Guidelines for the Use of Vibro-Tactile Displays in Human Computer Interaction

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Abstract

Vibro-tactile displays convey messages by presenting vibration to the user's skin. In recent years, the interest in and application of vibro-tactile displays is growing. Vibratory displays are introduced in mobile devices, desktop applications and even in aircraft [1]. Despite the growing interest, guidelines on the design of vibro-tactile displays are still lacking. Existing guidelines are mainly concerned with passive displays, such as Braille labels on controls, nibs on keyboards and notches on smart cards [2, 3, 4]. In this paper we focus on active displays, either consisting of a single vibrating element (used in for example mobile phones and computer mice) or numerous elements (used in for example active Braille displays and body suits [5, 6]). This paper discusses a first set of guidelines, dealing with the basic vibro-tactile parameters. The set is mainly derived from neurophysiological and psychophysical data. The guidelines indicate the relevant parameters as well as possible pitfalls. As such they can serve as a point of departure for interface designers. Important expansions of the set can come from user evaluation studies and examples of best practices.

1. Introduction

It is not common practice to use the sense of touch in Human Computer Interaction (HCI). Traditionally, the visual modality is the main presentation channel, sometimes complemented with auditive information. However, there are several reasons why this is changing. First, there is a rapid development in technology that makes the usage of the sense of touch in daily life applications within reach (e.g., vibration functions on mobile phones and low cost computer mice with force and vibro-tactile capabilities). Second, there is a strong trend to include touch in multi-modal interfaces. Important push for the latter is the Design for All (DfA) approach to HCI design. The DfA approach promotes that all people, regardless of perceptual, cognitive or psychomotor capabilities can use information and communication technology. As a result, designers are searching for possibilities to provide multi-modal redundancy (e.g., spoken messages for visually impaired users). A third push comes from the need for an alternative or complementary information channel [7]. There are several situations in which the visual and auditive channels of an operator are heavily loaded or in which the visual and/or auditive information is degraded. The latter includes areas where the visual display possibilities are limited (e.g., in handheld devices), or where the auditive channel is unattractive (e.g., in mobile phones in public places).

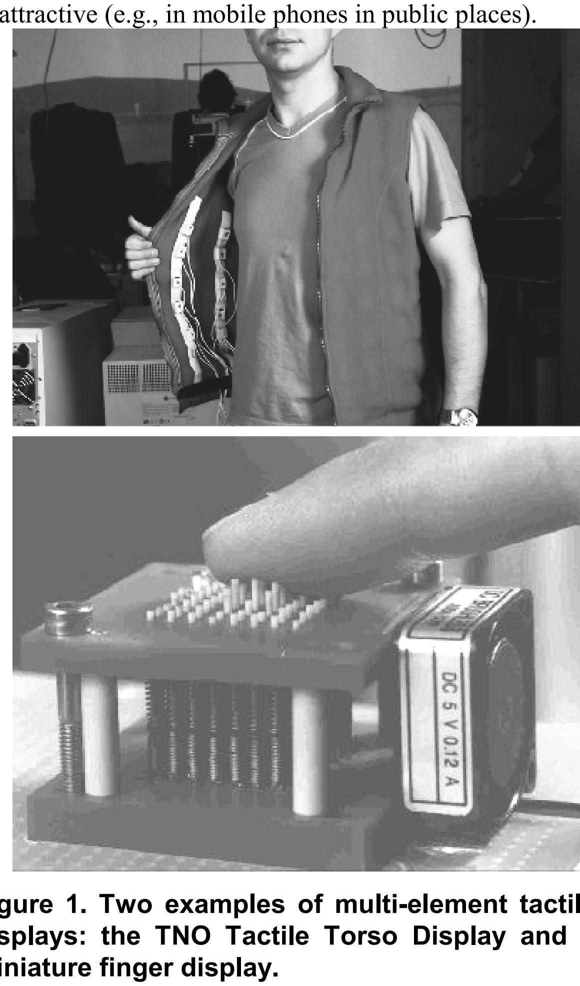

Figure 1. Two examples of multi-element tactile displays: the TNO Tactile Torso Display and a miniature finger display.

There are two common techniques to generate vibration, either based on a moving coil (usually driven by a sine wave), or on a DC motor with an eccentric weight mounted on it (the usual technique applied in mobile phones). Other, less common, actuators are based on for example piezoelectric benders, air puffs, and electrodes. Although the actuators differ in their characteristics as display element, basic psychophysical measurements are rather independent of actuator principle.

The best known application of vibro-tactile displays at this moment is probably the vibration function on mobile phones. However, the potential information transfer capacity of the tactile channel is much larger than the 1-bit message "your phone is ringing". For example, people who know Braille can actually read with their fingers. Currently, the variety in displays is large; ranging from Braille displays with a large amount of miniature vibratory pins, to single point vibrators in pagers and tactile suits consisting of numerous vibrators mounted on the body (see Figure 1).

Although the potential of vibro-tactile displays is recognized, there are very little data available on relevant guidelines. In most standard handbooks on HCI design, haptics receives little if any attention. Virtually every existing guideline is related to passive tactile messages, such as Braille labels on controls, nibs on the keyboard and notches on smart cards [2, 3, 4].

We mainly used neurophysiological and psychophysical data as most important sources to distill guidelines from. We present guidelines in a very general level to include a large variety of applications and displays. We stress that there is a definite need to expand the set with guidelines inferred from applications (best practices) and user evaluations. Because the field is young, the guidelines presented here might be tentative in some places and may also depend on technological developments.

2. Guidelines

Four primary parameters are studied in relation to vibro-tactile perception: amplitude, frequency, timing, and location. Although the primary parameters can be combined in higher order effects, these are seldom the subject of fundamental studies (with the exception of spatio-temporal interactions). We grouped the guidelines in four categories. Section 2.1 deals with the detection of a stimulus, section 2.2 with the discriminability of stimuli (or possibilities of information coding), section 2.3 is concerned with issues related to comfort, and 2.4 discusses the possible pitfalls in the application of (multiple) tactile stimuli. Only key references are given.

2.1. Guidelines on stimulus detection

Vibration stimuli will be detected when the amplitude exceeds a certain threshold. This detection threshold is dependent on several parameters [8, 9, 10, 11, 12], including the frequency (the skin is roughly sensitive to vibrations between 20 and 500 Hz) and the location on the body (e.g., the threshold for the trunk is only 4 microns at 200 Hz [13]; thresholds for fingers and hands are much lower). Lowering the detection threshold may have advantages (e.g., regarding power consumption). When this is an important design consideration, *lowest thresholds are found*:

a. on glabrous skin as compared to hairy skin,
b. with vibration frequencies in the range 200–250 Hz,
c. when the stimulus duration increases (so called temporal summation, which only works for frequencies above 60 Hz),
d. when there is a fixed surround around the vibrating element.

Furthermore, *the detection and percept of a stimulus is effected by the waveform*. Although usually a sine is used as vibratory input, a square wave is most intense, sine is the smoothest, and triangle is in between. However, manipulating waveform requires specific hardware. Also, there are large individual differences, so *the user must be able to adjust stimulus intensity*. There is a high variation in thresholds of sensation and pain, both between people, but also over the life span (spatial and temporal acuity degrades with aging).

2.2. Guidelines on tactile information coding

A detectable stimulus alone is not enough to code more than a simple message. For instance, the vibration function on a mobile phone needs two (or more) discernable stimuli to inform the user whether there is a call or an SMS coming in (e.g., by using different frequencies). For the four primary parameters, the following is relevant:

a. *coding information by subjective magnitude*. Subjective magnitude is a non-linear function of amplitude. Encoding information by using different intensity levels is possible [14], although the number of levels is small: not more than 4 different levels should be used between the detection threshold and the comfort / pain threshold. Psychophysical parameters indicate that there are two ways of enlarging the subjective magnitude of a stimulus: 1. enlarge the intensity for intensities near the threshold [15], and 2. enlarge the area of stimulation [16].
b. *coding information by frequency*. No more than 9 different levels of frequency should be used for coding information. Difference between the levels should be at least 20%. Presented with the same

amplitude, the levels will also lead to different subjective magnitudes [17].

c. *coding information by temporal patterns.* The temporal sensitivity of the skin is very high (close to that of the auditory system and larger than that of the visual system). When using a single actuator of a tactile display to encode information in some kind of temporal pattern (called touchtones by Van Erp and colleagues, see [1]), the time between signals must be at least 10 ms [18, 19] (i.e., 10 ms pulses and 10 ms gaps can be detected). Depending on the type of actuator and the load, a vibratory stimulus will take time to reach the set frequency, and may smother slowly. This is important for the temporal aspects of the presented stimulation.
d. *coding information by location*. In a multi-element display, information can be coded by location. Actuator density is an important parameter in the design of multiple elements tactile displays. When a high density is needed, only certain body parts have a sufficiently high spatial resolution (e.g., the fingers, hands, and face). When spatial acuity as low as 4 cm is acceptable, any locus will suffice [20, 21]. When the display is designed for trained users, the resolution may be higher.

Irrespective of the parameter choice, it is important to *make tactile messages self-explaining*. Most people are unfamiliar with tactile signals in HCI. This means that the tactile messages must preferably be self-explaining (in analogy one can speak of vibrocons [22]). Also, users will not experience tactile signals continuously and have limited opportunities to learn to know the meaning of tactile messages (tactile continuity is low).

When *complex tactile messages* are used, they must preferably be composed of well-known meaningful components. However, combing different vibro-tactile signals may also alter the percept, for instance through spatio-temporal interactions (see section 2.4). Another drawback is the risk of *tactile clutter*. The simultaneous or sequential presentation of multiple tactile messages on the same display can potentially result in tactile clutter (reduced comprehension) [6] or a sensory overload situation.

2.3. Guidelines on comfort

Since tactile information presentation requires actual contact between the display and the user it is important to *ensure comfort over longer periods of time*. Tactile displays that are worn on the body must be unobtrusive and comfortable for longer periods of usage. Electrodes and *vibrators can even generate sufficient heat to cause a painful sensation* of heat as well as burns. Also, tactile stimuli are hard to ignore if the user doesn't want to use them, so *avoid annoying the user*.

Comfortable stimuli range 15-20 dB above the absolute threshold. Analogue to vision and audition, a high intensity tactile stimulus may lead to discomfort and finally to a sensation of pain. Amplitudes above 0.6 - 0.8 mm will result in a pain sensation. *The vibrations of the hand-arm should always be limited*. The most critical frequencies are around 12 Hz; the critical range is from 1 to 5 m/s^2. In some circumstances, *over exposure to vibration* may potentially be harmful. A recent example concerns a case of a boy who played his Sony Playstation 7 hour per day [23]. The effects reminded the practitioners of the hand-arm vibration syndrome (also known as vibration white finger).

2.4. Pitfalls

We included this section to make the designer aware of several potential pitfalls of applying tactile stimulation. Very relevant is the fact that the skin often integrates stimuli. This may result in a new percept that differs completely from the sum of the original stimuli. Important in this respect are:

a. *spatial effects*. *Spatial masking* means that the location of a stimulus is masked by another stimulus. Spatial masking may occur when stimuli overlap in time, but not in location. Especially when using pattern recognition, the designer should be aware of the negative effects of masking. Both the detection and the identification of stimuli may be degraded. Using stimuli with different frequencies (one below 80 Hz and one above 100 Hz) may prevent masking [24]. *Apparent location* is the percept of a single stimulus induced by the simultaneous activation of two stimuli at different locations [25]. The apparent location is in between the two stimulus loci and depends on their relative magnitude. Both stimuli should be in phase to evoke a stable percept. The positive aspect is that apparent location may be used to increase the number of subjective stimulus sites, without enlarging the number of actuators.
b. *temporal effects*. Presenting two stimuli closely in time may alter the percept in different ways. *Temporal enhancement can affect the subjective magnitude of a second stimulus*. Temporal enhancement of a second stimulus occurs when two stimuli are separated by 100 - 500 ms. Temporal enhancement occurs only when the stimuli are in the same frequency band [26]. Another temporal effect is *temporal masking*. Temporal masking effects the timing aspects of a certain stimulus. Temporal masking can occur when the stimuli are presented to the same location, and when the onset of the target stimulus is within a certain time interval from the onset of a 'distracter'; this interval ranges from -100

up to +1200 ms [27]. *Temporal masking can be prohibited by using different loci or frequencies* (one below 80 Hz and one above 100 Hz) [28]. A third temporal effect is adaptation. *Adaptation corresponds to a change in the perception of a stimulus after prolonged stimulation.* Adaptation increases the absolute threshold and decreases the subjective magnitude [29]. This is a gradual process that takes up to 25 minutes. The effect on the threshold is larger (up to 20 dB) than on the subjective magnitude (up to 7 dB). Recovery time is about half the adaptation time, and is faster for the subjective magnitude than for the absolute threshold. Adaptation effects only occur for stimuli within the same frequency range. *Adaptation effects can be prevented by switching between a frequency below 80 Hz and one above 100 Hz* [28].

c. *spatio-temporal interactions*. Stimuli that are presented closely in time and space can alter the percept and may even result in a completely new precept [30]. An example of the latter is presenting two or more stimuli in a specific spatio-temporal pattern that evokes apparent motion. Apparent motion can be used to simulate actual motion in for example tracking displays. Most important parameters for the phenomenon are the burst duration (minimum duration of 20 ms) and the time intervals between the onsets of the consecutive stimuli [31, 32]. Another example is the tactual rabbit, in which a number of taps at distinct locations A and B results in a percept of a continuously hopping stimulus from A to B [33].

Another important aspect of vibro-tactile stimuli is that vibration also emits acoustic energy. Unwanted acoustic output may be a source of interference to persons or equipment near the display user. Also an issue is the spreading of activation among actuators. Especially when actuators have the same resonance frequency, there is a risk of passing vibration onto inactive vibrators. A rigid surround can reduce the spreading. Finally, vibrations applied to finger, hand or arm can potentially interfere with a manual control task (vibration as tremor).

3. Conclusions

We expect that the use of vibro-tactile displays, although a rather new field in interface design, will grow extensively in the near future. A review showed that the development of relevant guidelines is lagging behind considerably. Some handbooks are simply ignoring the vibro-tactile channel and existing guidelines are merely restricted to passive displays. This paper makes a first attempt to list relevant, albeit very basic, guidelines predominantly based on psychophysical data. The designer should keep in mind that psychophysical data are acquired in a laboratory setting with motivated and experienced subjects, under optimal perceptual circumstances, etc. This means that the data will usually reflect optimal performance, which will not be viable in applied settings.

We presented data on the four primary parameters for vibro-tactile perception: amplitude, frequency, timing, and location. All four are related to the detection threshold and all four can be used to encode information. Amplitude and frequency seem to offer limited possibilities of encoding information. There is a restricted number of discernible intensity levels (or just noticeable differences) between the detection threshold and the maximum comfort level. Also, the number of frequency levels between the lower and upper frequency limit is restricted. On the other hand, the temporal sensitivity of the vibro-tactile channel is rather large. For example, breaks as small as 5.5 ms in a further steady signal can be detected. Timing as coding parameter has not been studied extensively. Especially the higher order manipulations (i.e., tactile gradients, rhythms or melodies) may offer interesting possibilities, particularly for single element displays. Location may also be an important parameter, although it requires multiple element displays. However, location can be used to encode a large variety of information. For instance, active Braille displays can present abstract information using location only, while (whole) body displays are successfully applied in mapping spatial information on the body coordinates.

The four primary parameters may also interact. Only some of these interactions are studied, for example the effect of amplitude and frequency on the detection threshold, and several spatio-temporal interactions (e.g., masking and apparent motion). Some of these interactions are potential pitfalls for the designer because they may change the percept in an undesirable way. However, several other higher order effects can also be favorable to the designer, for instance: apparent position may enhance the display resolution. Other higher order effects haven't been studied at all, but can potentially be used to encode information. Examples include amplitude and frequency gradients, for example dependent on time (indicating the progress of a specific process) or location (indicating the distance to specific object in a computer generated environment).

Important extension of the present guidelines must come from applications, for example by systematically measuring the effect of different designs on the usability of vibro-tactile displays.

4. References

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