

# Perceptual Design of Haptic Icons: Towards an Expressive Haptic Language

**Karon E. MacLean**

Department of Computer Science  
University of British Columbia  
2366 Main Mall  
Vancouver, B.C. V6T 1Z4  
Canada  
{maclean, enriquez}@cs.ubc.ca

**Mario J. Enriquez**

**Vincent DiLollo**  
Department of Psychology  
University of British Columbia  
2136 West Mall  
Vancouver, B.C. V6T 1Z4  
Canada  
vince.dilollo@ubc.ca

## ABSTRACT

The most common applications for haptic feedback employ “direct rendering” techniques wherein a user touches a virtual model, usually displayed graphically as well. We propose a new class of applications based on abstract messages, ranging from “haptic icons” – brief signals conveying an object’s or event’s state, function or content – to an expressive haptic language for interpersonal communication. Building this language requires us to understand how synthetic haptic signals are perceived, and what they can mean to us.

Experiments presented here address the perception question by using Multidimensional Scaling (MDS) to extract perceptual axes for complex haptic icons: once this space is mapped, icons can be designed to maximize both differentiability and individual salience. Results show that a set of icons constructed by varying the frequency, magnitude and shape of 2-sec, time-invariant wave shapes map to two perceptual axes, which differ depending on the signals’ frequency range; and suggest that expressive capability is maximized in one frequency subspace.

## Keywords

Haptic interfaces, icon design, multidimensional scaling analysis, language.

## INTRODUCTION

Sensory overload is a common problem with contemporary computer user interfaces, particularly for those that connect users to computation embedded in portable devices and non-desktop environments. These are increasingly pervasive, often have complex functionality, and are frequently used in contexts which pose multiple demands on a single sensory modality: *e.g.*, accessing a cell phone while driving or sitting in a theatre, or using a remote control that requires visual inspection while watching TV. A theme of our research is to explore how the underutilized haptic sense can absorb some of the demand that modern interfaces place on vision and audition.

With few exceptions, haptic force feedback research has been devoted to “direct rendering” of virtual environments.

Most force feedback devices enable 3D manipulation of graphically displayed models, and tend to be expensive and non-portable. They are used in desktop applications such as training simulators for laparoscopic surgery, sculpting of 3D models and design of mechanical assemblies. The user feels and manipulates the same thing he sees; the graphical image is rendered haptically.

Haptic feedback is well suited for a radically different kind of contribution, potentially of much larger scope, by rendering abstract models or concepts. This might be a physical metaphor to manipulate virtual models that don’t have a literal physical representation [13]; or, as presented here, a new modality for communication. At the lowest level, devices and objects notify users of an event, their identity or their current state or contents. Simplistic versions, such as pager vibrators, have existed for years. However, we argue that this binary or amplitude-graded signal contains far less intelligible information than may be possible with systematic, perceptually guided design; and that in the future, it may support expressive and nuanced communication that qualifies as a haptic language.

## Haptic Icons

We define “haptic icons” for our purpose as brief computer-generated signals, displayed to a user through force or tactile feedback to convey information such as event notification, identity, contents or state. While these icons might also be constructed from real texture or mechanisms, such an approach would not permit dynamic computer control and are thus ultimately of more narrow applicability. Synthetic icons may be experienced passively or explored actively; they may be composed from a single or many parameters; and their signal can be steady or vary over time (*e.g.*, a sinusoid with an amplitude envelope that increases or decreases). The possible variety is illustrated by the haptic icon editor of Enriquez *et al.* [5]. However, this kind of manual, intuitive design makes it difficult to predict whether a set of icons will be easily distinguishable, or salient in combination.

### **Approach: Perceptual Design**

The first step towards abstracted haptic communication is to understand how synthesized haptic signals are perceived: which parameters are most salient, how they interact perceptually, and what kind of signals are easily distinguished. We wished to represent this knowledge in a multi-dimensional design space, within which an icon designer can systematically compose a set of icons with specified characteristics and maximum information carrying capacity. For example, to create a set of 5 easily distinguished icons, he could pick 5 maximally-spaced locations in a volume defined by the parameters that his display can control, and rotate them to find the most appealing set. This early stage is a necessary prerequisite to the specification of higher level characteristics which would eventually allow assignment of semantic meaning.

The goal of the research presented here is to begin to map haptic perception of complex stimuli in terms of key input dimensions for synthesized, passively presented haptic icons. We have chosen to analyze synthetically composed icons rather than natural ones (*e.g.* real textures) because we are looking specifically for a mapping between controlled display parameters to human perception.

Our approach is based on Multidimensional Scaling Analysis (MDS), which has already proved useful for perceptual mapping. Once validated for a small number of design parameters, this technique can be extended to more parameters and classes of icons.

### **PREVIOUS WORK**

#### **Human Perception of Forces and Textures**

There is substantial literature on human tactile and force perception; most relevant here are studies that focus on perception of synthetic stimuli. Tan *et al.* summarizes a series of experiments determining various perceptual capabilities, including pressure, stiffness, position resolution and force magnitude [14]; while Klatzky & Lederman have studied texture perception extensively, most recently touching through a stylus (a common haptic interface handle) [9]. However, these results apply to “pure”, single-parametered stimuli, and do not attempt to place them in an information-bearing context as we aim to.

Rinker *et al.* examined human ability to discriminate finger movements according to amplitude and frequency with the goal of receiving synthesized speech information [12]. We adopted some aspects of Rinker’s method to perform perceptual equalization for the stimuli produced by our setup.

#### **Iconography for Other Senses**

Graphical and auditory icons have long been integral to computer interfaces, as a means of indicating functionality, location and other low-dimensional information. Easily identified by the user, they can be used to relate specific functions to abstract controls. Auditory and haptic icon design share key attributes: for example, both must be

temporally sequential, even though humans are poor at discriminating temporal amplitude and period.

Gaver *et al.* [6] defined “auditory icons” as representations of objects or notions which embody a literal, intuitive meaning: the sound of a paper being crushed indicates deleting a computer file. However, there is no systematic basis for determining relative icon salience or differentiability, which can lead to problems. For example, a sound for an unimportant event might dominate or be confused with the signal for a more urgent event.

Conversely, Brewster *et al.* focused on quantifying people’s ability to perceptually differentiate “Earcons”: sounds and rhythms with no intrinsic meaning, whose meaning has to be learned [2]. They found that structuring bursts of sound aided in differentiation, as did varying musical timbre rather than using simple tones.

Our own study shares more philosophically with Brewster’s, but we also have a long-term aim of adding the intuitive benefits of Gaver’s approach when we better understand the perception of complex haptic stimuli.

#### **Multidimensional Scaling of Perceptual Quantities**

MDS is a tool for analyzing complex scenarios, and provides a means of representing complex perceptual data by uncovering its “hidden structure” [3].  $N$  items or stimuli (here, haptic icons) are analyzed according to their perceived dissimilarity. The algorithm takes as input a dissimilarity matrix containing perceived distances between items and places them in a Euclidean space of specified dimension, such that inter-item distances approximate the specified dissimilarities. “Stress” is a measure of the fitness of the space’s dimension based on perceived distances between stimuli and aids in selecting an appropriate dimensionality: as with fitting a 2-D curve to a dataset, a greater number of dimensions generally give a lower stress value, but reduce the model’s abstraction.

Once an appropriate dimensionality has been found, some ingenuity may be required to interpret the meaning of the axes. The dimensions recovered by MDS are taken to be the salient aspects for the organism, and the stimulus coordinates recovered in the scaling are interpreted as the location of the objects along these salient aspects.

Some studies that have used MDS in sensory perception illustrate possible approaches, payoffs and pitfalls. They exhibit a variety of means for obtaining dissimilarity data, and interpreting MDS solution axes.

The initial and perhaps most well-known use of MDS to model perception is Grey’s analysis of timbre space, which resulted in a 3-D model of a percept which had long defied characterization [7]. Grey collected data by requiring participants to rate pairs of tones relative to one another. He employed synthetic rather than natural tones in order to control factors such as perceptual equalization, tone complexity and physical properties – the latter because, his

ultimate goal was to synthesize tones with well-understood control over perceived timbre as is ours.

Ward devised a collection strategy whereby participants sort stimuli into clusters, rather than rating stimulus pairs [16]. This increased the efficiency of evaluating large sample sets, and improved repeatability and accuracy.

Hollins *et al.* tested passive perception of real tactile surface texture [8]. Participants sorted 17 stimuli (*e.g.* wood, sandpaper, velvet) into categories on the basis of perceived similarity, from which a 3-D MDS solution space was derived. Two axes were roughly associated with hard/soft and slippery-sticky; the third was difficult to interpret. While valuable for understanding tactile perception, Hollins' naturalistic stimuli does not clarify the *synthesis* of tactile sensations, since it is not clear how to relate simulation parameters to the sensory percepts identified.

Most recently, Bonebright devised a GUI to expedite collecting dissimilarity data for everyday sounds [1]. Participants were asked to sort 74 sound stimuli into categories; here, the large sorting task was eased by representing each stimuli with a graphical icon which the participant could repeatedly test and move about.

## EXPERIMENTS: GENERAL METHOD

### Overview

Two iterations of dissimilarity data collection (employing Ward's cluster-sorting technique) and MDS analysis were performed. The first iteration was conducted with a broadly spaced set of stimuli, to survey the space; the second iteration focused on the subregion promising greatest participant sensitivity.

Unlike many MDS studies of naturalistic stimuli, we chose not to obtain perceptual ratings or rankings in support of axis interpretation at this time. Our knowledge of the input parameters for these synthetic icons better serve our primary goal of identifying a correspondence between icon design parameters and user ability to differentiate the resulting icons. Rather than name the output axes, we need to know how the *input* parameters act together to affect user perception.

### Experiment Setup

The same experiment setup and general procedures were used for both phases.

The haptic interface was an actuated knob interfaced through a motion control board (Immersion Impulse Drive) in a 1.2 GHz Pentium 3 computer running Windows 2000 in realtime mode. The knob was mounted directly on the shaft of a 20-W DC motor (Maxon #118752, stall torque 240 mNm, mechanical time constant of 5 ms) with a 4000 cps post-quadrature optical encoder to provide position feedback.

The knob was rubber-covered brass with an outer diameter of 10.5 mm and a length of 16.5 mm ( 8). The 1-mm



**Figure 1: Haptic display.** A brass knob mounted directly on the motor shaft was covered with stiff rubber to prevent slipping. The vise mounting allowed adjustment of motor position for each participant.



**Figure 2: Setup.** Participants were asked to hold the knob lightly between their thumb and index finger as shown here. The haptic knob was placed horizontally in a position easily reachable by the participant while resting the forearm on a cushioned armrest.

thick rubber coating prevented slipping and allowed a better grip of the knob while minimizing grip compliance. The motor/knob assembly was held horizontally in a vise on a table; a padded arm support held the forearm comfortably while forcing a specific grasp (Figure 2).

The experiment control and I/O software was written by the authors in Visual Basic and C++, respectively.

### Participants

All participants were recruited through postings in UBC's Computer Science building, and all were between 20 and 29 years of age. None had any disabilities or limitations in the sight or touch senses, nor known special abilities. All were initially naïve to haptic perceptual experiments and were paid \$10 in cash for a 1-2 hour session.

### General Procedures

Following instruction and adjustment of the display position, the participant was allowed to interact with the display and practice several trials. He/she then donned

noise-canceling headphones to block audible artifacts from the haptic display.

### Choice of Icon Design Parameters

In effect, the parameters used to construct the set of haptic icon stimuli comprise the “input” to the MDS analysis, and as such were carefully chosen as both most likely to be individually salient based on our past experience in haptic design, and straightforward to modify experimentally. The MDS analysis would then tell us how these stimuli worked in combination with one another. Aiming for a final stimulus set of between 30-50, we decided to use three basic parameters combined at 3-4 levels each; the exact number and value of levels for each parameter to be determined based on perceptual thresholds as revealed through Phase 1. Eliminating *duration* on the concern that it would interact too strongly with the other parameters, the obvious parameter choices were thus signal *wave shape* (initially sine, square, triangle and sawtooth), *frequency* and *force amplitude*.

### Determination of Perceptual Thresholds for Stimuli

To create a balanced stimulus set with parameters set at consistent “loudness”, particularly at the low end of the perceptual scale, we determined representative perceptual thresholds for each of the three parameters when delivered alone. To this end, we found the minimum detectable (a) amplitude and (b) change in frequency for “pure” haptic stimuli presented through our knob. Both tests were based on an adaptive identification technique called Parameter Estimation by Sequential Testing (PEST) [15]. Details are provided elsewhere [4] and summarized here.

The results of a Detection Threshold (DT) test, based on 6 participants and 10 frequencies between 0.1 and 200 Hz, were used to determine the smallest easily detectable torque magnitude as delivered by our setup. For the least sensitive wave shape at the least sensitive frequency (sine at 0.1 Hz), participants required a force magnitude of 6.2 mNm to detect the signal 80% of the time.

A Frequency Differentiation (FD) test confirmed that icons could be spaced as closely as 10% in frequency and still be clearly differentiable. That is, at 100 Hz base frequency, participants noticed a change of 10 Hz.

### Implications for Icon Composition

Because the triangle and sine wave shapes proved difficult for participants to distinguish in informal pilots, we eliminated the triangle shape from the initial shape lineup.

The DT test’s minimally detectable torque amplitude level was doubled to 12.3 mNm for the “low” torque magnitude setting for all wave shapes and frequencies.

Frequency was varied exponentially in size, beginning with 0.5 Hz and maintaining uniform intervals of 10%

or greater.

## EXPERIMENT 1

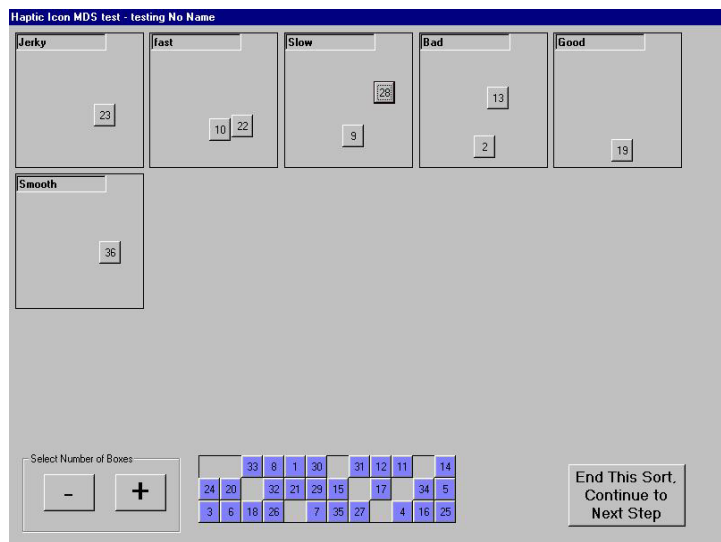
### Method

**Participants:** Experiment 1 used 8 right-handed participants (4 females and 4 males), each of whom conducted one session.

**Stimulus Set:** The initial experiment used 36 stimuli, created by combining 3 wave shapes (sine, square and sawtooth), 4 frequencies (0.5, 5, 20 and 100 Hz) and 3 amplitudes (12.3, 19.6 and 29.4 mNm), each with duration of 2 seconds. All force magnitudes are scaled as torque values in peak-to-peak mNm (Newton/millimeters).

**Sorting procedure:** An experiment session consisted of 5 blocks. For each block, participants sorted stimuli – represented by graphical markers that were displayed haptically on the setup when clicked with a mouse as many times as the participant wished (Figure 3) – into a number of groups; they were instructed to use “any criteria you want”. For the first block, participants chose the number of groups. For the remaining 4 blocks, they placed the stimuli into a predetermined number of groups so as to form a complete test-set of approximately 3, 6, 9, 12, and 15 groups. Thus, if a participant freely selected 5 groups for the first block, in the following 4 blocks he was forced to employ 3, 9, 12 and 15 groups. The order of number-of-groups was randomized among the 4 blocks. A complete session required from  $\frac{3}{4}$  -1 hour.

**Calculation of dissimilarity matrix:** For each block in the session, if two particular stimuli coincided in the same group, a similarity value equal to the number of groups for that block was assigned to the particular stimulus pair.



**Figure 3:** Screenshot of the program used to obtain the dissimilarity matrix for the haptic icons, after several placements. Each group must contain at least 1 haptic icon, and allows participants to type a description.

These values were added for all blocks in the session.

For example, if stimuli 1 and 3 were grouped together for the blocks with 3, 9 and 15 groups but not for the blocks with 6 and 12 groups, the similarity measure for this pair was calculated as  $3+9+15=27$ . The maximum possible similarity measure was thus  $3+6+9+12+15=45$ .

For each participant, similarity values for each stimulus pair (0-45) were linearly converted to dissimilarity (1000-0), with 1000 being most unlike; and used to populate that participant's dissimilarity matrix. An aggregate dissimilarity matrix was then constructed with the average values for all participants: thus for Experiment 1, each cell of the final matrix contained the average of 8 values. The result was processed using *Alscal PC* [10] to obtain the MDS solution.

**Results**

Figure 4 shows stress (revealing fit to data for a selection of dimensions) for Experiment 1. The marked “elbow” at 2 dimensions suggests that a 2-D representation of the results is appropriate on the basis of parsimony, although the fit does improve again perceptibly for 4 dimensions.

Figure 5 shows the 2-D MDS solution for the 1<sup>st</sup> icon set, and demonstrates a strong grouping based on frequency, particularly at 0.5 and 100 Hz; in fact, frequency seems to subsume most of both dimensions, as evinced by its central occupation of 4 quadrants. Wave shape is of second importance in the grouping, followed by amplitude. Stimuli sharing a 20 Hz frequency have the greatest spread of other stimulus parameters. 3- and 4-D solutions (not shown) offered little further clarification.

**EXPERIMENT 2**

Experiment 1 results suggested that frequency dominates the other parameters, except in the region of 20 Hz and to a lesser extent, 5 Hz. On the hypothesis that a stimuli set composed solely from this region would increase overall expressive capability, we performed an iteration focusing on frequencies between 5-20 Hz but using the same shape and magnitude. Greater information capacity would be revealed by more spread in the overall solution, as opposed to the tight clustering shown in Figure 5.

**Method**

**Participants:** Experiment 2 employed 9 right-handed participants (5 females and 4 males), each of whom conducted one session. 3 participants had also participated in Experiment 1.

**Stimulus Set:** We adjusted the number of frequencies and amplitudes based on the assessment of their relative importance in Experiment 1, and to keep the stimulus set size reasonable. Thus the second experiment used 30 stimuli, created by combining 3 wave shapes (sine, square and sawtooth), 5 frequencies (3, 7, 10, 16 and 25 Hz) and 2 amplitudes (12.3 and 24.5 mNm), each with duration of 2 seconds.

**Sorting procedure and computation:** The same methods were used as for Experiment 1.

**Results**

Figure 6 shows the stress measure for Experiment 2. Again

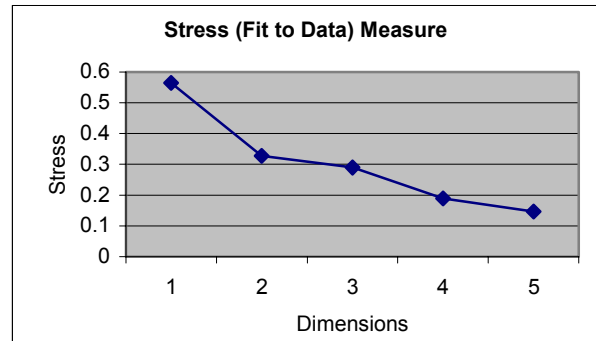


Figure 4: Stress values for Experiment 1 MDS solutions at 1, 2, 3, 4 and 5 dimensions.

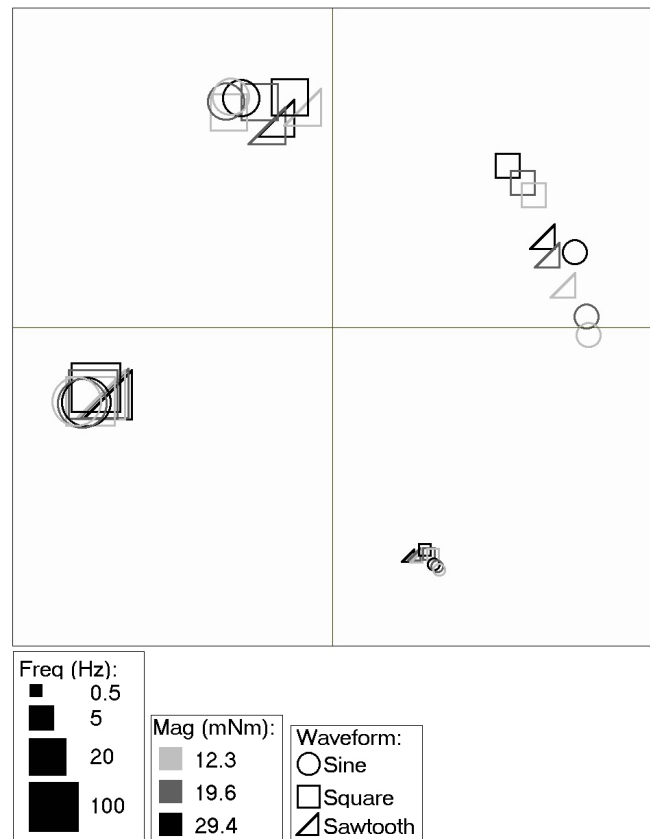


Figure 5: MDS solution for the Experiment 1 icon set at 2 dimensions (average of solutions for all participants). Marker size, shade and shape encode stimulus amplitude, frequency and wave shape: e.g. the smallest, lightest circle represents the sine stimulus with 12.3 mNm magnitude and 0.5 Hz frequency.

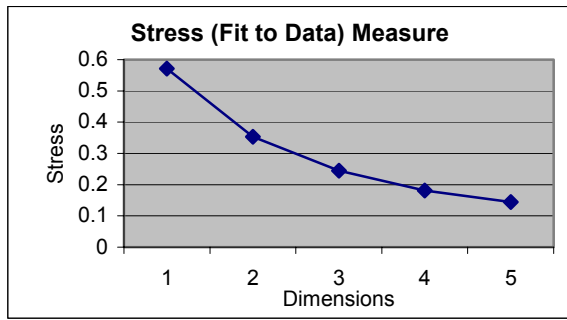


Figure 6: Stress values for Experiment 2 MDS solutions at 1, 2, 3, 4 and 5 dimensions.

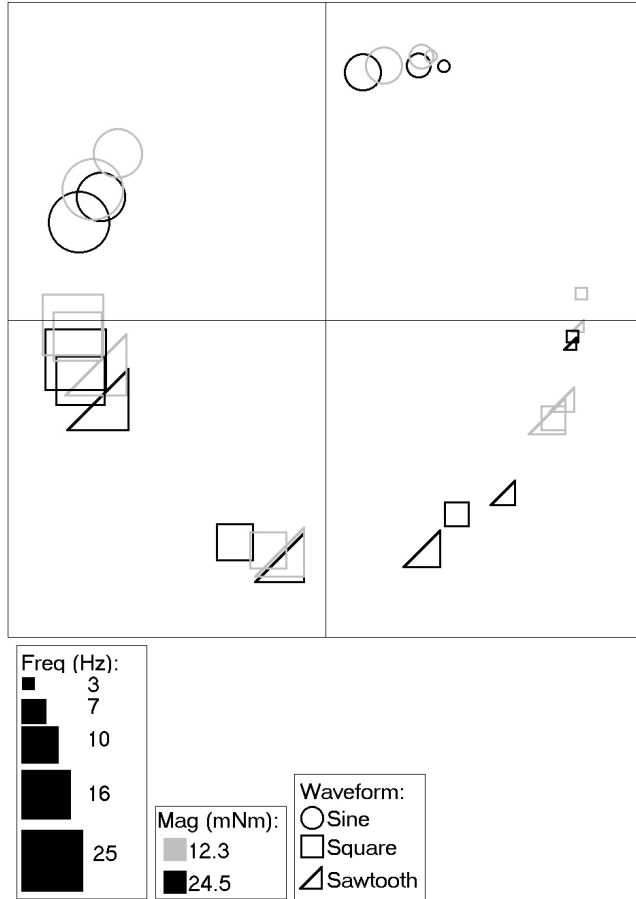


Figure 7: MDS solution for the Experiment 2 icon set at 2 dimensions (average of solutions for all participants).

the greatest elbow in the curve suggests a 2-D representation although in this case the curve is flatter overall.

Figure 7 shows the MDS solution for the 2nd icon set for 2 dimensions, averaged across subjects. Again, 3- and 4-D representations (not shown) were examined and rejected. A few features of the 2-D solution bear mention:

(a) While still most important, frequency no longer overwhelms other parameters. It maps roughly onto the horizontal axes, increasing from right to left; however,

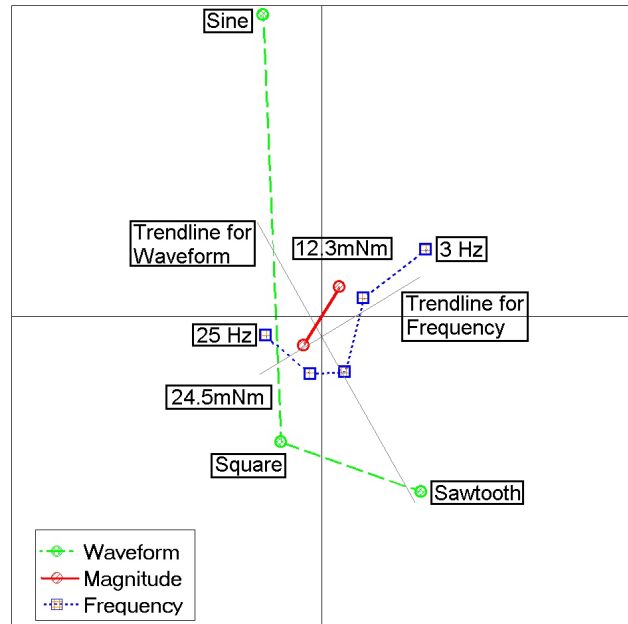


Figure 8: Projection of design parameters onto the Experiment 2 MDS solution. Each marker represents the average MDS coordinates for all stimuli containing the parameter level indicated: for example, the Frequency marker labeled “3 Hz” is the average of coordinates for 6 stimuli (30/5); whereas the Magnitude marker labeled “12.3 mNm” is the average of 15 stimuli (30/2). Markers of a given parameter family are linked to illustrate the overall trend for direction for that family, and a straight line has been fit to those families containing more than 2 points. For example, Frequency shows a trend falling downwards to the left with increasing frequency, at an angle of about 32 degrees; whereas Wave Shape progresses upwards (26 degrees off of vertical) from Sawtooth, Square and finally Sine, showing a separation between smooth and discontinuous shapes.

frequency axes for different wave shapes do not precisely align.

(b) The circumplex arrangement of the stimuli in the two dimensional space – suggested by the results of Experiment 1 but explicit here – is a consequence of the participants’ judgments of the similarity of the stimuli as “very similar” when they shared the same frequency (regardless of wave shape or amplitude) and “very dissimilar” when they did not share the same frequency. The resulting distribution of judgments along the similar-dissimilar scale results in the stimuli being arranged as far as possible from each other in the two dimensional plane, thus the circumplex.

(c) There is a clear separation between the sine and the square / sawtooth wave shapes.

Figure 8 shows essentially a projection of the original input parameter space onto the Experiment 2 MDS solution. Each point in the frequency set is the average of all MDS solution coordinates for a single frequency (including every

shape, magnitude and subject); and likewise the shape and magnitude sets. This view suggests a possible interpretation of the accommodation of stimulus variability among the two solution axes, with shape and magnitude largely sharing the vertical dimension while frequency absorbs most of the horizontal dimension.

**Expressive Capability:** To more precisely ascertain the test frequency allowing the greatest perceived spread in other parameters, we defined a measure of “Discriminability” amongst a given set of icons for a specific frequency.  $D_f$  is the square root of the sum of the squared distances between dissimilarity values (pre-MDS) for all stimuli sharing that frequency:

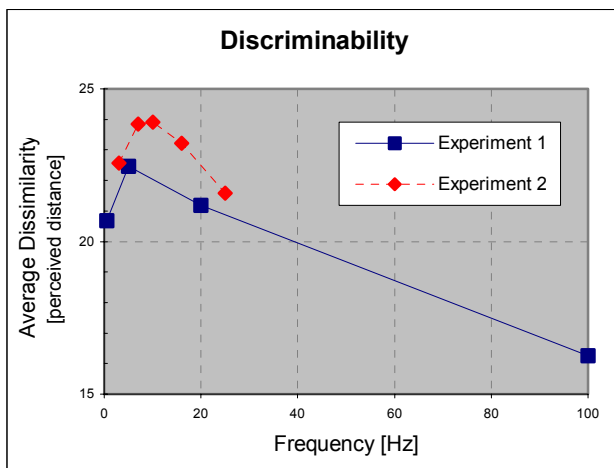
$$D_f = (\text{discriminability of freq } f) = \sqrt{\sum_{i=1}^{N-1} \sum_{j=i+1}^N (d_{fij})^2} \quad (1)$$

where  $N$  is the number of stimuli at a given frequency and  $d_{fij}$  is the dissimilarity value for stimuli  $i$  and  $j$ , averaged over all subjects. Thus, a larger value for  $D_f$  means more perceived variability due to non-frequency parameters at that frequency. Figure 9 shows  $D_f$  for each frequency tested in both experiments. 7-10 Hz permits the greatest spread (Exp. 2); and the narrower range of Exp. 2’s stimulus set results in higher overall discriminability.

## DISCUSSION

### Number of Dimensions

Two dimensions appear to provide the best fit to the dissimilarity data collected for both sets of stimuli, based on evidence of the stress values and inspection of higher-dimensional solutions. The stress curve is flatter for the narrower frequency range of Experiment 2 (Figure 6); one possible interpretation is that as other parameters become more important, overall perception becomes more complex. Furthermore, since it is to be expected that individuals vary in the complexity of their distinctions, the 2-D case might



**Figure 9:** Perceived discriminability for the frequencies used in both experiments’ stimulus sets: The vertical axis has been clipped to improve the view of detail.

represent a reasonable generalization.

### Interpretation of Dimensions

A principal goal of our experiments was to relate our three stimulus design parameters to human perceptual axes. Perhaps the most important finding of this study is that while both sets of stimuli are perceived in two dimensions, the interpretation of those dimensions is markedly different for the two sets. For the first experiment, whose stimulus set exhibited wide variation in the most salient parameter, that parameter dominated both perceived dimensions. That is, participants sorted stimuli based on frequency and little else – yet found two dimensions out of one control parameter.

In Experiment 2, all three parameters were evident in the MDS solution – frequency and shape the most strongly and most nearly orthogonal to one another, while magnitude shares shape’s dimension as illustrated by Figure 8.

The fact that frequency axes for different wave shapes do not precisely align (Figure 7) could mean that participants perceive frequency differently for each wave shape. This and similar observations for the other parameters imply the effect of moderate to strong individual differences, which will need to be accommodated in future icon design.

### Maximizing Expressive Capacity through Frequency

The inconsistent domination by frequency of the 1<sup>st</sup> experiment MDS results (least evident for 5 and 20 Hz) suggested that there might be a “sweet spot” for frequency where the information carrying capability (expressive capacity) of the signal was maximized. Thus, choosing a frequency range for the 2<sup>nd</sup> stimulus set which optimized discriminability permitted more stimuli to be perceived as markedly different from one another. Among the 5 frequencies considered in Experiment 2, 7 and 10 Hz had the maximum expressive capacity according to our simple measure; and the entire range (3-25 Hz) permitted a much greater expressive capacity of the stimulus set as a whole than did that of Experiment 1 (Figure 9).

Thus, to maximize information delivery in haptic icons which employ frequency as a design parameter, frequency range should be carefully considered; and at least for the set of design parameters and stimulus duration used here, a range between about 5 and 20 Hz is optimal. Frequencies outside this range may also be used, but the contribution from other design parameters will not be perceived.

### Evidence of Range Effect in Groupings

When a set of stimuli contains variations on a specific characteristic over a range, the results of a perceptual test for those stimuli might exhibit a clustering at the extremes of the range. The “Range Effect” is a consequence of participants’ ability to identify one or both of the extremes more easily than points within it [11]. The extremes serve as anchors from which to base perceptual judgments, near which responses are grouped. The range effect may be one explanation for the tight clustering observed in the MDS solution for Experiment 1 (Figure 5).

### **Effect of Shape: Smooth vs. Jerky**

As observed in Figure 7, there is a clear separation between the sine and the square / sawtooth wave shapes. Both the square and sawtooth waves are discontinuous while the sine wave has smooth derivatives. Further, the MDS solution's separations between smooth (sine) and sharply changing (square and sawtooth) shapes diminish; suggesting that at higher frequencies, shape differences become less perceptible.

### **CONCLUSIONS AND FUTURE WORK**

The stimulus design, data collection and analysis techniques presented here together comprise an innovative approach to the design of haptic icons, which in turn have the potential of becoming a new communication medium for many kinds of interactive devices. The current results support the promise of the overall method.

Specific contributions of the present study include observations that for synthetic haptic icons, (a) frequency plays a dominant perceptual role; (b) the meaning (in terms of design parameters) of users' perceptual dimensions across an entire set of icons is strongly affected by the *range* of frequencies employed in that icon set; (c) to maximize expressive capability of other design parameters, frequency should be varied around a relatively narrow range – probably 5-20 Hz; and (d) beyond frequency, wave shape and finally force magnitude appear to be most important perceptually.

There are important limitations both to the scope of the present study (which covered only a few design parameters, and confined itself to passively felt stimuli) and to the MDS technique in general – which tells us about differentiability, but not about salience. It will provide more useful results, for example, if supplied with data from novel wave shapes that are judged as "somewhat similar" and "fairly similar" rather than at the two extremes of the similarity-dissimilarity scale, regardless of frequency. We consider this work an important first step, and are already widening its impact through modifications of the current technique, and combining it with other forms of analysis that will broaden its applicability.

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### **REFERENCES**

[1] Bonebright, T. L., "Perceptual structure of everyday sounds: a multidimensional scaling approach," in Proc. of 2001 Int'l Conf. on Aud. Display, Espoo, Finland, 2001.

[2] Brewster, S. A., Wright, P. C., *et al.*, "A detailed investigation into the effectiveness of Earcons," in Proc. of First Int'l Conf. on Auditory Display, Santa Fe Institute, Santa Fe, pp. 471-498, 1992.

[3] Cox, T. F., *Multidimensional Scaling*: Chapman & Hall, 1988.

[4] Enriquez, M., *A study of haptic icons*, M.Sc. Thesis, Univ. of British Columbia, 2002.

[5] Enriquez, M. and MacLean, K., "The Haptic Editor: A Tool in Support of Haptic Communication Research," in review.

[6] Gaver, W. W., "The SonicFinder: An Interface that Uses Auditory Icons," *Human-Computer Interaction*, vol. 4:1, 1989.

[7] Grey, J. M., "Multidimensional perceptual scaling of musical timbres," *J. Acoust. Soc. Am.*, vol. 61:5, pp. 1270-1277, 1977.

[8] Hollins, M., Faldowski, R., *et al.*, "Perceptual dimensions of tactile surface texture: a multidimensional scaling analysis," *Perception and Psychophysics*, vol. 54, pp. 697-705, 1993.

[9] Klatzky, R. L. and Lederman, S. J., "Tactile roughness perception with a rigid link interposed between skin and surface," *Perception & Psychophysics*, vol. 61:4, pp. 591-607, 1999.

[10] Lewyckij, F. W. Y. R., *Alscal User's Guide*: Chapel Hill, 1996.

[11] Poulton, E. C., *Bias in quantifying judgments*: Hove Publications, 1989.

[12] Rinker, M. A., Craig, J. C., *et al.*, "Amplitude and period discrimination of haptic stimuli," *Journal of the Acoustical Society of America*, vol. 104, pp. 453-463, 1998.

<http://www.cs.ubc.ca/~danilkis/fusion/publications/related/rinker98.pdf>.

[13] Snibbe, S. S., MacLean, K. E., *et al.*, "Haptic Metaphors for Digital Media," in Proc. of ACM Symp. on User Interface Software & Technology (UIST 2001), Orlando, FL, 2001.

[14] Tan, H. Z., Srinivasan, M. A., *et al.*, "Human Factors for the Design of Force-Reflecting Haptic Interfaces," in Proc. of the 3rd Ann. Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME/IMECE, Chicago, IL, DSC:55-1, 1994.

[15] Taylor, M. M. and Creelman, C. D., "PEST: Efficient estimates on probability functions," *Journal of the Acoustical Society of America*, vol. 41, pp. 782-787, 1967.

[16] Ward, L., "Multidimensional Scaling of the Molar Physical Environment," *Multivariate Behavioral Research*, vol. 12, pp. 23-42, 1977.