

# Towards Vibrotactile Direction and Distance Information for Virtual Reality and Workstations for Blind People

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**Abstract.** In the current paper psychophysical aspects of a vibrotactile feedback device were investigated and its potential of signal modulation was analyzed. We identified magnitude calibration factors for equal perceptions of the different stimulation locations of the device and determined the spatial acuity with which the user is able to correctly detect the stimulation's location. Furthermore we investigated different approaches of vibrotactile stimulation for communicating direction and distance information to the human arm (motion guidance) and also explored different approaches of signal modulation for the transmission of additional information content.

The knowledge of these vibrotactile perception aspects is a fundamental requirement in order to design and evaluate different parameters for the design and application-oriented optimization of vibrotactile stimulation patterns.

**Keywords:** Vibrotactile stimulation · Vibrotactile perception · Motion guidance · Distance coding · Virtual reality

## 1 Introduction

During the last years, vibrotactile displays are more and more subject of research for many different purposes [2, 7] such as human-machine-interfaces for virtual reality [10] and telerobotics [3], attention direction [6], sensory substitution [14] or navigation [4]. Vibrotactile stimulation has great potential as (1) it is an intuitive form of feedback (stimuli are directly mapped to body coordinates e.g. in motion guidance the user simply follows the direction of vibrotactile stimulation), (2) it can be used successfully in situations where auditory or visual presentation is not possible (e.g. noisy or visually cluttered environments), (3) it avoids overloading the usually involved auditory and visual perception channels, (4) information is displayed in an unobtrusive way without annoying others or drawing their attention to confidential matters, and (5) it is a possible modality for sensory substitution (e.g. vibrotactile presentation of inaccessible information due to visual occlusion).

Compared to the well-known and very simple forms of vibrotactile stimulation in cell phones, spatially- and direction-resolved information can be presented with devices designed for a distributed perception. At the German Aerospace Center (DLR), a vibrotactile feedback device has been developed for a broad range of applications.

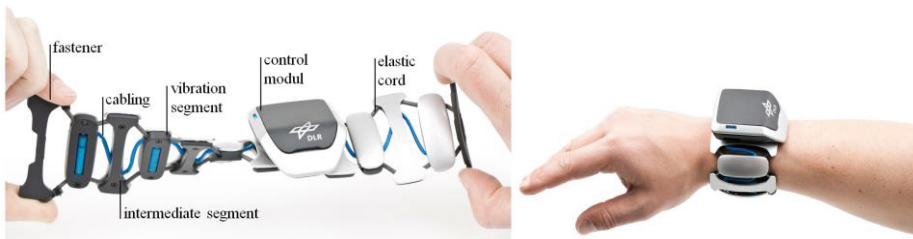
The so called VibroTac is a wrist band with six vibrotactile actuators and is described in Sect. 2. The device will be used - among other things – for motion guidance in virtual reality (and augmented reality) applications and in the context of workstations for blind people. Thus, relevant positions, objects or events to which the user should move the hand can be indicated through adequate stimulation patterns (e.g. a blind person can be guided to the correct shelf of a goods issue). Vibrotactile assistance should be realized as intuitive and effective as possible. Furthermore, prolonged use of the device has to be as comfortable as possible.

In order to evaluate and judge different parameters in the design and application-specific optimization of vibrotactile stimulation patterns, it is a fundamental requirement to have knowledge about certain aspects of perception. Therefore, in this paper we investigate psychophysical aspects such as the magnitude calibration for equal perceptions of different stimulation locations (Sect. 3) and the spatial acuity with which the user is able to correctly detect the stimulation's location (Sect. 4).

Furthermore we analyze the potential of signal modulation for distance coding in Sect. 5 (principal approaches of vibrotactile stimulation for communicating direction and distance information to the human arm are compared) and for the transmission of additional information content in Sect. 6.

## 2 The Vibrotactile Feedback Device VibroTac

At DLR, a battery driven and wireless controllable wrist band with six vibration motors (called tactors) has been developed. Its design with respect to the type of tactors, number of stimulation locations and their arrangement is based on the outcome of evaluations with a prototype reported in [12].



**Fig. 1.** The vibrotactile feedback device VibroTac

Due to the ergonomic concept, the device [13] can be worn on a wide range of arm or leg diameters while all tactors correctly self-align in equal distances independent from the circumference. Each tactor can be activated and controlled separately in frequency (0–190 Hz). The tactors are direct current (DC) cylindrical motors which generate vibrations by rotating an unbalanced mass. Therefore, in order to vary the perceived magnitude of stimulation, the drive voltage has to be changed. Different vibrotactile stimulation patterns such as impulses, ramps, waves, knocks, trembling etc. can be generated and displayed to the user.

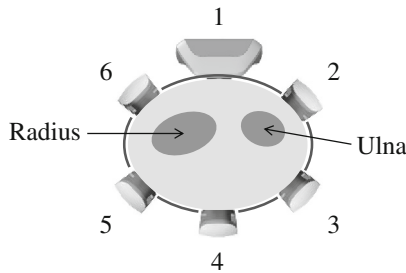
### 3 Magnitude Calibration

Dependent on the factors' locations e.g. on the lower arm, the stimulus magnitude of a certain frequency might be perceived differently. For instance, factors that are placed on the ulna or the radius could produce different sensations of vibrotactile stimulation compared to factors located on muscles or fatty tissues.

In applications such as collision feedback or motion guidance, information is not only coded with stimulation patterns but also with the signal strength itself. Thus, the knowledge of calibration factors is essential in order to be able to present stimuli at different factor locations that are perceived with equal magnitude.

#### 3.1 Method

Calibration factors for all factors were determined using the magnitude estimation method [15]. The device was attached to the right wrist of eight sighted subjects (two females, six males,  $M_{Age} = 39.5$  years;  $SD = 16.5$ ; age range 23–67 years).



**Fig. 2.** Schematic representation of factor locations relative to arm bones (right hand)

After a short introduction of VibroTac, subjects were asked to adjust the stimulus intensities of all factors. Therefore, a reference stimulus was provided on a randomly chosen factor. Subsequently, perceived stimuli intensities of the five remaining factors had to be matched to the reference stimulus. The pulse durations were set to one second. After each adjustment of stimulus intensity according to the subject's feedback, the updated and the reference stimulus were repeated in quick succession for direct comparison.

The adjustment procedure was performed in randomized order with each factor as reference and for two different frequencies (66 vs. 132 Hz). Altogether, twelve matching series had to be completed in random order.

After averaging the adjusted stimuli intensities for the lower and the higher frequency, the adjusted intensities of each factor were divided by the adjusted intensity of factor 1 as reference.

### 3.2 Results and Discussion

For both frequencies, we found that perceived stimuli magnitudes were higher for factors 2, 3 and 6 compared to factors 1, 4 and 5. Obviously, vibrotactile stimuli were perceived as more intensive at locations with a lower proportion of muscle, tendons or fatty tissue (see Fig. 2).

**Table 1.** Calibration factors at two different frequencies; Means (SD)

Tactor	Calibration factors at 66 Hz	Calibration factors at 132 Hz
1	1.00	1.00
2	0.85 (0.20)	0.72 (0.15)
3	0.86 (0.23)	0.81 (0.26)
4	1.12 (0.28)	0.90 (0.32)
5	1.06 (0.31)	0.89 (0.30)
6	0.90 (0.25)	0.72 (0.18)

Besides, in the case of reference stimuli with higher frequency (132 Hz), the calibration factors for factor 2–6 are consistently smaller than that of factor 1 (1.0). This means that the perceived magnitude of stimuli generated by factor 1 is noticeable lower than that of the other factors. This effect can be explained by the fact that factor 1 is coupled with the control module which results in a higher mass compared to the other factors that is set into vibration. Accordingly, participants reported that the perceived stimulus from factor 1 was noticeably different compared to the remaining factors. This effect was particularly evident for the higher frequency condition. Please note that the result pattern reported above was quite homogeneous across individuals.

Applying the calibration factors to the commanded intensities allows for similar perceptions of vibrotactile stimuli at the six different tactor locations (Table 1).

## 4 Spatial Acuity

As another basic feature of a vibrotactile system with several actuators, the spatial acuity with which the user is able to distinguish and localize the stimulation's position should be verified. Therefore, we determined the detection rate for the corresponding stimulated location as an indication of the user's performance that can be expected in applications such as motion guidance. In previous psychophysical studies, hardware issues such as type, number and alignment of vibration motors have been investigated. Experiments to determine the spatial acuity revealed that a configuration with six actuators distributed on the arm's perimeter in equal distances is a good compromise between the number of feedback locations and reliable detection of feedback locations when compared with configurations of four and eight actuators [12].

As the tactor size of the final VibroTac design has changed compared to the prototype of earlier studies, we determined the matching rate for VibroTac worn close to the wrist as this is the intended wearing position. Based on our earlier investigations

[12], we assume that the matching rate of the rest of the arm is better than that of the wrist due to the smaller arm circumference at this position compared to other positions of the arm.

#### 4.1 Method

In order to familiarize subjects with the different stimulation locations, three clockwise sequential activations of the actuators were given with VibroTac worn close to the wrist. Afterwards two clockwise sequential activations with 0.4 s pulse length and 3.5 s pause duration were presented and positions were visualized by the investigator on a cross-section drawing of the arm. In the following training phase, subject had to point at the corresponding location of perceived stimulation on the drawing for a series of 32 impulses on randomly chosen factors (on duration 0.4 s, off duration 3.5 s) and verbal feedback was given whether judgments were correct or not.

In the main study, three runs with 18 factor activations (each factor three times in randomized order with 0.4 s on-duration and 3.5 s off-duration) were presented to 16 sighted subjects (13 females, three males,  $M_{\text{Age}} = 33.7$  years;  $SD = 7.2$ ; age range 23–48 years;  $M_{\text{Arm\_circumference}} = 18.5$  cm;  $SD = 1.6$ ) – resulting in 1152 impulses. The off-duration was set to 3.5 s to avoid any time pressure. Besides, this pause duration is intended to avoid a relative orientation to other factors which is advantageous when determining the absolute spatial acuity.

We applied the 66 Hz calibration factors for equal perception of stimuli intensities. Except for the familiarization phase, subjects had to wear acoustic ear protection in order to avoid auditory influence of the low-level factor noises. Subjects were not allowed to touch the device with their hands.

#### 4.2 Results and Discussion

The detection rate of stimulated and recognized location is listed separately for all runs and for all factors (T1 – T6) in Table 2.

There is no indication for any time effects (like learning or fatigue) across the four runs, as indicated by a one-way ANOVA performed on the hits in each trial ( $F(3;1148) = .53$ ; ns.). The correct detection rate across all subjects and runs (in total 1152 activations) was 95.2 %. This shows that factor locations of VibroTac can be detected reliably - even with very little training.

**Table 2.** Matching rate of stimulated and recognized location (%)

	T1	T2	T3	T4	T5	T6	Average
Run 1	97.9	93.8	93.8	91.7	89.6	100.0	94.5
Run 2	97.9	93.8	97.9	93.8	95.8	97.9	96.2
Run 3	100.0	93.8	93.8	95.8	95.8	95.8	95.8
Run 4	100.0	89.6	93.8	95.8	91.7	95.8	94.5
Average	99.0	92.8	94.8	94.3	93.2	97.4	95.2

An explanation for the particular good detection rate for factor 1 might be the different stimulation (despite magnitude calibration) that is generated by this segment due to its larger housing mass which is set into vibration compared to the other segments.

**Table 3.** Contingency table of activated and perceived factors (%)

		Perceived					
		T1	T2	T3	T4	T5	T6
Activated	T1	99.0	1.0	0.0	0.0	0.0	0.0
	T2	0.5	92.7	6.8	0.0	0.0	0.0
	T3	0.0	1.0	94.8	4.2	0.0	0.0
	T4	0.0	0.0	3.1	94.3	2.6	0.0
	T5	0.0	0.0	0.0	0.5	93.2	6.2
	T6	0.5	0.0	0.0	0.0	2.1	97.4

Table 3 shows the relation between activated and perceived factor locations based on the complete set of data (all runs of all subjects). Hit rates on the principal diagonal differ significantly from all other values in the corresponding line. In cases of wrong matching, only immediately adjacent factors were identified. There is a significant (Z-test;  $p < 0.05$ ) number of cases in which T2 is mistaken for T3 and in which T5 is mistaken for T6. Obviously it is more difficult to localize factors that are located close to a bone (e.g. ulna or radius) than factors that are located on soft tissue.

The interrelation between activated and recognized location of stimulation was analyzed with Goodman and Kruskals' Lambda [5] and shows a significant relation ( $\lambda = .94$ ;  $p < .001$ ).

## 5 Distance Coding

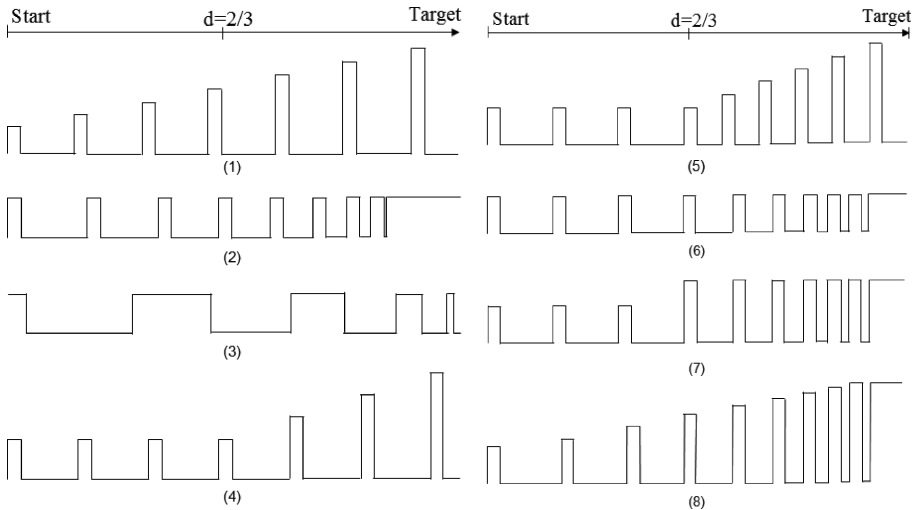
Vibrotactile cues can be used to convey movements in navigation [18] and for guiding human hands or arms [8, 9]. Although adding distance information to navigation tasks could not improve the performance (speed, time) for reaching a target [16, 18], distance information can be advantageous for intuitive and effective motion guidance for the hand [17]. In [11], different cues in order to convey the distance to a target are evaluated. Approaches with continuous and discrete stimulation and variations of the interstimulus interval (ISI) are compared. Stimuli intensities are kept constant in all cases.

In the present study we explore different vibrotactile cues with variations in intensity, ISI and pulse lengths for their suitability to convey distance information.

## 5.1 Methods

In a within-subjects design with randomized condition orders, ten blindfolded subjects (two females, eight males,  $M_{Age} = 23.8$  years;  $SD = 1.2$ ; age range 22–27 years) were spatially guided with eight different distance coding schemes. For each coding condition, fifteen pre-defined target positions at different distances located in the fronto-parallel plane had to be matched. The starting position was in the middle of the workspace of the human arm. There were three randomly chosen directions from the starting position (downward, upper left, upper right) that had to be followed until reaching the target positions at randomly chosen distances (with a minimum of 13 cm and a maximum of 33 cm). In all conditions, the vibrotactile stimulus is deactivated when reaching the target area and is re-activated when the target is overshoot beyond a 2 cm distance threshold. The distance to the virtual target was calculated based on the subject's hand position which was tracked by an optical motion capture system (Vicon). Corresponding stimulation patterns were generated and commanded to the device wirelessly.

In Fig. 3, eight different distance codings for reaching near distance targets with the hand or arm are visualized. We compared three continuous distance codings (1–3) and four two-phases codings (4–7). The two-phases codings were implemented with an initial phase without any distance information and a subsequent phase with distance information (intensity or interval variation) after having reached the target area (one third of the start to target distance). Besides, we compared three codings with intensity codings (1, 4, 5) vs. four codings with pause/signal length variations (2, 3, 6, 7) and one coding combining both approaches (8).



**Fig. 3.** Different approaches for distance coding (signal intensity plotted against target distance)

Coding schemes were evaluated by performance measures (completion time, i.e. the required time for matching the target position and holding it for one second; number of overshootings of the target position; relative path length: actual movement path length in relation to ideal path length) as well as subjective ratings (questionnaires) subsequent to each of the eight experimental trials.

## 5.2 Results

**Performance Data.** In a first step of analysis, the performance data (see Table 4) were explored using analysis of variance (ANOVA). Performing a repeated measures ANOVA, no significant differences between the codings were found for the number of overshootings ( $F(3;7) = 2.98$ ; n.s.). Nevertheless, the number of overshootings were relatively high for the coding schemes providing distance information by varying intensity solely (i.e. codings 1 and 4). In conditions 7, the lowest number of overshootings occurred. Analyzing completion times, ANOVA revealed a significant coding main effect ( $F(3;7) = 20.4$ ;  $p < .05$ ). In general, participants were faster when being supported by two-phases coding schemes, except for the continuous coding scheme 2 (variation of pause intervals). In condition 7, participants performed best. Next, a marginally significant coding main effect was evident for the relative path length (real path length/ideal path length) variable ( $F(3;7) = 8.64$ ;  $p = .05$ ). Similar to the overshooting data, participants performed least accurately when being supported by coding schemes 1 and 4. Similarly, performances decreased with the distance-dependent variation of signal and pause intervals (3). The highest degree of precision was reached when working with coding scheme 7.

**Table 4.** Performance data of the different distance codings; Means (SD)

	Overshootings	Completion times (t)	Relative path length (%)
Coding 1	1.23 (0.55)	10.23 (1.06)	2.58 (0.71)
Coding 2	0.74 (0.39)	7.58 (2.04)	1.68 (0.35)
Coding 3	0.89 (0.53)	9.73 (3.13)	2.09 (0.45)
Coding 4	1.08 (0.50)	7.47 (1.87)	2.10 (0.66)
Coding 5	0.74 (0.31)	7.30 (1.8)	1.69 (0.26)
Coding 6	0.80 (0.30)	6.48 (0.93)	1.63 (0.18)
Coding 7	0.44 (0.19)	6.08 (1.45)	1.40 (0.16)
Coding 8	0.65 (0.38)	7.17 (1.40)	1.58 (0.30)

**Subjective Ratings.** Next, subjective ratings in questionnaires (seven-point Likert scales ranging from 1 to 7) were analyzed. In a first question subjects were asked “How appropriate is the coding scheme for displaying distances” (1 = “not at all”; 7 = “very”). Coding schemes 2, 7, and 8 were rated as most appropriate for distance coding, with mean ratings far above the scale mean of 4 (see Table 5). Yet, no significant effect was found in ANOVA ( $F(3,7) = 4.2$ , n.s.). We also did not find significant effects ( $F(3,7) = 3.7$ , n.s.) for the following question (“I was able to estimate the current distance to the



target at any time”; 1 = “does not apply at all”; 7 = “fully applies”). Not surprisingly, the both coding schemes with a continuous distance-dependent variation of pause intervals (2 and 8) were rated best. Relatively high ratings were also reported for both two-phases coding schemes with a discrete change of pause intervals (5) or intensity (7) when reaching the target zone. Finally, we asked subjects “How difficult was it to interpret the signals” (1 = “not at all”; 7 = “very”). A marginally significant was evident in ANOVA ( $F(3,7) = 5.5$ ;  $p < .10$ ). Coding schemes with distance-dependent signal intensity variation only (1 and 4) were rated worst.

**Table 5.** Subjective data for the different distance codings; means (SD)

	Appropriateness	Estimation of target distance	Interpretation difficulty
Coding 1	3.2 (1.0)	2.9 (1.3)	4.2 (1.7)
Coding 2	5.9 (0.9)	5.4 (1.0)	2.3 (0.8)
Coding 3	3.8 (1.8)	3.3 (1.7)	3.3 (1.8)
Coding 4	3.6 (1.4)	2.7 (1.6)	3.6 (1.7)
Coding 5	4.8 (1.6)	5.1 (1.4)	2.1 (1.0)
Coding 6	4.3 (1.9)	4.4 (1.6)	2.5 (1.4)
Coding 7	5.4 (1.6)	4.9 (1.6)	2.1 (1.1)
Coding 8	5.7 (0.9)	5.3 (1.3)	2.0 (0.9)

### 5.3 Discussion

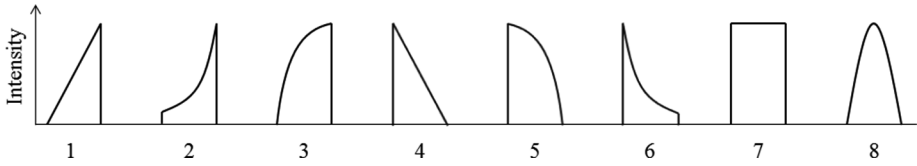
Altogether, we found evidence that a distance-dependent variation of pause intervals only (coding 2) allows a higher performance than variations of signal intensity (coding 1), as mirrored by all objective and subjective data. This is in accordance with the findings of [1]. Obviously, signal frequencies can be distinguished much easier than signal intensity increments with an arbitrarily chosen intensity maximum.

This problem is also evident when implementing a two-phases approach, with intensity variations in the target area (coding 4). Shortening the pause intervals in the second phase (coding 5) had a positive effect, because it is much easier to recognize that the target zone has been entered. An even more successful approach is an abrupt intensity increase when having reached the target zone in combination with a distance-dependent signal pause interval (coding 7). Here, we obtained the best performance data and convincing subjective ratings.

## 6 Signal Shaping for Additional Information

So far, in applications such as collision feedback or motion guidance, we concentrated on the variation of patterns and intensity of vibrotactile stimulation in order to convey information.

Additional information might be transmitted by modulating the stimulation pulses themselves. In this study, we investigate whether signal shapes such as ramps, square-wave, saw tooth or e-function can be distinguished and examine their potential



**Fig. 4.** Modulated signal shapes: different stimuli classified into categories “increasing” (1–3), “decreasing” (4–6) and “symmetric” (7–8).

of communicating impressions such as acceleration, deceleration, warnings and the like.

## 6.1 Methods

In Fig. 4, eight different signal shapes categorized in three different types (increasing, decreasing and symmetric) are depicted. We are aware that the real signal shapes differ from these theoretical shapes particularly at steep flanks due to the time constant ( $T \approx 30$  ms) of the motor.

The signal duration above the perception threshold was set to 500 ms for all variations. Signals were presented in a rhythm with one second pause. The maximum intensity was set to 40 %.

In three training sessions, 15 subjects (two females, 13 males,  $M_{Age} = 33.0$  years;  $SD = 6.4$ ; age range 26–48 years) wearing ear protectors were familiarized with the different signals. In the first two sessions each shape was presented five times followed by a session with randomized order of signal presentation and visual feedback whether the correct signal was identified was given by the investigator. In the final run, each signal shape was presented three times in a sequence with randomized order. As soon as the subject assigned a signal to one of the eight shapes, the output was switched to the next signal. Afterwards, all signal shapes were presented again and subjects were asked to rate their subjective impressions (such as acceleration, deceleration etc.) they associate with the signal shapes.

## 6.2 Results and Discussion

Table 6 shows the interrelation between commanded and recognized signal shape. The number of correct assignment is low except for the signals 2, 6 and 7. These signals have been assigned correctly to the commanded signal significantly often.

Regarding the assignment of signals to the correct category (see Table 7. Interrelation of commanded and recognized category for signal shapes 2, 6 and 7 (%), we found a significant relation (Goodman and Kruskal's  $\lambda = .92$ ;  $p < .001$ ) for signal shapes 2, 6 and 7.

When imagining motion guidance with a pull-metaphor (moving towards the signal), subjects mostly associated -as intended- impressions like “Continue!” with signal shapes of the category “increasing” whereas impressions such as “Stop!” or “Slow down!” were mainly assigned to signal shapes of the category “decreasing”. Signal shape eight was understood as a warning signal.

**Table 6.** Interrelation of commanded and recognized signal shapes (%)

	1	2	3	4	5	6	7	8
Shape 1	50.0	23.3	13.3	6.7	1.7	0.0	0.0	5.0
Shape 2	11.7	78.3	1.7	0.0	1.7	5.0	0.0	1.7
Shape 3	23.3	5.0	25.0	1.7	5.0	0.0	33.3	6.7
Shape 4	0.0	1.7	0.0	33.3	18.3	36.7	0.0	10.0
Shape 5	1.7	0.0	11.9	22.0	35.6	1.7	8.5	18.6
Shape 6	0.0	3.3	0.0	1.7	8.3	83.3	0.0	3.3
Shape 7	0.0	0.0	1.7	0.0	0.0	0.0	95.0	3.3
Shape 8	20.0	3.3	10.0	18.3	15.0	1.7	3.3	28.3

**Table 7.** Interrelation of commanded and recognized category for signal shapes 2, 6 and 7 (%)

	Increasing	Decreasing	Symmetric
Signals of category increasing	98.3	1.7	0.0
Signals of category decreasing	1.7	91.7	6.7
Signals of category symmetric	3.3	3.3	93.3

The results of this study show that signal shapes with an abrupt change of intensity can be distinguished reliably and have potential to transmit additional messages. These findings are consistent with our findings for distance codings where fine variations of intensities are detected less reliably.

## 7 Conclusion

The experiments presented in this paper are the second step in the development of a vibrotactile feedback device for motion guidance of the human hand. Aspects of fundamental relevance for the design and optimization of vibrotactile stimuli patterns used to convey direction and distance information have been investigated.

We determined calibration factors which allow for stimuli with equal perceived magnitudes despite of different factor locations. Furthermore, the investigation of spatial acuity has revealed a very good detection rate which constitutes a promising basis for the presentation of directional cues. In the distance coding study we evaluated different approaches to convey distance information. We found evidence that a distance-dependent variation of pause intervals resulted in better performance than variations of signal intensity. Best performance was obtained with a two-phases approach characterized by an abrupt change of stimuli when distances to the target are below a certain threshold.

Besides coding distances, we successfully conveyed additional information by modulating the signal shapes of stimuli. Subjects were able to distinguish signal categories (“increasing”, “decreasing”, “symmetrical”) and associated impressions such as “slow down”, “continue” or “watch out” with the different categories.

Based on the findings of the conducted studies we will extend the vibrotactile motion guidance for targets in three-dimensional space. Furthermore, we will evaluate the proposed system with individuals who are blind.

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