive) control process of handwriting under vibration exposure.

Recommendations
The fact that it was more difficult to work on the table is a strong indicator that improvements of the table vibrations would render a better working environment on the trains. In most of the studied trains the tables and seats showed higher vibration levels than the floor. This clearly points out that there is room to improve the damping of the passenger seat as well as how the tables are mounted in the train. The tables should provide sufficient damping of vibrations in the range 2 - 4 Hz, since it is the most sensitive range for writing and reading, but also a very common range for vibrations in trains today. Poor table height may be another reason why passengers who use laptop computers prefer to work with the computer on the lap instead of the table. Much can be done to improve the working environment at the seating place in the trains. Such improvements would inevitably give the passengers a better ride comfort and overall well-being.

More specific weighting filters for vibrations will most likely help to improve the ability to work onboard. Increased travelling speed and fewer resources for maintaining the infrastructure will nevertheless be the more crucial issues for the ride-comfort in the future. The question is how much effort the train manufacturers and operators are willing to make in order to obtain better working environment for the train passengers.

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