Estimating text legibility of a mobile display on the basis of translational vibration caused by walking

Maria Olkkonen
Terhi Mustonen

Abstract — In this study, the effect of vibration on mobile-phone text legibility caused by walking was examined. Legibility was measured as reading performance and subjective task load when reading from a mobile-phone display while walking on a treadmill at 1.5 km/hour, 3 km/hour, and an individually defined speed (3.9 km/hour on average). Vibration was measured on the vertical, lateral, and fore-and-aft axes during walking. Vibration amplitude was calculated in five different frequency bands (1, 2, 4, 8, and 16 Hz), and correlated with the legibility measures. The amplitude increased most on the vertical and fore-and-aft axes as a function of walking speed, and the increase was largest in the 2-Hz frequency band. Legibility decreased concurrently with increasing vibration. The strong correlation between vibration characteristics and legibility measures suggests that vibration characteristics could, to some degree, be used in estimating small-display legibility while walking.

Keywords — *Legibility, mobile phones, small displays, vibration, walking.*

1 Introduction

Different aspects of the legibility of computer displays have been studied for several decades,[1–5] but the legibility of small displays such as used in mobile phones is a far-less studied area. One of the major differences between mobile and conventional computer displays in addition to size is the variety of environments in which they are used. Mobile displays can be viewed practically in all imaginable lighting conditions and when either still or moving. One of the conditions particular to mobile phones is that of reading from a display while walking, which demands that the gaze be stabilized during body motion. Every heel strike with the ground sends a shockwave through the body to the head causing transient vibration, which, if visual acuity is to be maintained, must be countered.[6]

Vibration is known to interfere with an individual's ability to observe quickly and accurately. Vision is impaired by vibration when adjacent details on the display become blurred or confused, and fine details, *i.e.*, high spatial frequencies, are usually the most degraded.[4] Threshold for the visual detection of motion depends on retinal image displacement, which may occur as a result of vibration of the eye, vibration of the display in view or vibration of both the eye and the display. Oscillatory motion becomes visible when the retinal image shows a perceptible change from the image of the stationary object. Resulting blur of the vision is typically alleviated with the compensatory eye-movement mechanisms that may include both predictive and adaptive elements depending on the characteristics and the source of vibration.[4,5,8–10]

Effects of vibration on vision depend on both the magnitude and the frequency of the oscillation.[4] The extent of the motion is most often expressed in terms of vibration acceleration and, thus, root-mean-square acceleration is generally adopted as the method of quantifying vibration exposures. Most commonly encountered motions contain vibration at more than one frequency, defined as the repetition rate of the cycles of oscillation, and often the vibration involves some motion occurring throughout a range of frequencies. In addition to magnitude and frequency, the direction of vibration needs to be covered in studying human vibration exposure.[4,5] ISO 2631 standard specifies an orthogonal co-ordinate system for the expression of the magnitudes of vibration occurring in different directions relative to the body.[11] According to this definition, translational vibration can be observed on vertical, lateral, and fore-and-aft axes perpendicular to each other, and on three rotational axes that rotate about them.

The effect of whole-body vibration on visual perception has been studied extensively in laboratory settings.[4,5,7,12] Although vision might be affected by any vibration frequency, whole-body vibration at frequencies 2–12 Hz seems to interfere with visual performance most, and the detrimental effects of lateral vibration are small compared to that of fore-and-aft vibration.[5,12] The largest effect of vibration on reading has been reported at 4 Hz within a relatively large range of vibration magnitudes (0.63–1.25 m/sec^2) for both fore-and-aft and lateral vibration.[12] However, it must be noted that vibration generated in the laboratory is typically sinusoidal or random and does not necessarily apply to natural movement. Until recently, vibration created by natural action has not received much attention.

Our recent results demonstrated that both vibration magnitude and frequency increase with walking speed.[13] The vibration caused by walking was shown to be fairly periodic including magnitudes of 0.1–1 m/sec^2 rms and fre-

Revised version of a paper presented at the 11th International Display Workshops (IDW '04) held December 8–10, 2004, in Niigata, Japan.
The authors are with the Nokia Research Center, Itamerenkatu, 11-13, Helsinki, 00180 Finland; telephone +358-5048-67528, fax +358-71-8037135, e-mail: maria.olkkonen@nokia.com

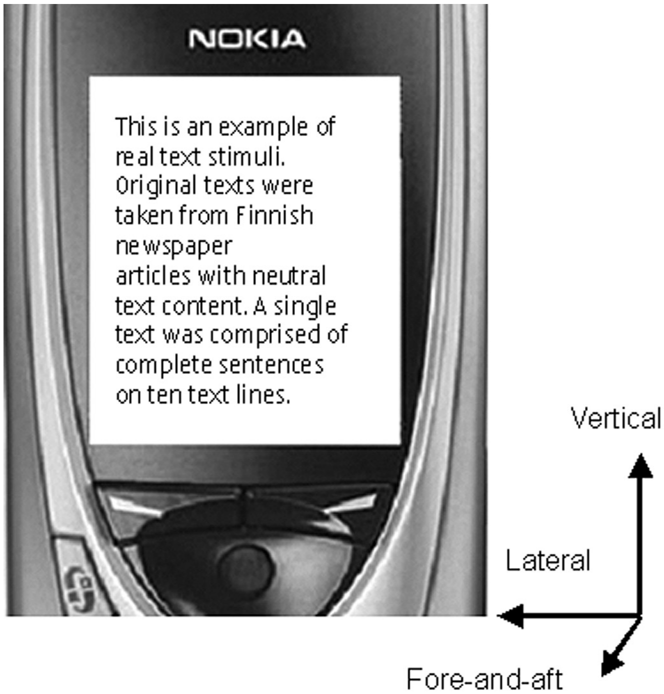

FIGURE 1 — An example of the reading stimuli. Vibration axes: vertical, lateral, and fore-and-aft are shown next to the stimulus.

quencies of 0.5–10 Hz, depending on the walking speed (1.5–4.5 km/h). Also, vibration generated by walking has been shown to decrease the legibility of a mobile-phone display, which was indicated by the decrease in visual performance as well as the increase in subjective task load.[13,14] Visual performance, *e.g.*, speed and accuracy of reading, is assumed to reflect the ability to extract information from the display, but the performance does not necessarily reflect visual comfort.[15] Furthermore, a greater subjective impairment has been reported across a wider frequency range and for all vibration magnitudes than that measured from visual performance.[12] These findings emphasise the importance of subjective measures in legibility testing in addition to reading speed.

The vibration of a display held in the hand while walking can be assumed to be rather simultaneous with the vibration of the head at slow walking speeds. Simultaneous low-frequency vibration of both the display and the viewer is suggested to be less detrimental to visual performance than the vibration of either the display or the viewer alone although this benefit seems to disappear at higher frequencies.[4,12] Faster walking speeds might introduce higher frequencies that would cause the head and the display to vibrate out-of-phase making the vibration more difficult to compensate for. This study was aimed at characterizing (1) the magnitude and frequency of vibration caused by walking on three translational axes; lateral, vertical, and fore-and-aft, as well as (2) the effect of walking speed on the vibration measures, and (3) the relationship of the vibration characteristics to mobile-phone text legibility. Especially, the separate effects of vibration axes and vibration frequencies were of interest in order to elucidate their relationship with small-display legibility.

2 Methods

2.1 Subjects

Thirteen subjects with normal or corrected-to-normal vision participated in the test. Their ages ranged from 25 to 36 years (mean 29, sd 3.2). All subjects had normal near-visual acuity and normal near-distance contrast sensitivity for five spatial frequencies (1.5–12 CPD).

2.2 Stimuli and apparatus

The stimuli used in the reading tasks were texts taken from Finnish newspaper articles with neutral content. A single text was comprised of ten lines of complete sentences, and contained approximately 200 characters, depending on word length (Fig. 1). A stimulus sequence was composed of ten consecutively presented texts that together formed a meaningful text section.

The stimuli were presented on a Nokia 7650 mobile phone (display resolution, 176 × 208; pixel pitch, 0.198 mm). The text was always black (luminance 0.5 cd/m^2) on a white background (luminance 47 cd/m^2). The smallest character size in the application was chosen to present the visual stimuli since small details are the most sensitive to the detrimental effects of vibration.[4] The letter height (uppercase H) was 9 pixels/1.8 mm, which corresponds to 0.26 degrees of visual angle from a viewing distance of 40 cm.

2.3 Legibility and vibration measures

Legibility was measured as reading velocity (characters per second) and subjective task load. Task load was assessed with the NASA Task Load Index (TLX), which provides an overall workload score based on a weighted average of ratings on six subscales: mental demand, physical demand, temporal demand, effort, frustration, and performance.[16] The TLX has two parts: in the beginning of the test, subjective weights for the dimensions are collected with the paired comparison method. After the test (or subtest), task load ratings on every dimension are given on a 100-point scale. These ratings are then weighed according to the subjective weights for each dimension.

Lateral, vertical, and fore-and-aft vibration of the mobile phone were measured with a three-axis accelerometer (measurement range, –49 to +49 m/sec^2; sampling frequency, 100 Hz) attached to the back of the phone while the subject was walking and performing the reading task. Vibration axes relative to the phone are shown in Fig. 1.

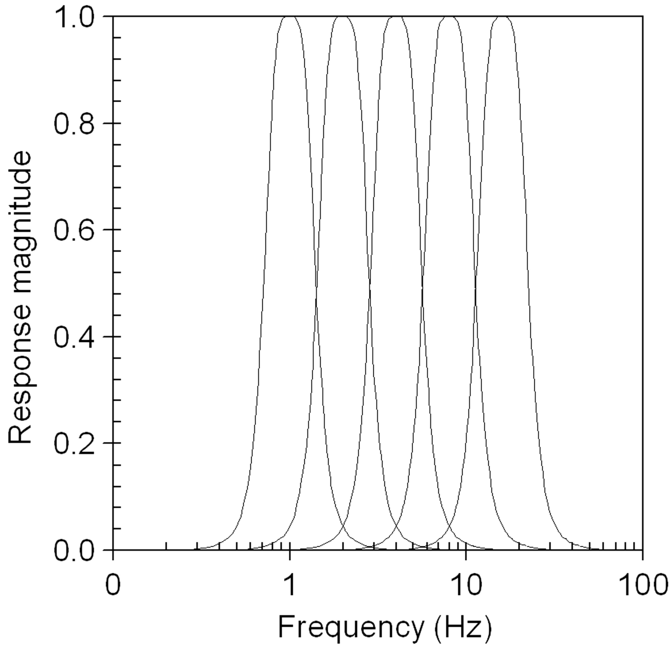

FIGURE 2 — Second-order Butterworth filters with center frequencies of 1, 2, 4, 8, and 16 Hz (from left to right). Normalized magnitude response of the filter is on the ordinate and frequency is on the abscissa (see Table 1 for details).

2.4 Walking conditions

Text legibility was tested and vibration measured at three different walking speeds: (1) walking on a treadmill at 1.5 km/hour, (2) walking on a treadmill at 3 km/hour, and (3) walking on a treadmill at an individual speed (range, 3.4–4.6 km/hour; mean, 3.9; sd, 0.4). The individual walking speeds were defined by allowing participants to walk freely down a corridor for 100 m and registering the time with a stopwatch. In addition to walking, the task was performed in a stationary position as a control.

2.5 Procedure

The subjects were instructed to read the texts carefully and quickly. Weights for the TLX dimensions were defined after a practice sequence at the beginning of the testing session. Subjects were allowed to accustom themselves to the treadmill before each walking condition. While walking on the treadmill at the appropriate speed, subjects started the reading task by pressing the right control button below the display. Pressing the same key indicated that the subjects had finished reading that segment and caused the following text to appear. After each stimulus sequence, the TLX ratings were collected and the subjects were asked two questions about the text to confirm that they were read through properly.

The order of the text sequences and walking conditions were counterbalanced across subjects. All test conditions were performed twice in two testing sessions. The lighting of the test room was kept constant at 400 lux during all testing.

TABLE 1 — Filter center frequencies along with low-frequency and high-frequency cutoffs.

Centre frequency (Hz)	Low frequency cut-off (Hz)	High frequency cut-off (Hz)
1	0.7	1.4
2	1.4	2.8
4	2.8	5.6
8	5.6	11.2
16	11.2	22.4

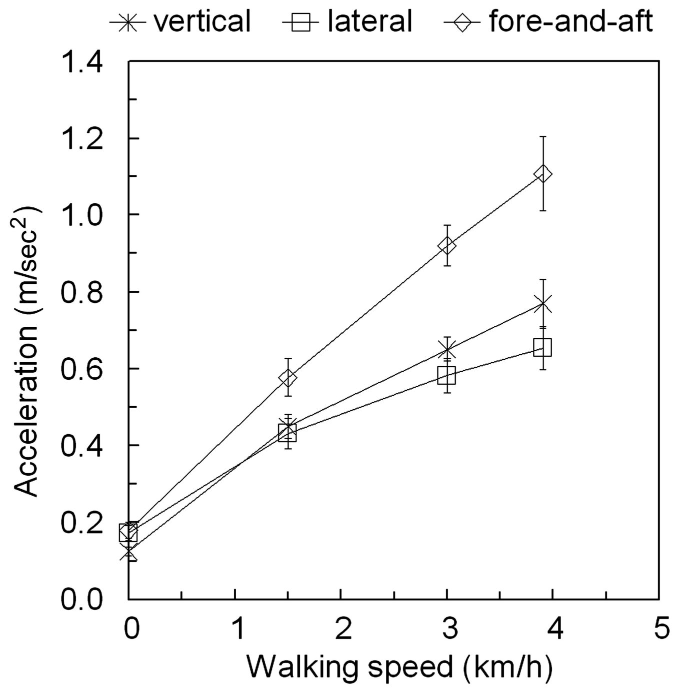

FIGURE 3 — Average vibration amplitude on vertical, lateral, and for-and-aft axes plotted as a function of walking speed. Error bars are standard errors of the mean.

2.6 Data analysis

Acceleration amplitude was calculated as root-mean-square acceleration from the raw data according to Eq. (1). Also, the raw data was filtered with five one-octave–wide bandpass filters with center frequencies of 1, 2, 4, 8, and 16 Hz (Fig. 2 and Table 1). Acceleration amplitude in each frequency band was again calculated according to Eq. (1).

$$\text{rms acceleration} = \sqrt{\frac{\sum_{i=1}^{i=n}[x(i)-\bar{x}]^2}{n-1}}, \quad (1)$$

where

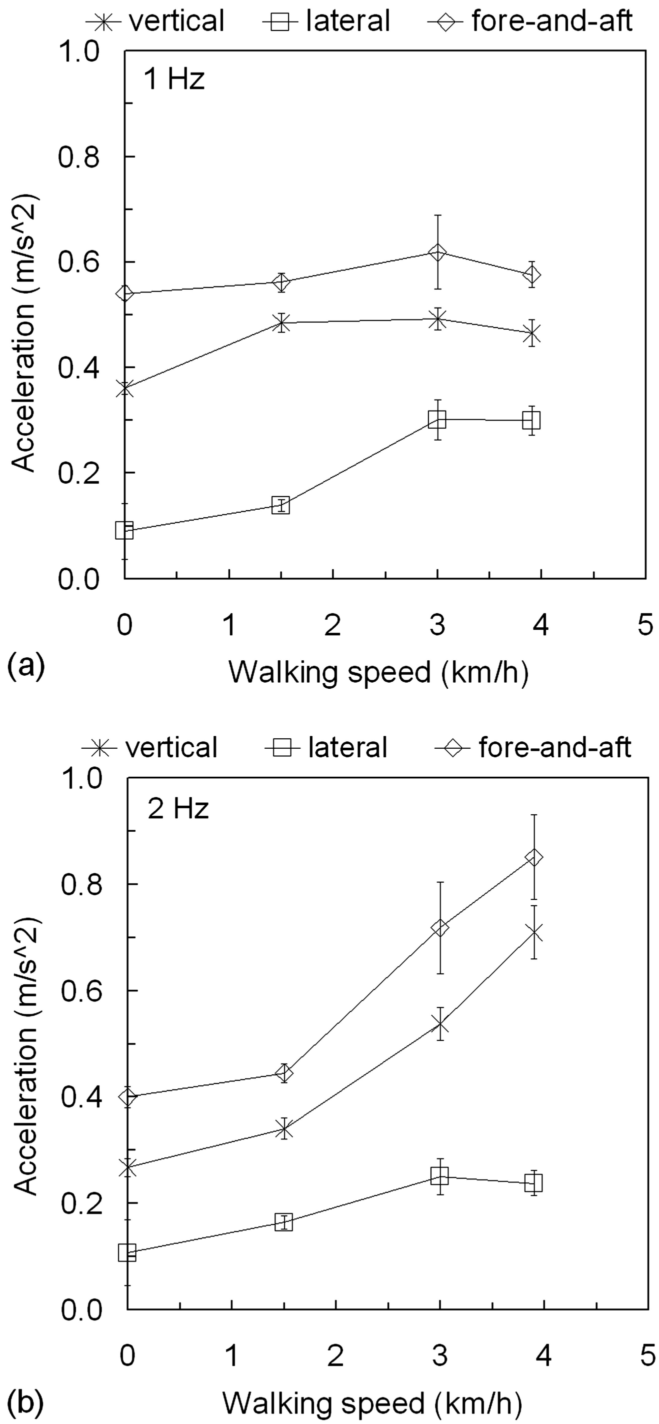

FIGURE 4 — Vibration amplitude on vertical, lateral, and fore-and-aft axes plotted as a function of walking speed in (a) 1-Hz and (b) 2-Hz frequency bands. Error bars are standard errors of the mean.

$$\bar{x} = \frac{\sum_{i=1}^{i=n} x(i)}{n} \tag{2}$$

and n is the number of elements in the sample.

Reading velocity, task load index, and vibration measures in different test conditions were analyzed with repeated measures analyses of variance. In addition, Pear-

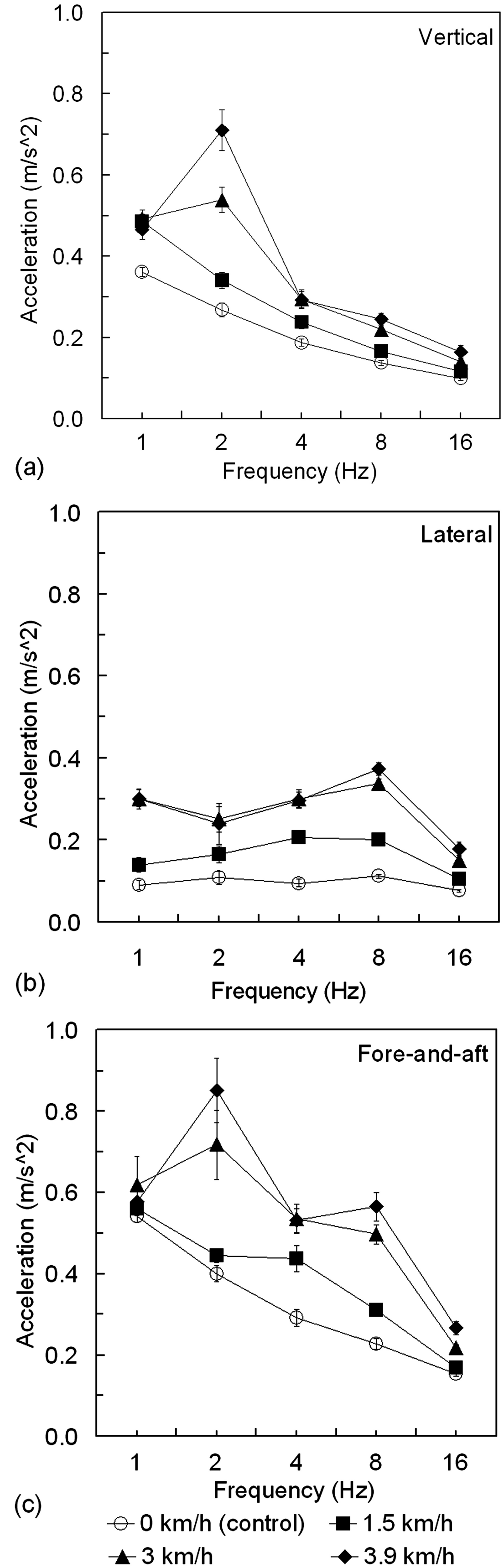

FIGURE 5 — Vibration amplitude in each test condition plotted as a function of filter center frequency on (a) vertical, (b) lateral, and (c) fore-and-aft axes. Error bars are standard errors of the mean.

son correlation coefficients were calculated for the legibility and vibration measures.

3 Results

3.1 Vibration

Vibration amplitude increased significantly with increasing walking speed in the vertical [$F(3, 33) = 81.3$, $p < .001$], lateral [$F(3, 33) = 87.5$, $p < .001$], and fore-and-aft axes [$F(3, 33) = 71.8$, $p < 0.001$] showing a strong relationship between amplitude of vibration and walking speed (Fig. 3). Vibration amplitude was the largest in the fore-and-aft direction and smallest in the lateral direction at all walking speeds.

In addition to general inspection, vibration amplitude was analyzed separately in frequency bands with center frequencies of 1–16 Hz. Figure 4 plots the vibration amplitude as a function of walking speed separately for the 1- and 2-Hz frequency bands in different test conditions. It can be seen that in the 1-Hz band amplitude did not increase very strongly with increasing walking speed, whereas in the 2-Hz band the increase was very clear. At higher frequencies, the increase was largely similar as in the 2-Hz band.

As can be seen in Fig. 5, vibration amplitude was the largest in the lowest-frequency bands and declined towards higher frequencies, especially in the vertical [$F(4, 44) = 320.7$, $p < 0.001$] and fore-and-aft [$F(4, 44) = 15.0$, $p < 0.001$] axes. Figure 5 also reveals the similarities between vertical and fore-and-aft vibration. In the control condition and at 1.5-km/hour walking speed, vibration on these axes was largest at 1 Hz and decreased towards higher frequencies. Vibration amplitude peaked at 2 Hz at walking speeds over 3 km/hour. Walking at speeds over 3 km/hour also caused higher-frequency vibration, which can be seen as the 8-Hz peak on the fore-and-aft axis. In contrast, vibration on the lateral axis was quite different from either vertical or fore-and-aft vibration. In the control condition and at the 1.5-km/hour speed, vibration was small and did not differ between the frequency bands. At higher walking speeds, vibration peaked at 1 and 8 Hz.

Correlations between vibration amplitude and walking speed were significant at all frequencies and axes. At the vertical axis, the 2-Hz frequency band correlated most strongly with walking speed ($r = 0.48$–0.86). At the lateral axis, the correlation was strongest in the 8-Hz frequency band ($r = 0.40$–0.73) At the fore-and-aft axis, the correlation was strong in all other frequency bands except 1 Hz ($r = 0.67$–0.87).

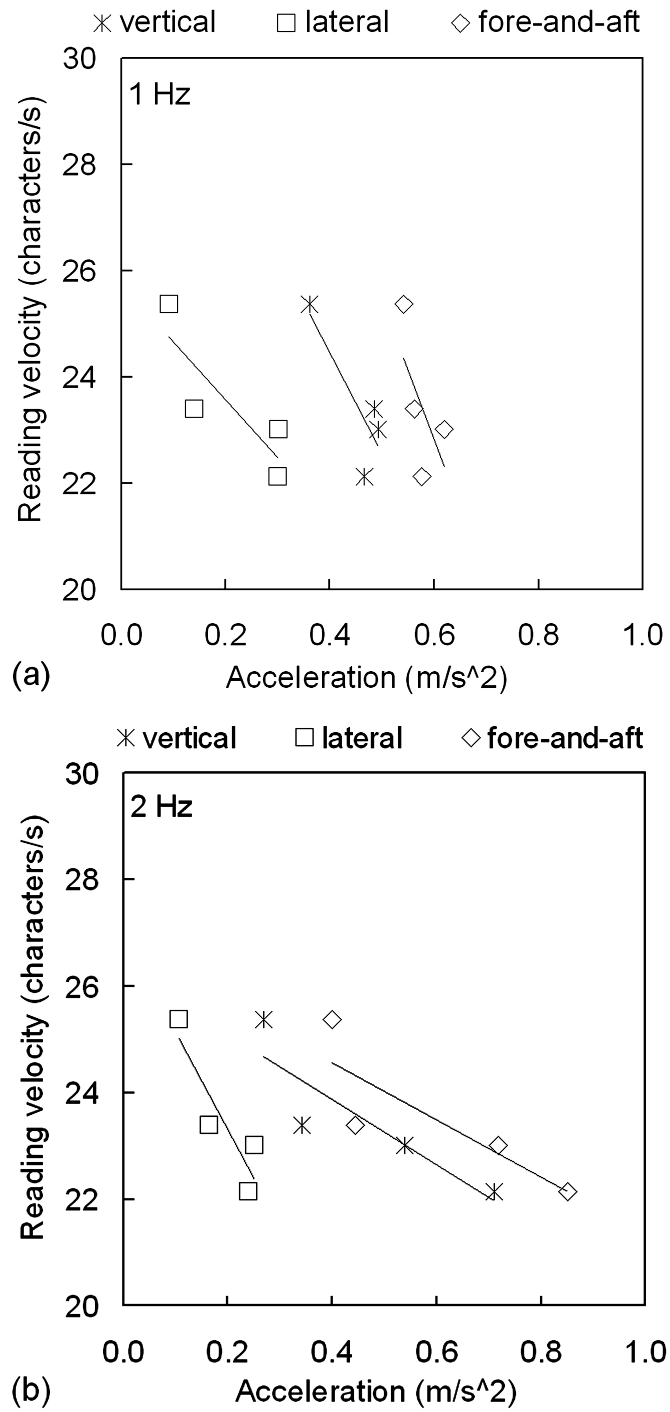

FIGURE 6 — Reading velocity plotted as a function of vibration amplitude on vertical, lateral, and fore-and-aft axes in (a) 1-Hz and (b) 2-Hz frequency bands. Linear regression lines for each axis are drawn through the data points.

3.2 Reading performance and task load

Reading performance deteriorated clearly with increasing walking speed [$(F3, 33) = 4.6$, $p < 0.05$]. When comparing the walking speeds, only the difference between the subjects' individual speed (average, 3.9 km/hour) and the control reached statistical significance, however. The adverse effects of walking were visible in the task load index as well [$F(3, 33) = 4.3$, $p < 0.001$]. Task load ratings on all TLX dimensions increased as a function of walking speed, increase in temporal and physical demand reaching statistical significance (Table 2).

The decrease in average reading velocity correlated moderately with the amount of vibration on all axes. Vibra-

TABLE 2 — Average reading velocity, task load index, and TLX dimensions in each test condition are presented below. Standard errors of the mean are in brackets. The *F* values for the main effect of test condition are shown with corresponding probability values.

Legibility measures	Test conditions					
	Control	1.5 km/h	3 km/h	Own speed	F(3, 33)	p
Reading velocity (characters/s)	25.4 (1.3)	23.4 (1.0)	23.0 (1.1)	22.1 (0.8)	4.6	.05
Task load index	23.0 (3.7)	28.2 (4.8)	34.2 (5.3)	36.0 (5.1)	4.3	.001
Mental demand	28.6 (5.5)	32.5 (6.7)	38.3 (6.3)	41.5 (6.0)	1.7	ns
Physical demand	7.2 (2.2)	32.9 (5.5)	39.4 (7.4)	42.9 (6.9)	16	.001
Temporal demand	18.1 (4.1)	23.0 (4.0)	29.5 (6.2)	32.4 (6.6)	3.1	.05
Effort	25.4 (5.9)	30.4 (5.5)	35.1 (6.2)	39.2 (5.3)	2.7	ns
Performance	19.4 (4.1)	22.8 (6.2)	29.5 (5.6)	26.1 (4.8)	2.4	ns
Frustration	13.7 (3.5)	18.7 (4.7)	18.4 (4.8)	25.8 (6.2)	1.8	ns

tion on the vertical axis in the 1-and 2-Hz frequency bands correlated most with reading velocity (r = –0.31 and –0.36, respectively). Vibration on the lateral and fore-and-aft axes in the 2-Hz frequency band correlated most with reading velocity (r = –0.28 and r = –0.32, respectively) (Fig. 6).

4 Discussion

Vibration on all measured directions, vertical, lateral, and fore-and-aft, increased as a function of walking speed. Concurrently, the legibility of displayed text, measured as reading velocity and subjective task load, decreased. The increase in vibration was especially evident on vertical and fore-and-aft axes, showing that the movement caused by walking on a treadmill manifests mostly on these vibration directions.

Most of the measured vibration occurred in the 1–8-Hz frequency bands. The highest amplitudes were observed in the 2- and 8-Hz bands. The 2-Hz peak was visible in both vertical and fore-and-aft axes, whereas the 8-Hz peak occurred only in the fore-and-aft axis. Vibration around 2 Hz probably reflects the average walking pace, which was ca. two steps per second at the faster walking speeds. Since vibration in the 1-Hz band was fairly large even in the control condition, it seems not to depend on the walking speed unlike the other frequencies. Vibration around 1 Hz may be generated more by the hand and upper body movements caused by the handling of the phone when performing the reading task.

Reading performance was deteriorated even at a slow walking speed and the effect grew stronger as the speed increased. Also, self-reported task load, especially physical demand, increased with the amount of vibration. Together with the degradation of performance, this suggests that the subjects were trying to compensate for the adverse effects of the vibration. The negative influence of vibration might be explained by the system of co-ordinated eye movements that is typically used to compensate for self-induced motion.[10] It can be hypothesised that this controlling system was not fully able to compensate for the effect of the frequencies present during the reading task. It has been shown that with low-frequency (0–2 Hz) object vibration, vision is aided by pursuit eye movements, which are used to maintain the image stable on the same part of the retina.[4] As the vibration frequency increases, the lags involved in pursuit eye movements become too great and the eye makes a series of saccadic movements to redirect the eye to the correct point.[8] At higher frequencies (over 2 or 3 Hz) the saccadic movements are unnecessarily fast causing the image to appear confused or blurred.[4] The present results can also be understood in terms of the difficulties with stabilizing the upper parts of the body that 2-Hz vibration is known to cause.[5] Similarly, frequencies around 8 Hz measured in the fore-and-aft axis may be accompanied with body resonances interfering with manual control, vision, and performance, especially in tasks involving hand positioning.[4,5]

Although the different vibration parameters could not be manipulated separately due to the nature of the movement, the results of the present study clearly indicate a relationship between vibration characteristics and legibility. It is evident that vibration of the hand and the body that walking generates interferes with reading performance. The strong correlation between vibration caused by walking and small-display legibility suggests that legibility could, to some degree, be predicted from the amount and frequency of vibration. The next stage would be to connect the present approach with the more controlled laboratory studies in order to gain a deeper understanding of the relationship between small-display legibility and vibration caused by natural movement.

References

1 G E Legge, D G Pelli, G S Rubin, and M M Schleske, "Psychophysics of reading. I. Normal vision," *Vision Res* **25**, 239–252 (1985).

2 J D Gould and N Grischkowsky, "Doing the same work with hard copy and cathode ray tube (CRT) computer terminals," *Human Factors* **26**, 323–337 (1984).

3 C B Mills and L J Weldon, "Reading text from computer screens," *ACM Computing Surveys* **19**, 329–358 (1987).

4 M J Griffin, *Handbook of Human Vibration* (Academic Press, London, 1990).

5 K R Boff and J E Lincoln (eds.), *Engineering Data Compendium: Human Perception and Performance,* Wright-Patterson AFB, Ohio (1988).

6 E J Hillman, J J Bloomberg, P V McDonald, and H S Cohen, "Dynamic visual acuity while walking in normals and labyrinthine-deficient patients," *J Vestibular Res* **9**, 49–57 (1999).

7 M J Moseley and M J Griffin, "Effects of display vibration and whole body vibration on visual performance," *Ergonomics* **29**, 977–983 (1986).

8 A T Bahill and J D McDonald, "Smooth pursuit eye movements in response to predictable target motions," *Vision Res* **23**, 1573–1583 (1983).

9 J L Vercher, G M Gauthier, E Marchetti, P Mandelbrojt, and Y Ebihara, "Origin of eye movements induced by high frequency rotation of the head," *Aviation, Space and Environmental Medicine* **55**, 1046–1050 (1984).

10 J D McDonald, "An adaptive control model for human head and eye movements while walking," *Institute of Electrical and Electronic Engineers Transactions on Systems, Man, and Cybernetics* **SMC-13**, 167–174 (1983).

11 ISO 2631/I-1985. "Evaluation of human exposure to whole body vibration," *International Organization for Standardization.*

12 M J Griffin and R A Hayward, "Effects of horizontal whole-body vibration on reading," *Applied Ergonomics* **25**, 165–169 (1994).

13 M Olkkonen and T Mustonen, "Walking-caused vibration and small display legibility," in: *Proc 11th IDW '04,* 1523–1526 (2004).

14 T Mustonen, M Olkkonen, and J Häkkinen, "Examining mobile phone text legibility while walking," *CHI 2004 Conference Proceedings, Conference on Human Factors in Computing Systems*, 1243–1246 (2004).
15 J A J Roufs and M C Boschmann, "Text quality metrics for visual display units: I. Methodological aspects," *Displays* **18**, 37–43 (1997).
16 NASA TLX subjective workload assessment scale. URL: ttp://iac.dtic.mil/hsiac/docs/TLX-UserManual.pdf.

Maria Olkkonen received her M.A. degree in psychology from the University of Helsinki in 2004. She has been working as a researcher at the Multimedia Technologies Laboratory of Nokia Research Center since June 2003, where her main focus has been on small-display text legibility. At the moment, she is working on the mechanical ergonomics of mobile devices.

Terhi Mustonen received her M.A. degree in psychology from the University of Helsinki in 2004. She joined Nokia Research Center in 2001 and currently works as a researcher in the Display Entity of Nokia Technology Platforms. Her research activities are on the area of display ergonomics and visual perceptions, focusing on perceived quality and legibility of small diaplays.