Designing Large Sets of Haptic Icons with Rhythm

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Abstract. Haptic icons (brief tangible stimuli with associated meanings) are a new way to convey information, but are difficult to design in large quantities due to technological and perceptual constraints. Here, we employ *rhythm* in combination with frequency and amplitude to systematically produce 84 distinguishable tactile stimuli for use as icons. The set's large size is made possible by an analysis of how users perceptually organize tactile rhythm. Through our evaluation, we find that the two primary characteristics by which users distinguish its tactile rhythms are *note length* and *unevenness*.

Keywords: haptic icons, tactile, multidimensional scaling, MDS, rhythm.

1 Introduction

Informative haptic feedback can make a valuable, eyes-free contribution in embedded applications, by conveying abstracted information through touch. However, we do not know how much can be conveyed, nor how best to design such signals. Broadly defined, *haptic icons* are brief, active, tangible stimuli associated with a meaning: delivered e.g. as tactor waveforms, by a vibrating screen and felt through a stylus, or by the motion of a force-feedback knob. They have been recognized under various names as a new and valuable interaction technique [10, 2, 4] but are hard to deploy in large sets.

Here, through systematic use of *rhythm* we sought to substantially increase the set-size of tactile *stimuli* (icon precursors in their tactile variant) that are (a) distinguishable within the set, and (b) organized along perceptually natural dimensions to facilitate their eventual association with meanings. In ongoing work, we use this set to explore the subsequent and also demanding step of user association and identification.

Principled design. Unless haptic signals are deployed with awareness of our perceptual and attentional capabilities, they will be just another distracting annoyance. Here, we extend a principled validation methodology based on perceptual optimization, which has already resulted in strong user performance for smaller sets [3, 10].

Heuristics for rhythm. Rhythm's temporal variation and salience sharply expands the design space. With visibility into how users organize it, we can shape distinctive and expressive groupings using the *design heuristics* proposed and refined here.

Large sets. Past larger stimulus sets contain 36 [11] and 59 [18] items. 75-100 items may maximize our associative capacity for some time to come.

M. Ferre (Ed.): EuroHaptics 2008, LNCS 5024, pp. 199–208, 2008.

1.1 Approach

We developed a rhythm-based stimulus set in two steps. In *design* (Sec. 3), we used hypothesis-driven informal testing to explore the design space. These resulted in initial *heuristics* we used to choose 21 rhythms, which were combined with two other variables (vibration frequency and amplitude) for an 84-item stimulus set.

In *evaluation* (Secs. 4-5) we explored the set's perceived dimensionality and verified that it was fully distinguishable, using *Multidimensional Scaling (MDS).* This visualization tool translates user-supplied dissimilarity ratings for stimulus pairs into an *n*-dimensional plot of the stimulus space, in which distances reflect similarity. Analysis of these maps revealed how set characteristics influenced user perception, and revealed unsuspected patterns relating to note length and sequence regularity.

Display Platform: Piezo-Mounted Touchscreen. Our stimuli were displayed on the Nokia N770T, an enhanced 770 handheld tablet with a piezo-actuated 90x54 mm touchscreen, perceptually characterized in [17, 9]. The piezo pulses the screen with small normal displacements: single pulses make it "click", and a train creates a texture. Other tactile touchscreen technologies (solenoids or eccentric motors) provide stronger feedback, but we found this display to be the most crisp and controllable.

1.2 Related Work

Psychophysical evidence for tactile communication exists in studies of tactual information capacity [15] and texture perception [8]. These and other results provide guidance in low-level perception, but tend to emphasize basic waveforms and laboratory situations. This leaves questions as we bring tactile stimuli into applied use.

Tactile Stimulus and Icon Set Design. Recent approaches to creating informative tactile stimuli can be distinguished by whether the anticipated meaning will be associated on an *abstract* or *symbolic* basis. The former focus on the *set's* characteristics; the latter builds semantic meaning into individual stimuli.

In the *abstract* approach, MacLean *et al* perceptually optimized 36 vibratory stimuli varying in waveform, amplitude and frequency with the MDS tool employed here [11]. Enriquez *et al* [5] attached two arbitrary meanings matrix-style to two superposed sensations per stimulus, and observed 73% recognition for 9 composite icons. Brown *et al.* [1] tested 9 signals with 3 amplitude-modulated textures and 3 rhythms (71% recognition). Adding a 3rd parameter, spatial location, recognition dropped [2].

For 7 metaphorically-inspired (*symbolic*) and optimized icons, Chan *et al* found recognition rates of 95%, with and without workload [3]. Van Erp *et al* took 59 real-world melodies, transferred them into the tactile domain and analyzed this largest stimulus set to date; no meanings were assigned [18].

Tradeoffs abound between these approaches [12], but in these results perceptual optimization tends to improve icon learnability for both. Finally, Enriquez *et al*'s finding no difference in learning (80%) and 2-week recall (86%) of arbitrarily assigned (abstract) vs. user-chosen (semantic) associations for 10 optimized icons [6] could mean that optimization is more important than semantics.

Rhythm in Tactile Information Display. The most common parameters used in tactile stimuli are signal frequency and amplitude, as well as location and rhythm. The studies in [1] used 3 rhythms; while encouraging, they were too different and too few to establish clear patterns. Using MDS along with other statistical methods, [18] revealed two main characteristics in their melodically-derived rhythms: intrusiveness and tempo. Familiar tunes allowed the creation of a large set (59), and showed considerable promise for rhythm and other musical parameters. However, scalability is a concern due to nonsystematic sampling of the design space, with potential for non-uniform coverage, poor salience and differentiability management, and unexpected user pre-associations. We are inspired to use rhythm, but more systematically.

Perceptual Multidimensional Scaling. MDS is an established technique for perceptual analysis; in an early haptic use, Hollins *et al* found dimensions such as hard/soft and slippery/sticky for real tactile surfaces [7]. However, gathering dissimilarity data from users can be time-consuming and error-prone. Here, we use the relatively efficient cluster-sort method introduced by [11] and further validated in [10, 14]. This set pushes the technique's limits; in parallel we have developed a scalable variant [16].

2 Creation of a Large Stimulus Set

Herein we summarize how we designed our stimulus set using rhythm. Considerably more background and rationale for our heuristics may be found in [16].

Overview of Rhythm. We define rhythm here as a repeated monotone pattern of variable-length *notes*, arranged relative to a beat (4/4) and played at a set tempo, manipulated by changing the *length*, *number* or *rests* (gaps between notes). Rhythm has some pitfalls. It requires duration, which jeopardizes recognition in a "haptic glance". Its salience can dominate or mask other parameters; and it can evoke individual and sometimes emotional familiarity responses.

Stimulus Design Overview. Our detailed analysis of the tactile rhythm space, based on extensive informal user testing, guided an *exclude/include* heuristic/constraint-based design procedure. (Our heuristics are informed choices; a constraint is a measured necessity). First, we identified the entire rhythm space reachable by our display hardware, and eliminated parts of it based on practical, hardware, or perceptual constraints (*exclude*). From the remainder we selected those that appeared most promising based on positive (*include*) heuristics, up to a target size. Additional positive heuristics could be devised; the available rhythm space was not exhausted.

Eliminative Heuristics and Constraints

E1. ***Practical Heuristic: Monotone Rhythms.*** To keep things initially manageable, all notes in a stimulus had the same amplitude and vibratory frequency.

E2. ***Perceptual Constraint: Distinct Notes***. A gap is required between successive notes for them to register as separate.

E3. ***Practical Constraint: Overall Duration.*** We estimated the greatest useful length of an icon as 2 sec, through prior basic, applied and situated research [11, 13, 10].

E4. ***Perceptual Constraint: Rhythmic Repetition.*** Unless a rhythm recurred, it was not identified as a pattern. The best compromise between rhythmic emphasis and duration was 4 repeats (500 ms each), allowing a reasonable number of notes.

E5. ***Perceptual Constraint: Shortest Note.*** The shortest notes which users perceived as discrete consecutive events were 1/16 of the 500 ms interval (31.25 ms) plus a same-length break. We termed this basal 62.5 ms unit an "eighth" (1/8) note.

E6. ***Perceptual Heuristic: Note Types.*** We identified five discernible note lengths: 1/8 (62.5 ms), ¼ (125 ms), ½ (250 ms), ¾ (375 ms) and whole (500 ms). Each includes 62.5 ms off-time, except the 1/8 notes (31.25 break).

Platform Specifics: Our platform dictated some specific parameterizations, which minimally impact generality: e.g. signal strength (minimum perceptible note time and inter-stimulus interval). Architectural limitations can also constrain the number / type of notes achievable; here, we were able to work around these.

Positive Selection Heuristics

S1. ***Short Notes.*** We began with a subset containing only ¼ notes and rests. A 4/4-time, beat-aligned rhythm is among the most basic (Grp 3, Table 1).

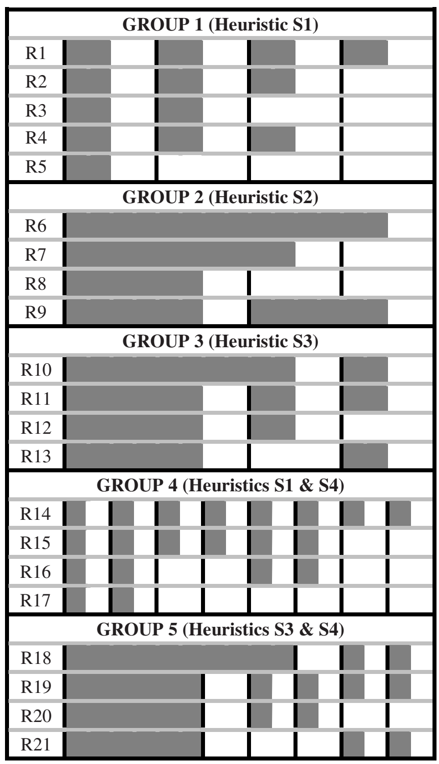
S2. ***Long Notes.*** Subjective remarks suggested a group with only notes *longer* than ¼: ½, ¾ and whole (Grp 2).

S3. ***Mixed Short and Long Notes.*** At least one "short" (¼) note and least one ½ or ¾ note (Grp 3).

S4. ***Very-Short Replace Short Notes.*** We replaced ¼ notes with two 1/8 notes (Grps 4 and 5).

Complete 3-Factor Stimulus Set: We multiplied the rhythms in Table 1 by frequency and amplitude. Based on piloting and [17], we modulated amplitude with one voltage *wave duration* (1 ms), two *curve rise levels* (1.0 and 13.2 kOhm), and two *frequencies* (200 and 300 Hz, bracketing peak sensitivity at 250 Hz). Stimuli 1-21 use rhythms 1-21, played at high amplitude and frequency. Stimuli 22-42 are the same rhythms at high amplitude, low frequency; 43-63 (low amp, high freq); 64-84 (low amp, low freq).

Table 1. Rhythms. Each row represents one *bar,* to be repeated 4 times a 2-sec stimulus. Each *note* contains vibration on- (grey) and off-time (white) that separates it from the next. *Rests* are entirely white.



3 Evaluation of the Rhythmic Haptic Stimuli Set

The goals of the study summarized here were to (1) identify the *perceptual dimensions* along which people organize these stimuli as a group (which are not necessarily the same as the engineering dimensions used to construct them); and (2) to confirm that the set's elements are *internally distinguishable*. A useful by-product of the method used is a *perceptual map* to aid in assigning meanings appropriately. We point out that distinguishability is not the same as ability to independently recognize and identify individual items. In ongoing work, we use this set to explore the latter.

While we generally followed previous applications of the perceptual MDS technique [11, 10, 14], our large stimulus set (nearly tripling our previous efforts) required some adjustments which are outlined here. More detail can be found in [16].

Participants: Six students (5 male),aged 24-40 were compensated $20. A six-person sample has been shown to produce consistent results (i.e. low between-subjects standard deviation, and consistent overall structure in MDS result [14]). In light of the exacting 2-hour session, we recruited individuals who would remain vigilant and with some experience in evaluating tactile stimuli through past experiments. This resulted in a relatively small number of high-quality datasets, confirmed post-hoc by uniformity of standard deviations of averaged dissimilarity matrix cells, and subjective reports of comfort with the task's duration and confidence in performance. The individuals were exceptional only in their moderate degree of past exposure to haptic stimuli, but not in their basic acuity; and are thus representative of a future user base.

Data Collection. All participants sorted the full stimulus set on the Nokia 770T. Each stimulus was associated with a numbered graphical button, activated when touched with the stylus. Users could play each stimulus repeatedly and "pre-sort" as they strategized. Each completed 3 sorts on the same stimulus set, following the method of [11] with ~3, 9 and 15 groupings; this approach is shown to yield trustworthy results when some consistency among the source matrices can be assumed [14]. Users wore noise-canceling headphones playing music to block auditory noise.

3.1 MDS Map Creation and Its Reliability

Following [11], each participant's 84x84 dissimilarity half-matrix was produced by combining the three sorting results, each cell containing the dissimilarity rating [0-1000] for the respective pair of stimuli. Individual data were averaged to create an aggregate dissimilarity matrix for the group. The overall average standard deviation for all dissimilarity values used to form the aggregate matrix is 160.02 out of the 0-1000 range, an acceptable level [11]; with similar levels in individual results.

The resulting dissimilarity matrix was run through the SPSS ALSCAL algorithm for 1 to 6 dimensions. Stress values (a measure of goodness of fit) were reasonable for both 2D and 3D results, at levels shown to produce informative and trustworthy results when the underlying data is consistent. Since higher dimensional models provided little improvement and are far harder to interpret, we used the 2D solution; with reference to the 3D solution when needed for disambiguation.

MDS is a visualization rather than a statistical technique; it does not deliver p-values. Solution reliability is inferred based on multiple views which triangulate data uniformity, consistency and reasonableness, stress, and subjective reports among others, as mentioned throughout. [16] further details the thorough validation performed.

Result. The resulting 2D map (Fig. 1) shows a characteristic circumplex arrangement. Stimuli are spread fairly evenly, with suggestions of three large clusters which are however too broad for much insight. Below, we explore more specific groupings.

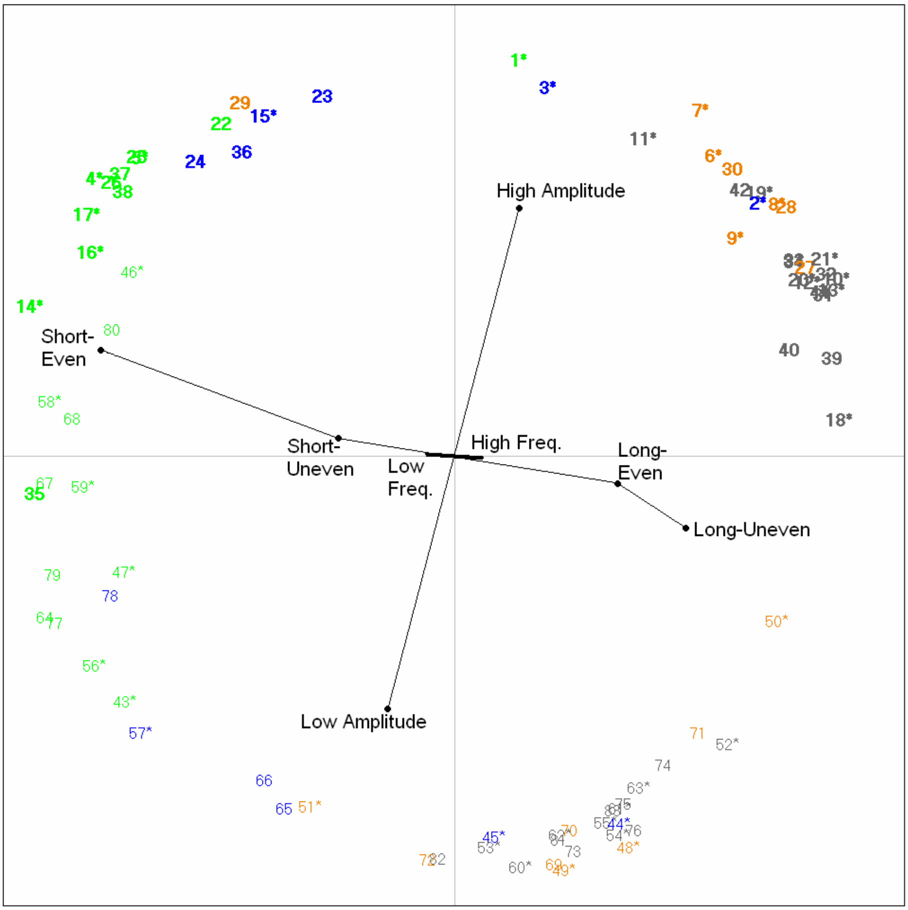


Fig. 1. 2D MDS output for all 84 stimuli (numbered as described on pg. 4). Amplitude and frequency trends are plotted as described in Sect. 4. The rhythm trend is composed using four centroids, which reflect the coloration of the stimulus numbers: green stimuli are short-even, blue are short-uneven, orange are long-even, and black are long-uneven. High-amplitude stimuli are large-font and bold; high-frequency are indicated with a ‘*’.

4 Discussion

How do the *engineering* parameters (used to create the stimuli) map to the *perceptual* parameters that participants used to mentally organize the stimuli? We can visualize this on the MDS map by comparing the centroid of all stimuli composed with one level of a design parameter, with the centroids of other subgroups. Drawing a line between these centroids creates vectors indicating the trend's direction and strength.

Projecting the two levels of *amplitude* onto the map of Fig. 1 shows a strong, clear-cut trend, indicating an important and straightforward perceptual role in our stimulus set which is in accord with previous research [11, 14].

However, interpretation of *frequency* and *rhythm* required more sophisticated analysis. In the following, we will explore how these two input dimensions become intertwined, and investigate the usable set size actually attained.

4.1 The Frequency Dimension, and Distinguishable Set Size

The centroids of the two frequency levels ("tonal" pulse-modulation rate, as opposed to the rate at which the rhythm was played) lie nearly atop one another in Fig. 1: frequency's *aggregate* perceptual impact was negligible. The actual distribution of stimulus pairs that varied only by frequency levels is quite varied, ranging from near-neighbors to quite spread out. A review of individual maps (not shown) further shows high/low frequency pairs *regularly separated, but differently by individual.*

This, with the general lack of noise and our otherwise consistent results, suggests that *stimulus frequency was indeed perceptible*; but due to individual variance (resulting in a small net percept), there is not a consistent trend in *how* each used frequency to categorize stimuli. Given the consistent, dominant effect observed for frequency in absence of rhythm [11], we infer that interaction with other parameters has rendered its impact *inconsistent by individual*, although present. Possible mechanisms include:

(a) Rhythm modulation might have *attenuated* frequency display: shorter note duration could limit exposure, reducing its impact. → We re-analyzed in MDS a data subset containing only "long note" rhythms (most similar to the 2-second, continuous vibrations in [11]), but still observed no strong, direct effect of frequency.

(b) The frequencies chosen may have been *insufficiently different* to compete strongly and consistently when in the presence of both rhythm and amplitude (the high frequency was hardware-limited). → We re-examined and confirmed that stimuli varying only by frequency *could* always be distinguished. This, plus evidence in individual maps, indicates that *we did indeed have 84 perceptually different stimuli.*

This finding of an apparent but personalized effect of one of our parameters is neither unexpected nor discouraging. However, it does have important design implications: it may be more natural to create personal haptic icon mappings when such a trend is observed, rather than "one size fits all".

For the present purposes, without a consistent trend to employ we chose to sideline frequency in the remainder of the analysis, while recognizing its apparent presence as a factor. In future work, it will be relevant to consider a larger frequency differential, and to test individuals for internal repeatability in this context.

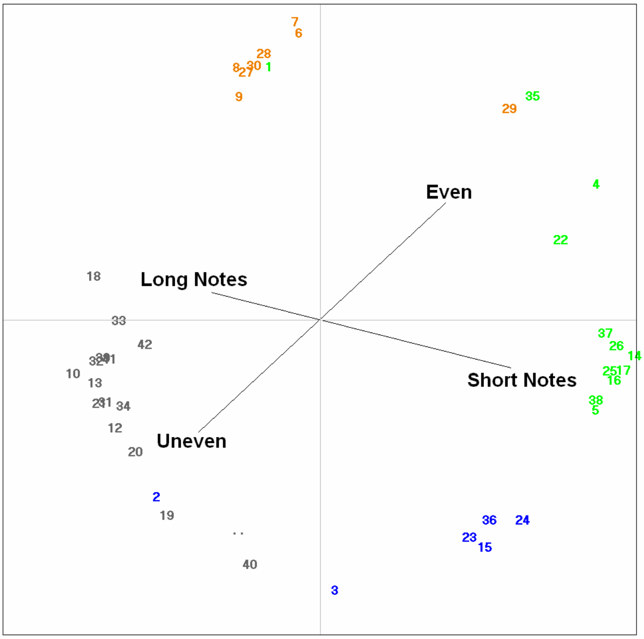


Fig. 2. High-amplitude 2D MDS sub-analysis (42/84 stimuli shown; colors are as for Fig. 1). In MDS, map rotation is arbitrary.

4.2 Rhythm

We designed our 21 rhythm stimuli with groupings derived from considerations of tactile rhythm perception. Here, we use MDS to investigate how users *actually* organized the stimuli. However, simply plotting the 21 rhythm centroids (not shown) revealed no obvious pattern.

Rhythm structure was better visualized by removing the dominant amplitude parameter. We can "unfold" regions of the map which we suspect hide "local dimensions" by separately mapping a subsection of the total dissimilarity matrix, allowing factors that were hidden in the larger solution to appear when higher-level constraints are relaxed [14]. We performed two such sub-analyses on the low and high amplitude subsets.

Fig. 2 shows the MDS map for all high-amplitude stimuli; the low-amplitude map is similar. From roughly left-to-right, we see stimuli distinguished according to the longest note present in their respective rhythms, with "long note" rhythms to the left and "short note" rhythms to the right. Approximately orthogonal, we find another grouped according to the feeling of "evenness" (regularity). These two perceptual axes – which do not exactly follow our initial groupings – are discussed in detail next.

Note Length. In design, we defined "long note" rhythms to contain at least one of a ½, ¾ or whole note. Our data suggest that the longest note present in a rhythm defines how it is perceived along this perceptual axis. Rhythms containing ¾ or whole notes fall near one end of the axis, those with ½ or shorter notes towards the middle, and those with *only* short or very short notes towards the other end. Furthermore, the more short notes there are relative to long notes, the closer to the axis' center the rhythm will fall. For example, stimuli 11, 19 and 40, which contain long/short notes in equal measures (a ½ as well as ¼ and 1/8), fall between the long and short note groups.

There is, however, more. Taking Group 1 (all consisting of multiple ¼ notes): R1 and R2 (3-4 notes) tend to "long", R3 and R4 (2 notes) mid- to short, and R5 (1 note) short. With this and other examples, we extrapolate that the *number of notes* (overall on-time) contributes to an impression of note length. But only down to ¼ notes: R14 and R15 (1/8 notes) register as much shorter than their ¼ counterparts R1 and R2.

Summary: Perceived note "*length*" is increased by a single long note, or (less strongly) by increasing the number of medium-length notes present.

Evenness of Rhythm. The even/uneven perceptual axis is more clearly delineated. Although we did not notice it at design time, we confirmed post hoc that this characteristic can be felt distinctly and consistently in actual play. "Even" rhythms have a regular repeating nature in which each part of the rhythm feels the same as every other part, throughout the duration of the stimulus. Uneven rhythms have an irregular, lurching feel with emphasis emerging on the first part. The most obvious "uneven" examples are in Groups 3 and 5: one long note (emphasis) followed by shorter notes.

Unevenness can occur in a variety of ways. R2, R3 and R15 contain only same-length notes; here, unevenness comes from the *pause* following consecutive notes with the initial string providing the emphasis. However, the rhythm must contain multiple notes before the rest period (in contrast, R5, R7 and R8 [even] all contain just one note then rest; repeated, they register as a single bar with a note played four times). Finally, there must be variation in blank period durations: in R2, R3 and R15, short rests separate the notes, while longer rests separate the bars.

Summary**:** "*Unevenness*" can come from variation in either note or rest length.

Rhythm Groups in Full Map. Returning to the full 2D map (Fig. 1), we now see how the short-long and even-uneven axes manifest in the presence of amplitude. The 4 group centroids (short-even, short-uneven, long-even, long-uneven) all fall roughly in a line orthogonal to the amplitude trend. Further, note length has a stronger effect than unevenness: stimuli are grouped first by note length, and then by evenness.

5 Conclusion

In this paper, we contribute both to haptic icon design methodology, and to a detailed understanding of an important design parameter and its relation to others. We met our aim of advancing both set size and design rigor: this 84-stimus set is considerably larger than previous standards, and meanwhile the validation of its perceptual structure and individual distinctiveness maximizes is usability. Finally, our analysis produced valuable insights into tactile rhythm perception.

Our MDS visualization and analysis confirmed some of our designed clusters and also uncovered new perceptual features we had not anticipated. Amplitude was the strongest perceived differentiating factor, but frequency's effect became individual and more subtle than in rhythm's absence; this is likely due to a salience shadow.

Rhythm: Past design efforts demonstrated the potential of rhythm. We build on them through a systematic approach supported by clearly expressed assumptions, constraints and rationale, rather than relatively arbitrary sampling; and by deriving generalizable rationale from haptic perceptual principles rather than auditory experience. In a significant new result, we found our rhythms to be distinguished primarily by note length and "evenness". The rhythms used are only a sampling of this design space.

This work has exposed ways to further exploit this rich channel. Rhythm's discovered length/evenness sub-dimensions will be easy to deploy; frequency's individualized effect, if repeatable by individual, points to user-customized icon sets. We anticipate that melody, emphasis, tempo and leveraging of cultural associations will be effective but will also require more sophistication in the design process.

In future work, we are using this large, validated set in a longitudinal study to assess users' ability to learn large numbers of icon associations.

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