Physical and Perceptual Characterization of a Tactile Display for a Live-Electronics Notification System

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ABSTRACT

In this paper we present a study we conducted to assess physical and perceptual properties of a tactile display for a tactile notification system within the *CIRMMT Live Electronics Framework (CLEF)*, a Max-based [1] modular environment for composition and performance of live electronic music. Our tactile display is composed of two rotating eccentric mass actuators driven by a PWM signal generated from an Arduino microcontroller. We conducted physical measurements using an accelerometer and two user-based studies in order to evaluate: intensity and spectral peak frequency as function of duty cycle, as well as perceptual vibrotactile absolute and differential threshold. Results, obtained through the use of a logit regression model, provide us with precise design guidelines. These guidelines will enable us to ensure robust perceptual discrimination between vibrotactile stimuli at different intensities. Among with other characterizations presented in this study, these guidelines will allow us to better design tactile cues for our notification system for live-electronics performance.

1. INTRODUCTION

In a preliminary study by Schumacher et al. [1] we presented a prototype system for tactile notifications within *CLEF* (the *CIRMMT Live Electronics Framework*) [2] composed of two vibrating actuators and a software control module seamlessly integrated into the Max [3] environment. The tactile display was designed to allow performers and composers to take advantage of haptic feedback in the context of live-electronics music performance.

The purpose of the current study is to investigate physical characteristics and perceptual correlates such as threshold and perceived intensity for the vibrating disk motors used in the tactile display mentioned above. The final goal is to develop a coherent and meaningful vibrotactile notification system; for this reason we designed two experiments in order to investigate the perceptual saliency of different vibrotactile stimuli.

Since several factors, e.g. experimental design, contact area, choice of actuator and body locus may affect threshold levels obtained in perceptual tactile experiments (see [2], [3], [4], [5]) we designed our experiment with the explicit aim of characterizing only the specific set-up for our vibrotactile application.

Subsequently we present guidelines for design of a set of Tactons [6] that can be used to encode and transmit information to performers via a software vibrotactile notification module[1]. [4]

2. PREVIOUS WORK

The use of live electronics, i.e. real-time processing of sound during a performance, is common practice in mixed music. In this context, facilitating the interaction between the performer and the live-electronics system has become a key concern for both musicians and system designers [7]. In interactive electronics, performers are often left without feedback regarding the internal state of the live-electronics system. This issue is commonly addressed by adding assistive visual or auditory displays, such as on-stage screens or auditory click tracks. Unfortunately, such solutions may often be intrusive and distracting for the performer.

In our previous work [1] we presented a possible solution to this problem by introducing a modular system for tactile notifications. Results indicated that the haptic modality can serve as an alternative communication channel for conveying musically relevant information.

2.1 Tactile Feedback in Live-Electronics

The role of haptic, and especially tactile, cues in the context of musical interaction has been thoroughly investigated over the past decades. Researchers have identified

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[1] `http://cycling74.com`

[2] `http://clef.sf.net` - CLEF is a Max-based live-electronics environment developed by the third author.

[3] See footnote 1.

[4] Tactons are tactile structural messages that can be used to communicate information.

tactile cues which can be sensed by performers while playing a traditional musical instrument, and tactile actuation technology has been extensively adopted in the design of Digital Musical Instruments (DMIs).

Tactile feedback, especially in the form of *tactile notification* [8] has already been used in the context of live-electronics performance to convey information regarding the performer's direct action and effect on a system [9]; the performer could for example receive a tactile confirmation after successfully triggering various effects via a foot pedal. Furthermore, tactile feedback has also been used to coordinate musicians in free-improvisation performances with live-electronics [10].

In our previous work [1] we aimed at generalizing and expanding these concepts. We provided performers and composers with a tool capable of displaying not only immediate feedback in response to specific commands from the user to the system, but also more abstract parameters that are not directly linked to the user-system control flow, e.g. score-related information such as tempo changes. Our tactile display consisted of two vibrating actuators (rotating eccentric masses) placed on the back of the performer. The tactile display was controlled via an Arduino Uno Microcontroller.

3. PERCEPTUAL AND PHYSICAL CHARACTERIZATION OF THE TACTILE DISPLAY

As an improvement to our previous work we aim to characterize the vibrating actuators used to display the tactile stimuli. This characterization can help overcome uncertainty when designing tactile cues, as one could not be sure of, for example, the perceived intensity and discrimination of a number of buzzes marking tempo changes in a complex passage in a piece.

We carried out several measurements and perceptual tests to assess the properties of the vibrating actuators used in the display. These data could provide a solid foundation for the development of a library of preset Tactons and Tacton editors in *CLEF*.

3.1 Physical Measurements

The actuators used in this project are two VPM2 flat rotating eccentric masses from Solarbotics Ltd [5]. These vibrating disks do not provide separate control of the frequency and amplitude parameters. The only control parameter for the actuators is the duty cycle of the PWM wave driving the eccentric masses (with values ranging from 0 to 1), which can be considered as indirectly linked to the intensity of the vibration [11]. The actuators were driven using a ULN2803A [6] IC unit as motor driver. This was connected to an Arduino Uno board generating a PWM signal.

We fixed a PCB 352C23 [7] 1-axis accelerometer on the top face of the actuator using a small piece of Petro Wax and measured the actuator vibration for ten discrete PWM duty cycle values (0.1 to 1.0) to assess the actual amplitude of vibration and average peak frequency at each step. Moreover, the ramp-up (i.e. the time in ms to reach the target vibration amplitude) and ramp-down (i.e. the time to return to the steady state after activation) were measured.

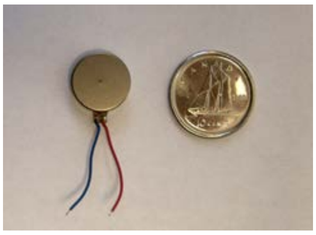

Figure 1. A VPM2 actuator next to a 10 cent coin.

Figure 2. PCB 352C23 1-axis accelerometer fixed to the actuator.

Figure 3. A test subject wearing our tactile display.

3.2 Perceptual Experiments

Two vibrating disk motors driven via PWM output from an Arduino Uno board were placed on the back of the torso of the subject using a Velcro® band. The actuators were placed symmetrically about the spine of the user (see Fig. 3). The software used in the experiments was coded in Max and the communication between the host computer and Arduino board was handled using the Firmata protocol.

With the specifics of musical performance in mind, loci were chosen to be as unobtrusive while still as effective as possible. Although sensory perception is known to be more sensitive on the fingertips, such loci are not suitable in the context of instrumental performance, as the hands are most often preoccupied with manipulating musical instruments. A locus on the back of the torso was therefore chosen, since this position is expected to interfere little with the movements of the performer. Furthermore, the large area of the back of the torso introduces spatial locus as an additional parameter for information display [12]. Sensory perception on the back has previously been investigated in [13, 14, 15] and the back has proficiently been used to convey information via vibration in numerous studies (e.g. [16, 17]).

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[5] `https://solarbotics.com/download.php?file=159e`

[6] `http://pdf.datasheetcatalog.com/datasheet/SGSThomsonMicroelectronics/mXssxrt.pdf`

[7] `http://www.pcb.com/Products.aspx?m=352C23`

Two perceptual experiments were carried out in order to investigate vibrotactile absolute threshold (1) and vibrotactile differential threshold (2). A total of 8 subjects (4 men and 4 women, 21-31 yrs) participated in experiment (1) and a total of 10 subjects (5 men and 5 women, 21-31 yrs) in experiment (2).

Vibrotactile stimuli had a length of 500 ms and the PWM duty cycle was set to go immediately from 0 to 1 for the attack and 1 to 0 for the release, respectively. The only difference between stimuli presented in the perceptual experiments were intensity (which, in turn, affected ramp-down time, see results presented in Table 1).

In order to prevent the risk of biased responses caused by auditory cues, subjects wore headphones with a low level of pink noise during the experiment. The level of the noise was adjusted so as to mask the sound produced by the vibrating motors for the highest duty cycle level.

3.2.1 Vibrotactile Absolute Threshold

A standard method of constant stimuli was used in order to estimate vibrotactile absolute threshold (from here on referred to as VAT). A set of 5 equally spaced stimulus intensities, corresponding to duty cycles of the PWM ranging from 0.1 to 0.5, was chosen. Each stimulus level was repeated six times in a randomized order, thereby giving a total of 30 stimuli. The length of each stimulus was set to 500 ms.

In order to prevent adaptation effects, i.e. that subjects experience a decrease in sensory magnitude of a stimulus due to continuous vibrations over extended periods of time [18] [19]), a number of 5 stimuli was presented on the left actuator, whereafter 5 were presented on the right actuator. As noted in [20], the time to recover from a decrease in sensory magnitude (the recovery time) is about half the time required for adaptation. A pause of the same length as the vibrational pattern was thus introduced after each shift of actuator in order to prevent adaption effects.

Participants were asked to press the space-bar of an external keyboard every time (s)he could perceive a stimulus. The proportion of detected stimuli was annotated for each stimulus intensity. VAT was defined as the point where the proportion of detected stimuli was above 50 %.

3.2.2 Vibrotactile Differential Threshold

The vibrotactile differential threshold (or Just Noticeable Difference, JND) corresponds to the change in duty cycle at which a difference in a detected stimulus can be detected. A two-alternative forced-choice experiment (2AFC) for "same" or "different" discrimination was adopted in order to approximate the difference in vibrotactile stimulus intensity level (corresponding to the PWM duty cycle) required for two stimuli as being different in terms of intensity.

A total of 81 stimuli pairs of various intensity levels were presented in randomized order. Each stimulus pair consisted of two vibrotactile pulses of a length of 500 ms length, separated by a pause of randomized length (750 to 1500 ms). The 81 stimuli pairs consisted of all combinations of duty cycles within the perceptual threshold, i.e. 0.2-1.0 (lower threshold determined via the VAT experiment), quantized in steps of 0.1. This resulted in 81 (9^2) stimuli pairs, where 9 pairs were combinations of the same intensity, and 72 were pairs with different intensities.

A total of 5 stimuli pairs were presented on the left actuator, whereafter a pause for recovery was introduced in order to prevent adaptation effects. The active actuator, i.e. the actuator presenting the tactile stimuli, then changed from left to the right side and the pattern of 5 stimuli continued. The vibrotactile pattern of 5 stimuli was approximated to last about 15 seconds in average. A pause of 15 seconds was thus introduced between each switch of actuator, enabling a total recovery time of 30 seconds.

The subject was asked wether (s)he could detect a difference in stimulus intensity between the two vibrotactile pulses by pressing one of two assigned keys labeled "same" or "different" on an external keyboard. The subject was given 4.5 seconds to answer before the next stimulus was presented. If no answer was recorded for one stimuli pair the answer was set automatically to "same", since it was assumed that a too long response time would suggest that it was hard to decide whether the stimuli were actually different, thereby indicating that they were perceived as similar.

4. RESULTS

4.1 Physical Measurements

The data collected at 192 kHz using the accelerometer attached to the actuator allowed us to investigate several characteristics of the specific vibrating motors chosen for the project.

Ramp-up time required for the motor to go from zero to full amplitude was lower than 15 ms for discrete duty cycle levels ranging from 0.1 to 1.0. The ramp-down time required for a decrease from full amplitude to zero ranged from 400 to 610 ms for duty cycles of 0.2-1.0 (the time for a duty cycle of 0.1 could not be consistently measured due to low signal-to-noise ratio). The ramp-down time was defined as the time from full amplitude of the PWM signal to the moment where the noise floor in the accelerometer signal was reached. A summary of ramp-down times for every PWM value (X_0) can be found in Table 1.

Duty cycle X_0	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
t (ms)	400	490	540	580	580	600	600	610	610

Table 1. Ramp-down times for different duty cycles. X_0 represents the duty cycle value.

As seen in the table, a duty cycle of 0.2 resulted in a 400 ms ramp-down. However, since results from the VAT experiment suggested that duty cycles below 0.2 are below perceptual threshold (see Sec. 4.2), we can consider the longest relevant ramp-down time for the actuators to be approximately 200 ms (ideally one can subtract the 400 ms of ramp-down time corresponding to 0.2 amplitude from all measured ramp-down times, since what happens in those 400 ms is not perceivable). It has to be remarked that these values might be influenced by our experimental setup where the actuator was placed on a table, and that results might change when the actuator is in contact with a user's skin.

Fig. 4 clearly shows that amplitude and frequency are both correlated with the PWM duty cycle and thus cannot be directly controlled with this specific type of actuator. Moreover, the relationship is also not linear, with a clear tendency to stabilize in the higher end of the duty cycle range.

These properties, and how they are perceived by final users when applied to their skin, have to be taken into account when designing tactile effects to be used with our tactile display.

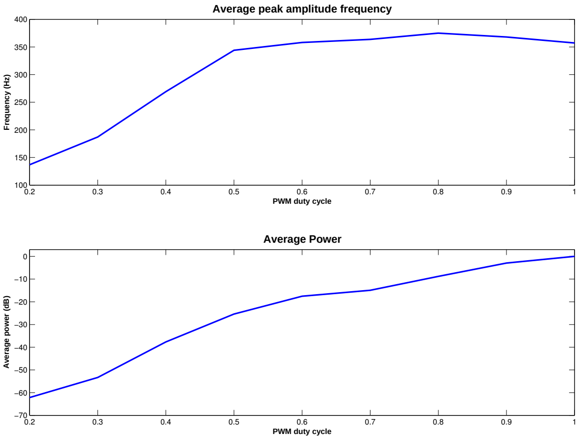

Figure 4. Average peak amplitude frequency (top) and RMS amplitude (bottom) at each discrete PWM duty cycle step from 0.2 to 1. Both these analyses were performed up to $1000\,Hz$ in the original spectrum, which is the upper limit for tactile perception. The average peak amplitude is a weighted average of the most significant frequency peaks found in the spectrum. The frequency range varies from 140 to $380\,Hz$. Average power is expressed in dB, with maximum amplitude used as reference power.

4.2 Vibrotactile Absolute Threshold

Surprisingly, all of the subjects were able to detect all stimuli ranging from 0.2 to 0.5. As for stimuli with a duty cycle below 0.2, only 4.2 % of the presented stimuli were detected. This is consistent with the results from the physical measurements, which showed a low signal-to-noise ratio for PWM values below 0.2.

Duty cycles below 0.2 could thus be considered to be below threshold. We can therefore conclude that duty cycles below 0.2 should not be used when designing Tactons in this particular set-up, i.e. with an actuator configuration with actuator locus on the back of the torso.

4.3 Vibrotactile Differential Threshold

The overall aim of the differential threshold experiment was to investigate which difference in duty cycle (X_1) that was required in order to ensure robust discrimination between vibrotactile stimuli. It has previously been found that a difference of at least 20-30 % in amplitude is necessary for such robust discrimination between vibrotactile stimuli [5]. An assumption before carrying out the differential test was that not only the difference between two vibrotactile stimuli but also the order of the presented stimuli would affect vibrotactile perception (i.e. that the results would depend on whether the lowest or highest PWM duty cycle was presented first in a stimuli pair).

From the 810 observations collected from the perceptual experiment an average *correctness* could be calculated for each difference in duty cycle (i.e. for each X_1) by collapsing the data over subjects. Correctness was defined as the percentage of the observations where a stimuli-pair was rated as "different" when there was actually a physical difference in duty cycle, i.e. a X_1 of 0.1 or more. The average percentage of correctness was in other words computed for each of the 72 stimuli pairs that were different in terms of intensity. Results can be seen in Table 2.

Duty cycle X_1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Percentage %	26	38	55	63	81	83	90	95

Table 2. Correctness for different duty cycles. For duty cycle differences X_1 greater than 0.3 correctness will be above chance.

By dividing the 72 stimuli pairs in two subgroups depending on whether a low stimulus level was presented first or secondly, two groups of 36 pairs each were obtained. In order to investigate if the order of the stimuli influenced the vibrotactile differential threshold, a two-sample t-test for comparing means was performed on the two samples (since $n > 30$). For a 95 % confidence interval a p-value of 0.97 was obtained, hence the null hypothesis of that the two distribution's true difference in means is equal to zero could not be rejected. We could thus conclude that the average correctness of a rating of a specific stimuli pair is not affected by the order in which the stimuli are presented.

Subsequently, a logistic regression analysis was performed on the data set. Logistic regression [21] has the advantage of predicting the probability of an event outcome from a set of predictors (in our case: start value of the duty cycle and absolute difference in duty cycle between two stimuli). The proposed model for probability of a perceived difference was defined as follows:

$$\begin{aligned} &logit\ P = x\beta = \\ &= \beta_0 + \beta_1 X_0 + \beta_1 X_1 + [\beta_2 \ldots \beta_1 0][X_2 \ldots X_{10}] + \epsilon \end{aligned} \tag{1}$$

Where β_n corresponds to the regression coefficients, X_0 and X_1 are the explanatory variables (start value of duty cycle and difference in duty cycle, respectively), $[X_2 ... X_{10}]$ a vector of dummy variables with corresponding coefficients $[\beta_2 ... \beta_{10}]$ and ϵ is a an error term. Dummy variables are incorporated in the regression model in order to account for effects caused by individual differences in sensory perception among the subjects, i.e. that some subjects consistently perceived the stimuli as being stronger

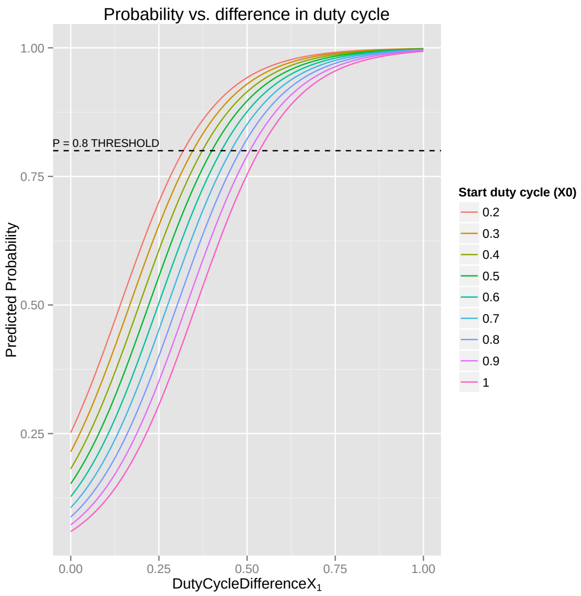

Figure 5. Predicted probability versus absolute difference in duty cycle X_1 plotted for different start values X_0.

or weaker. Subject 10 was set as reference for the dummy variables and clustered robust standard errors were used in order to correct standard errors for model specification.

The obtained β estimates, i.e. the regression coefficients, can be found in Table 3. According to the results, both difference in duty cycle and start value of the duty cycle were significant predictors of the probability of a response equal to “different” ($p < 0.001$).

The logit function was transformed back to the probability scale according to Equation 2 and 3. The probabilities for X_0 from 0.2 to 1.0 and X_1 ranging from 0.2 to 0.8 were subsequently computed. Results are visualized in Figure 5 and 6.

$$P_{\textit{different}} = \frac{1}{1 + e^{-x\beta}}\,, \tag{2}$$

$$x\beta = -0.67 - 2.09X_0 + 7.75X_1 \tag{3}$$

In order to ensure robust discrimination between vibrotactile stimuli of different start values X_0 we opted for a predicted probability of $P = 0.8$ and computed the required difference in PWM duty cycle (X_r) for a fixed start value (X_0) at this specific probability level. The obtained values can be found in Table 4. As a result of our requirement of 80 % predicted probability of correctness rate, our required intensity difference between stimuli is higher than what was suggested in [5]. As shown in Table 4, the required duty cycles range from 0.32 to 0.53, corresponding to a difference in percentage of approximately 40 to 67 % (if the total range is set to a duty cycle of $1 - 0.2 = 0.8$).

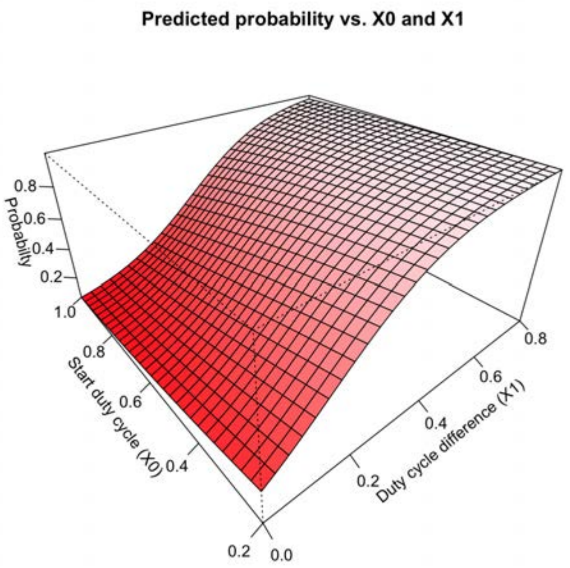

Figure 6. Predicted probability versus difference in duty cycle X_1 plotted for different start values X_0. Red intensity is a measure of how low the predicted probability is; couplings in the white area should be opted for, in order to ensure robust discrimination (see Table 5 for possible couplings).

	β	σ
β_0	-0.67***	0.39
X_0	-2.09***	0.61
$X1$	7.75	1.09
Observations	810	

Table 3. Regression coefficients with standard deviation $***p < 0.001$.

X_0	X_r	%
0.2	0.32	39.90
0.3	0.35	43.26
0.4	0.37	46.63
0.5	0.40	49.99
0.6	0.43	53.35
0.7	0.45	56.72
0.8	0.48	60.09
0.9	0.51	63.45
1.0	0.53	66.81

Table 4. Required duty cycle differences (X_r) in order to obtain robust discrimination between vibrotactile stimuli.

5. SUGGESTIONS FOR TACTON DESIGN

It has previously been found that it is possible to encode information by using different intensity levels of tactile stimuli [22]. Based on our findings presented above, we can conclude that subjects are able to discriminate between certain intensity levels presented using the actuator set-up in our tactile display. This indicates that the intensity parameter can be used to convey information to the musician while using our vibrotactile display.

Based on our findings, we can draw a number of conclusions that may serve as general guidelines for the design of a preset library of Tactons and arbitrary tactile notification cues in *CLEF*:

1. From the absolute threshold experiment we can conclude that duty cycles below 0.2 should not be used to encode information in our vibrotactile tool.
2. Results from the differential threshold experiment indicate that the order of stimulus intensity does not affect intensity discrimination and therefore does not need to be taken into account.
3. The logistic regression model provides useful guidelines for selection of duty cycles. As shown in Figure 5 and Table 4, the difference in duty cycle between two stimuli is a function of the absolute values with reference to the duty cycle scale $(0.2 - 1.0)$: a lower duty cycle will require a smaller difference between the two stimuli than a higher duty cycle, in order to ensure the same probability of them being perceived as “different”.
4. Considering temporal aspects related to the physical characteristics of the vibrating disk motors, we can conclude that ramp-up times are almost negligible and need not to be taken into consideration upon Tacton design. However, the relevant ramp-down times are significantly longer, ranging up to 200 ms. This asymmetry in the envelope should be considered when designing, for instance, Tactons with fixed decay time or pulse-train-like Tactons for the tactile display.
5. No discrete pulses with inter-onset-times less than 200 ms can be perceived with this particular actuator set-up.

After analysis of the values presented in Table 4 we propose information encoding in terms of the intensity parameter consisting of any combination of the couplings of discrete duty cycle values introduced below in Table 5. Presented together with their Weber fractions (the ratio of the difference threshold to a reference level) [23, 5], these couplings are likely to ensure robust intensity discrimination and thus effective information display. In contrast to the findings in [5], the Weber fractions are not clustered around a ratio of 1.1 to 1.3 in difference.

Stimulus 1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6
Stimulus 2	0.5	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0
$W_{fraction}$	2.5	3.0	2.3	2.7	2.0	2.3	1.8	2.0	1.7

Table 5. Suggested intensity couplings for effective information display.

As suggested in [20], not more than four different intensity levels between the detection versus comfort-pain threshold should be used when designing vibrotactile stimuli. Selecting couples from Table 5, we may propose three different intensity levels for information coding in our tactile display (e.g. 0.2, 0.5 and 0.9). Such a choice of intensity levels would, according to the predicted model, be perceived as different from each other for the probability value of $P = 0.8$.

The selection of three intensity levels for information encoding are in line with previous findings presented in [22], where it was found that intensity can be successfully used as a parameter in Tactons when three levels of intensity are presented using a standard mobile phone vibration motor.

Possible information coding of the three intensity levels could for example be mappings between urgency of a message and vibrotactile intensity level. Low level intensities (duty cycles of 0.2) could be used for less urgent messages; e.g. low-intensity click-tracks providing vibrotactile information, similar to the auditory feedback of a standard metronome. Higher intensities could be used in order to convey notifications or alerts of great importance or higher urgency, for example in situations where the performer needs to be informed about an important future event in a score.

If temporal factors such as ramp-down time is an important factor for the design of vibrotactile stimuli, one solution is the use of a different motor driver circuit. The motor driver circuit could use, for instance, a full h-bridge driver with switch capabilities. Such a driver allows an almost-instantaneous stop of the motor by rapidly inverting the plus and minus terminals. However, changing the hardware in such a manner might require a drastic redesign of Tactons.

Finally the results from the measurements of peak frequencies of the disk motors show frequencies ranging from 140 to approximately $380\,Hz$. This information is useful for the selection of loci for the vibrating disk motors, since different parts of the human body have different sensitivity to certain frequency ranges. In this context it is worth noting that the sensitivity peaks for the human tactile perception can be found around $250\,Hz$ [19]. According to the results presented in Figure 4, a frequency of $250\,Hz$ can be found somewhere between the duty cycles 0.3 and 0.4. This goes in line with the lower values of duty cycle difference X_r required for robust discrimination of vibrotactile intensity, as presented in Table 4.

6. CONCLUSIONS

In this paper we presented quantitative measurements and perceptual data for the characterization of a tactile display used for encoding and transmission of haptic notifications in *CLEF*, a live-electronics composition environment. Our work is motivated by the fact that vibrotactile thresholds are highly depending on the context of use. In order to guarantee design transparency and to provide a robust platform for design of tactile events, we evaluated both physical and perceptual characteristics of our specific set-up.

The results of our tests indicate that duty cycles below 0.2 should not be used for information display. Furthermore we provide a table of possible couplings of intensities that enable robust (i.e. more that 80 % success rate) discrimination of vibrotactile stimuli, in the case where stimuli of

500 ms such as those described in Sec. 3.2 are used. Ultimately, we listed a number of guidelines for the design of Tactons which can be used for mappings to specific musical parameters.

Although the work on our Tacton library design is *CLEF* specific, the results obtained from this study can be used as a perceptual basis for designing Tactons in other musical contexts as well.

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