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Perceptual Dimensions of Stage-Floor Vibration Experienced During a Musical Performance

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ABSTRACT

The human ability to distinguish differences in tactile signals generated by a musical instrument and experienced on typical stage-floor constructions is explored using an audio-tactile display (headphones and calibrated motion platform). Audio and vibration signals generated by a contrabass are combined with mechanical impedance measurements of five stage floors to create stimuli. Test participants are asked to report differences between tactile signals given a fixed audio environment. Multidimensional scaling is used to identify perceptual dimensions in subjective responses. Results show that stage vibration exceeds the threshold of perception, with acceleration up to 0.04 ms^{-2} $\mathrm{W_k}$ peak. Sensation level dominates perceived differences between tactile signals measured for different stage-floor constructions, while audio-tactile time delays have negligible influence.

1. INTRODUCTION

Expanding use of multi-sensory music reproduction calls for increased knowledge of human response to audio-tactile stimuli. The popularity of large, high-quality video displays in combination with multi-channel audio systems in the home has led to widespread acceptance of the surround-sound video as a primary format for recording music. While audio-visual displays already have a firm footing in both commercial and research applications, continuing advancements in technology and hardware have aided in the addition of tactile signals to music presentation systems.

In an ideal environment, studies on the perception of music would always include all five senses, but practical limitations currently make this prohibitively difficult. Historically, the senses that are selected for study are driven by their inherent importance in a situation. Sound is expected to be required for the average music listener, but may not be the primary contributor in select populations. Vision is always a likely candidate due to its importance in virtually all forms of communication; however, in some instances haptics may play a more important role. For example, audio-tactile experiments have long been used to evaluate the comfort and safety of transportation and working environments [7].

As tactile signals continue to be used more frequently in music presentation systems, it is important to develop an understanding of the fundamental qualities of musical vibration that govern our perception. How important is tactile stimulation in the perception of a musical performance? How do humans differentiate tactile signals? What physical characteristics of musical vibration in structures govern human perception? What requirements must be met in order to plausibly represent the tactile mode of perception in a virtual display?

2. MOTIVATION

Tactile stimulation plays an important role in the perception of many musical situations such as musician communication on a performance stage, masking in vehicle audio systems, and the feeling of presence in telematic communication. Common to all these situations is the desire to understand what makes the signals "feel" different from one another.

Gaining a better understanding of both the physical source of stimulation and psychophysical response in musical environments will add a new dimension to the wealth of knowledge on human response to tactile signals. It will also allow designers of both natural and simulated environments to tailor those environments to desirable parameters.

Recent research in human response to musical vibration has begun to outline essential psychophysical parameters such as perceived audio/tactile synchrony [5, 13], and tactile masking of sound [12]. Other work has focused on the interaction of aural and tactile senses in specific applications, such as listening to a sound system in an automobile [11]. All of these studies provide answers to specific questions about the role of tactile stimulation in the perception of musical performances. The purpose this study is to identify new questions that should be asked.

3. EXPERIMENTAL DESIGN

Taking inspiration from a preliminary study into the perceptual dimensions of timbre [6], the authors designed an experiment in which audio and vertical whole-body tactile music signals are presented to a listener in their natural form. In order to ensure the audio-tactile signals presented are as realistic as possible, a specific environment was selected: the vertical whole-body vibration experienced while seated next a musician during a performance on a stage. Tactile stimulation on-stage is expected to contribute to both musician communication and an overall feeling of "presence."

Test subjects were asked to listen to the musical performance and identify differences between tactile signals. A multivariate statistical method was then used to explore the data and correlate perceived differences in stimuli with physical differences in the tactile signals.

Prior to further development, a short pilot study was conducted to verify that the structural vibration generated by a musical performance is in fact perceptible.

3.1. Pilot Study

The objective of the pilot study was to measure the structural vibration generated by a contrabass being performed while coupled to a concert hall stage and compare magnitudes to thresholds of perception published in literature and standards.

Michael Bullock [4] performed several short music passages on the stage of the Experimental Media and Performing Arts Center (EMPAC) concert hall in Troy, New York. Structural vibration was measured at a distance of 2 meters from the contrabass, which was pinned directly to the stage in the traditional manner. Figure 1 is a plot of the instantaneous, absolute peak vibration measured during 400 seconds of the musical performance. Stage vibration was recorded with a PCB 333B50 accelerometer mounted directly to the stage. Both audio and tactile signals can be downloaded from www.loudensound.com.

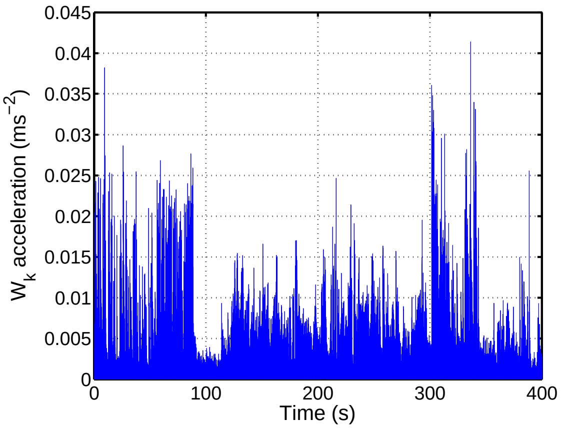

Fig. 1: Peak frequency weighted acceleration measured on a wood stage supported by a concrete slab during a musical contrabass performance at 2 m from the instrument. Absolute threshold of perception is approximately 0.01 ms^{-2} W$_k$ [1].

Approximately 2.4% or about 9.5 seconds of the measured signal exceeded the threshold of probable sensation at 0.01 ms^{-2} W$_k$ peak (frequency weighting according to ISO 2631 [1]). Above this level, perceptible vibration reached amplitudes of up to 0.04 ms^{-2} W$_k$ peak. Peak acceleration levels are used in order to maximize compatibility with other results and avoid inconsistencies that occur when averaging methods such as r.m.s. or r.m.q. are used, as suggested by Griffin [7]. Assuming a crest factor of $\sqrt{2}$, sensation levels associated with these magnitudes would range from "probably perceptible" to "clear perception" for vertical whole-body vibration as shown in Table 1. The implication of the measured distribution and magnitudes is that vibration is important for perception only during the strongest portions of performance, in this case the attack portion of notes. However, the vibration generated results in clearly perceptible levels of sensation.

3.2. Primary Study

With indication from the pilot study that structural vibration on the stage is perceptible and might play a significant role in the perception of a musical performance, objectives were laid out for a larger study using vibration measured on different stages, at different distances, and in different directions of propagation. The objectives were as follows:

- Present listeners with different musical tactile signals representing those experienced in different physical environments while listening to the performance in a multimodal display.
- Ask listeners to rate the degree of perceived difference between tactile signals in a paired comparison.
- Use multidimensional scaling to explore the physical characteristics underlying perceptual differences.

A description of the resulting experiment can be split into two components: the measurement of test stimuli and the subjective listening experiment

3.3. Tactile Signals

Because the purpose of the study was to explore differences in structural vibration resulting from a change in physical environment, the variable of source signal had to be eliminated. A unique tactile auralization technique was developed that combines a "decoupled" vibration signal with a mechanical impulse response by convolution [2]. Through the development of the technique, structural impulse responses were measured on 5 different stage floor constructions at 3-6 locations each.

Each structural impulse response measured is used to create a calibrated tactile test signal representing the structural vibration that would be experienced on different stage floor constructions in response to

Table 1: Semantic labels associated with physical magnitudes of acceleration (adapted from *Handbook of Human Vibration* [7].)

Semantic Label	ms^{-2} W$_k$ r.m.s.
Very strong perception	0.16-.315
Strong perception	.08–0.125
Very clear perception	.04–0.063
Clear perception	.02–0.0315
Perception probable	.01–0.016
Perception improbable	.0005–0.008

the same musical performance. A binaural dummy head microphone, the Head Acoustics HMS V.II, is used to record the audio portion of the musical performance while a PCB 333B50 accelerometer is used to record the decoupled vibration. The aural environment remains fixed across the experiment so that the listener can focus on changes in whole-body vibration. The performance was recorded on the stage of the EMPAC concert hall. The binaural audio recording and each of the tactile signals can be downloaded from www.loudensound.com.

Fourteen tactile stimuli were selected from the 26 different stage floor vibration signals in order to keep the duration of the listening experiment to a reasonable length. A criteria that the r.m.s. acceleration amplitude of the first 30 seconds of each signal must exceed the magnitude of clear perception for whole-body vibration at 0.025 ms^{-2} $\mathrm{W_k}$ was used to select the signals for subjective testing. Three fairly different types of stages are represented: a wood floor supported by wood joists, a wood floor supported by a concrete slab, and an orchestra pit lift deck.

The fourteen stimuli selected were presented to listeners using the audio-tactile display described in the authors' report on the development of the auralization system [2]. The display utilizes an electrodynamic motion platform with a rigidly attached chair to present whole-body vibration and closed-ear headphones to present binaural audio signals. Both audio and tactile stimuli are presented at magnitudes calibrated to the levels observed during the original performance. Frequency response of the platform is compensated by a minimum-phase, FIR filter.

A primary objective of this experiment is to find a connection between the perceptual dimensions and physical characteristics of the stimuli. Because listeners are not required to rate specific physical properties during the subjective experiment, the perceptual dimensions identified can be compared to any physical parameter chosen by the experimenter. Eleven physical parameters were selected for evaluation and are presented in Table 2.

The first seven values listed in Table 2 represent measures of sensation level, each responding differently to the stimulus' frequency content or temporal attributes. The values reported are measured at the middle of the platform chair with a 180-lb subject sitting on the platform. Vibration levels would be higher for lighter subjects. Comparing the W_k ms^{-2} r.m.s. values in column five of Table 2 to the semantic labels of perception in Table 1 reveals that perceived magnitudes should cover only a small range—imperceptible to "clearly" perceptible. However, differences between many of the values exceed the just-noticeable-difference threshold of 10% for sinusoidal signals at 5 and 20 Hz in the region of 0.1 and 0.5 ms^{-2} r.m.s. reported by Morioka and Griffin [10].

The eighth value is the difference in arrival time between tactile and audio signals presented to the listener, with a negative value indicating a tactile lead. Note that in all cases, the tactile signal lags the audio signal. While time differences exceeding several milliseconds are considered long in hearing perception, the values represented by audio-tactile signals in this study all fall within the general range of difference between points of subjective and objective simultaneity as reported by Daub/Altinsoy and Walker *et al.* [5, 13].

The remaining three parameters are measures of frequency content independent of magnitude. The two "bass ratio" values represent the ratio of energy below the crossover frequency to that above the crossover frequency. The spectral center of gravity is the frequency for which equal energy exists above and below, within the valid frequency in this experiment of 30-100 Hz [2]. Spectral measures are taken from the structural impulse responses rather than platform measurements for clarity. The frequency parameters were developed with the intent of quantifying perceived differences in low-frequency content versus high-frequency content as well as "balance" and "peakiness" observed by the authors and reported by the subjects during experimentation.

3.4. Subjective Listening Experiment

A psychometric procedure called multidimensional scaling (MDS) was selected to explore listeners' responses of subjective difference in tactile signals. This procedure is a popular choice for the exploration of subjective qualities and has been employed in past studies into the perceptual dimensions of timbre [6] and preference for concert hall acoustics [14].

Table 2: Physical parameters measured at the middle of the seat with a 180-lb human subject seated on the platform. %>thresh. = % of signal above human threshold for perception, W_k = frequency weighting, B.R. = bass ratio, Spec. CoG = spectral center of gravity.

Stim. #	**%> thresh.**	**ms^{-2} r.m.s.**	**ms^{-2} r.m.q.**	**W_k ms^{-2} r.m.s.**	**W_k ms^{-2} r.m.q.**	**ms^{-1} r.m.s.**	**ms^{-1} r.m.q.**	**dT (ms)**	**B.R. 50Hz**	**B.R. 72Hz**	**Spec. CoG (Hz)**
1	8.1	0.18	0.37	0.006	0.011	45.1	51.1	6.1	0.18	0.64	75
2	5.3	0.12	0.22	0.005	0.01	31.8	42.5	9.7	0.1	0.7	75
3	20.3	0.23	0.4	0.01	0.016	68	81.8	4.1	0.12	0.54	76
4	2.4	0.14	0.36	0.004	0.009	100.9	114	6.7	0.11	0.52	77
5	27.1	0.37	0.8	0.013	0.026	16.2	21.6	9.6	0.18	1.24	69
6	27.2	0.23	0.37	0.012	0.02	18.3	22	7.7	0.03	0.66	76
7	19	0.24	0.45	0.009	0.015	110.1	138.6	6.6	0.04	0.33	81
8	37.7	0.31	0.54	0.018	0.028	64.4	83.1	13.1	0.12	0.8	72
9	17.3	0.17	0.27	0.008	0.014	92.3	113.1	31.7	0.11	0.7	74
10	10.9	0.2	0.4	0.007	0.013	26	29.8	9.6	0.44	1.5	64
11	1.9	0.06	0.14	0.003	0.008	233	263.6	26.7	0.56	3.63	58
12	2.3	0.13	0.29	0.003	0.007	178.4	210.6	2.1	0.4	1	69
13	1.1	0.1	0.23	0.003	0.005	101.7	123.9	2.2	0.18	0.73	74
14	0.1	0.03	0.08	0.002	0.003	64.6	89.7	3.4	0.39	1.24	67

Multidimensional scaling is a method for exploring the underlying factors or "structure" of a data set [9, 3]. It is an exploratory data analysis technique in which an iterative process is used to find a mathematical transformation that maps a set of distances between objects or stimuli into an m-dimensional space. Within the stimulus space, Euclidean distances approximate the input distances. In this experiment, the "distances" are the users' reported difference ratings between tactile stimuli and the resulting coordinate space is a map showing similarities and differences bewteen signals perceived by the listeners.

Listeners used a simple computer interface implemented in Max/MSP software controlled by a handheld input device to run the experiment. The user was able to switch back and forth between a pair of stimuli in real-time while listening to the musical passage. The user could restart the passage from the beginning at any time. The subject was allowed to listen to as much of the 2-minute passage as they liked before deciding upon a difference rating. Once decided, the listener selected a difference rating from 1–7 and moved to the next pair of signals.

Each subject was presented with a total of 91 pairs of stimuli in A/B comparison format. Signals were not tested against themselves. The presentation order of stimuli was randomized and broken up into three segments (two of 30 stimuli and one of 31). The order of stimuli in each segment remained the same, but subjects took the three segments in a randomized order. The subject was asked to complete 5 trial tests in order to become familiar with the system and stimuli.

Ten individuals completed the subjective test, resulting in ten difference matrices. Volunteer subjects varied in age between 23 and 38 years and were recruited via email or personal invitation. Eight of the subjects play a musical instrument and four have had formal training.

4. RESULTS

Two methods of MDS are used: two-way and individual difference scaling (three-way). In two-way MDS, all the responses for each signal comparison are averaged into one collective response. In individual difference scaling (INDSCAL), the resulting group stimulus space takes into consideration the relative importance of each configuration axis displayed by each subject's responses. The resulting stimulus spaces should show similar trends and can be evaluated in the same way.

Ordinal MDS with broken ties is used to create configurations of 5 different dimensionalities for both two-way and individual difference scaling. The scree-plot in Figure 2 shows Kruskal Stress-1 values (a measure of error in the transformation) plotted against the dimensionality of the different stimulus space dimensionalities for both types of MDS. The two-way values indicate a very good level of fit across all dimensionalities—well below the fit expected for a random data set. The three-way INDSCAL scree-plot shows higher levels of stress, with values exceeding the goodness-of-fit for a configuration modeling

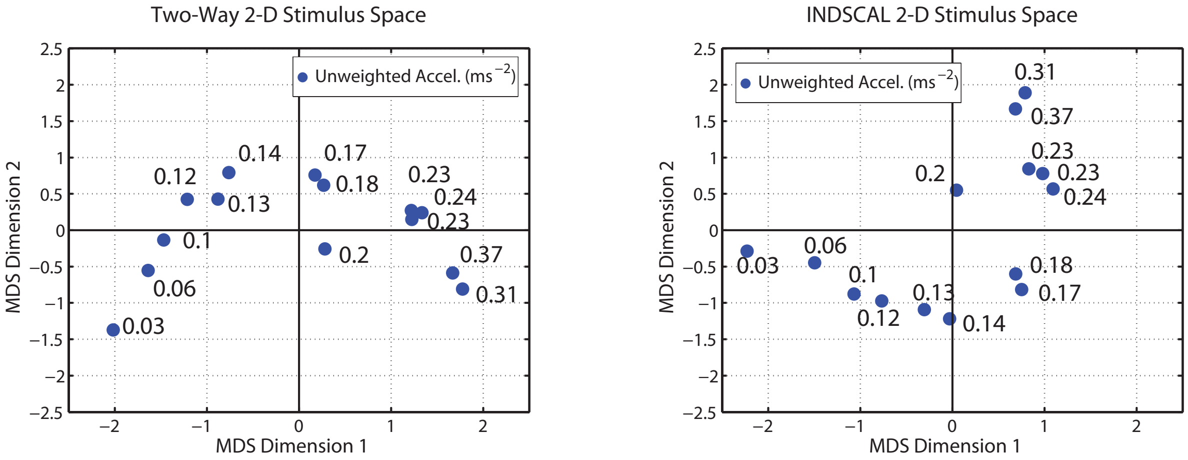

Fig. 3: Two-dimensional two-way and individual difference scaling MDS configurations. Each point represents structural vibration perceived on a different stage construction. Stimuli are labeled with unweighted acceleration values measured on the platform.

random noise at a dimensionality of three. Higher stress values for INDSCAL are expected due to the added difficulty of modeling differences in perception across individual subjects' responses.

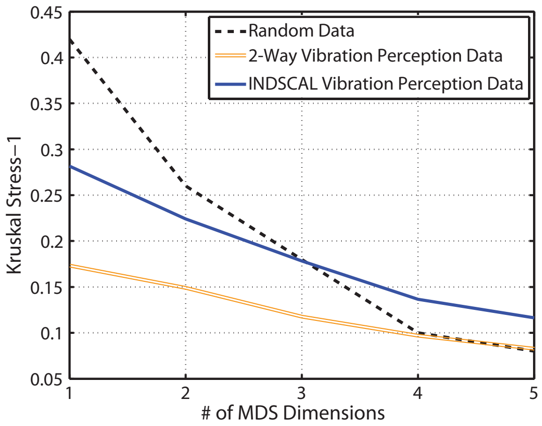

Fig. 2: Kruskal Stress-1 values calculated for two-way and individual difference scaling MDS configurations of five dimensionalities. "Random Data" represents Stress-1 values for an equivalent MDS configuration generated with a set of random numbers as the input.

A sharp change in the error values would indicate an ideal level of fit has been reached, but is not observed for this data set in either type of MDS. As a result, there is no apparent point at which an increase in dimensionality stops improving the fit. However, because the stress values for both the two-way and INDSCAL models apply to the same data set and stress values observed for INDSCAL indicate an excessive error above a dimensionality of three, it is unlikely that subjective differences measured in this test are made with more than two perceptual dimensions.

Two-dimensional configurations in both two-way and INDSCAL MDS are selected for evaluation and are shown in Figure 3. Each data point represents a vibration signal experienced on an individual stage construction and the two axes represent some perceptual parameter or combination of parameters by which subjects rated the differences in vibration.

Unweighted acceleration, the measure of sensation level with the highest correlation, is used to label and plot both MDS configurations, as shown in Figure 3. When acceleration magnitudes are plotted as labels, both models show a trend of increasing value along the axis of highest correlation. In addition, stimuli with similar acceleration magnitudes are mapped in groups. This grouping could indicate that both of the axes are related to sensation level.

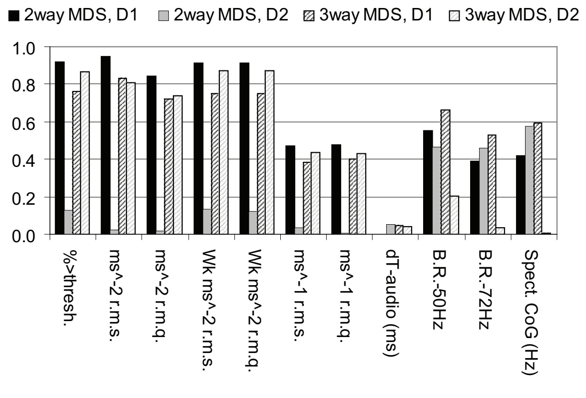

Fig. 4: Coefficients of correlation between phyiscal parameters and perceptual dimensions of two-dimensional MDS configurations. 2-way configurations are shown by solid bars. 3-way configurations represent individual difference scaling models, and are shown in dashed bars.

4.1. Correlation to Physical Parameters

Linear regression was used to identify correlations between the physical parameters shown in Table 2 and the axes of the MDS configurations shown in Figure 3. The Pearson product-moment correlation coefficients obtained from correlation of eleven parameters with the 1, 2 and 3 dimensional two-way and INDSCAL MDS configurations were examined. Absolute values of the correlation coefficients were used given because positive and negative correlations result from a rotation of the stimulus configuration, not opposite subjective reactions to stimuli. Correlation coefficients for the two-dimensional two-way and INDSCAL configurations are presented in Figure 4.

5. ANALYSIS

Strong correlation between a physical parameter and one or more dimensions in an MDS configuration provides indication that the physical parameter has strong influence over perceived differences in the tactile signals. A quick glance at the data in Figure 4 reveals that the physical measures of magnitude (% above threshold and acceleration) present the highest correlation with perceptual dimensions of difference in the tactile signals. The one-dimensional models showed the same trend. The addition of a third dimension to the models provided no correlation higher than 0.5 with any of the physical parameters, evidence that underlying data set is most appropriately modeled with a two-dimensional configuration.

If the models are perceptually orthogonal, a parameter that is highly correlated with one axis should have a low correlation to all other axes. Orthogonality is observed to some degree only in sensation level measures for the two-dimensional two-way model shown by the solid bars in Figure 4. The remaining frequency measures in the two-way MDS configuration and all parameters in the three-way MDS configuration show similar correlations to both axes, a lack of orthogonality.

It is possible that averaging all subjective responses into the two-way difference matrix normalized the importance of two competing dimensions to zero. The individual difference subject space shown in Figure 5 shows that all subjects found both axes of perception to be important in discerning differences, with some subjects leaning more heavily towards the first axis. Correlation coefficients for the INDSCAL model shown in Figure 4 suggest that both of these axes might be different perceptions of sensation level. When individual differences in perception are eliminated, the two axes of the INDSCAL model might have collapsed into one important axis in the two-way model with the other representing only a fit to noise.

The hypothesis that both the axes in the two-dimensional configurations represent some frequency dependent measure of sensation level is supported by the configurations themselves, shown in Figure 3. Even in the two-way model, groupings of stimuli seem to be controlled by the sensation level measure with the highest correlation coefficient: unweighted r.m.s. acceleration. Small differences in acceleration create tight groups of stimuli using *both* axes.

The most highly correlated measure of sensation level in all MDS configurations is unweighted r.m.s. acceleration. This finding supports the results reported by Howarth and Griffin that humans may be more sensitive to high frequency vibration than indicated by the ISO 2631 frequency weighting contour, especially in critical listening situations such

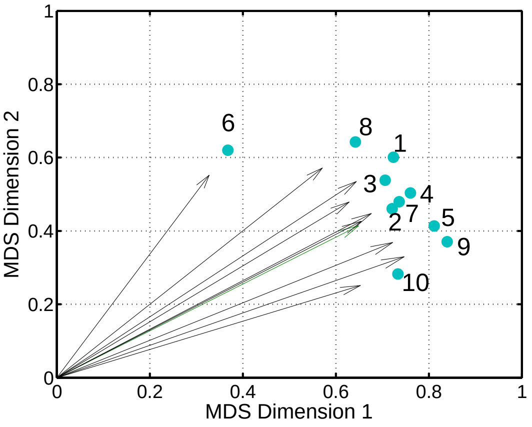

Fig. 5: Two-dimensional subject space for individual difference scaling MDS configuration. Each vector represents a different subject and the importance of each dimension used in making their difference ratings.

as music performance [8]. However, all of the acceleration measures show high correlation, perhaps indicating that the perceptual differences associated with different ways of measuring sensation level may be small.

Correlation to the time difference between tactile and audio signals is extremely low across all configurations. This low correlation indicates that audio-tactile time delays are relatively unimportant in evaluating differences in tactile signals in a multimodal environment. The results of this study show that when asked to evaluate signals in their natural form, audio-tactile time delays are swamped by differences in magnitude.

The variety of sound speeds measured in structures indicates that there may some ecological basis for the relative unimportance of audio-tactile time delays [2]. In other modes of perception such as the audio-visual relationship, differences in arrival time of information change have a clear relationship. The small variation of the speed of sound in air and the constant speed of light means that time delays at a given distance will remain constant across nearly all situations experienced in life. In the audio-tactile relationship, the time delay relationship between modes of perception is observed to change with floor construction and even position on a floor. The constant fluctuation of tactile propagation times means that humans do not get the chance to build up a reference upon which to compare tactile signals.

In response to a survey administered after the experiment, 7 of the 10 subjects stated directly that they used intensity or sensation level to differentiate signals. Four of the subjects stated a difficulty in putting words to their method of differentiating signals. Other methods of differentiation mentioned were “different types of tingling sensations in different areas of my body”, “ area of stimulation”, “highest frequency of vibration”, “frequencies that the stage responds to” and “directionality in the vibration signals”. One subject mentioned “quickest response to audio signal” in response to a question regarding preference. All 10 subjects stated that the presentation seemed realistic and added to the perception of presence.

6. CONCLUSION

The results of this study show that whole-body vibration is an important contributor to the overall experience of a musical performance on typical stage floors and that the physical magnitude of vibration and associated sensation levels are fundamental to perceived differences in signals. While this seems intuitive, it is interesting to consider that two signals with drastically different spectral balances and peaks might be differentiated primarily by their magnitude. Perhaps the proper quantifier of differences in frequency content was simply not identified.

The dominance exerted by sensation levels emphasizes the need for amplitude calibration in audio-tactile displays. Especially when used for music reproduction, inaccurate magnitudes of vibration could result in an undesirable disconnect between aural and tactile senses.

Listeners reported using differences in the frequency content to differentiate tactile signals and statistical analysis showed subtle evidence, but strong correlations proved elusive. Sensitivity to audio-tactile delays was observed to be very low, perhaps due to the constant variation of this parameter in everyday situations. While other perceptual differences are suppressed, the results show that frequency characteristics and time synchrony of audio and tactile signals are at least not as important as sensation level in general differentiation.

The results presented in this paper form the foundation for further exploration. With validation of the importance of sensation level, more subtle characteristics such as frequency content, structural reverberation, and temporal behavior should be explored.

7. ACKNOWLEDGMENTS

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