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Predictable and Distinguishable Morphing of Vibrotactile Rhythm

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***Abstract*— Vibrotactile (VT) icons are a ubiquitous, increasingly expressive and expected communicative element of many user interfaces, routinely deployed with technology from rumble motors to novel expressive tactile actuators. However, it is still difficult to design, customize, and experiment with VT feedback. Here we consider manipulation of one of the most salient VT design elements, rhythm, through *perceptual morphing*.**

The ability to create perceptual morphs between pairs of VT signal parents expands editorial scope and precision for designers, end-users, and hapticians. To assess perceptual morphs, we propose criteria of *predictability* – a morph has similarities to one or both parents; and *distinguishability* – a morph is different from its parents. We developed a new algorithm for perceptual rhythm morphing based on dynamic-time warping (DTW), implemented in an open-source online tool, MacaronMix. Two studies revealed limits and conditions under which DTW-produced VT rhythm morphs are predictable and distinguishable.

I. INTRODUCTION

Vibrotactile (VT) feedback can enhance many modern interactive experiences. From alerts on simple mobile devices to complex timing guidance [13], VT icons (vibrotactile signals associated with meanings [18]) are now an expected part of user experience. Designers, end-users, and researchers alike can draw from collections like VibViz [29], the UPenn texture library [7], and Immersion's TouchSense Platform to select pre-built VT sensations, while editors like Macaron [26] let them create new ones. But despite this maturity, we are limited in their ability to manipulate VT signal examples.

Morphing, common for images [4] and audio [8], is an easy yet powerful algorithm for leveraging existing media. For tactile media, the link of signal to meaning is often abstract and the perceptual design space constrained due to today's tactile hardware's limited expressive capacity, so the ability to create diverse tactile signals is particularly valuable. Mixing in perceptual qualities of another parent may help both to distance a signal from another item in a set, and to refine an evocative quality.

Further, the ability to morph parent signals can enable hapticians – people skilled at creating haptic sensations, technologies, and experiences [23] – to draw directly from examples, an important practice both non-haptic [10] and haptic [23] design. They can help end-users easily and effectively customize their haptic effects [27], and potentially aid researchers in understanding tactile perception, e.g., as in [4] for images and [19] for haptic perceptual space.

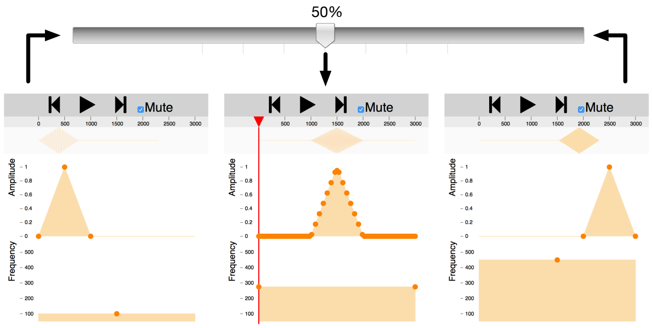

Fig. 1: Vibrotactile morphing. Parent signals (on left and right) are variably blended to create a new one (center) which is distinguishable from but predictably related to both.

Building on earlier demonstrations that tactile amplitude morphs, relatively simple to construct, can be generated in a perceptually predictable way [19], here we investigate morphing tactile *rhythm*. Rhythm is expressive, even with low cost displays; and because it can be mechanically generated independently of signal amplitude, it is amenable to combination with morphing of amplitude profiles.

In this paper, we present a validated, fully-automated algorithm for morphing rhythmic features between pairs of VT signals. We offer two criteria for effectiveness of a morph derived from two parents who are themselves distinguishable: *predictability* – a produced morph is similar to one or both parents, such that users have insight into the algorithm's potential result; and *distinguishability* – a morph is perceptually different from both its parents, and thus is not perceptually a clone of either. We then test our proposed algorithm with two psychophysical user studies. The first established algorithm predictability, and lack thereof for the status quo, a straightforward crossfading algorithm; the second established algorithm distinguishability.

Our contributions are:

- Criteria for perceptually evaluating haptic morphs.
- A VT morphing algorithm (open-source, online) with demonstrated ability to produce valid morphs.
- Insight into the algorithm's perceptual qualities and ways to evaluate morph quality, from two user studies.
- A structure that facilitates a more sophisticated approach to haptic morphing.

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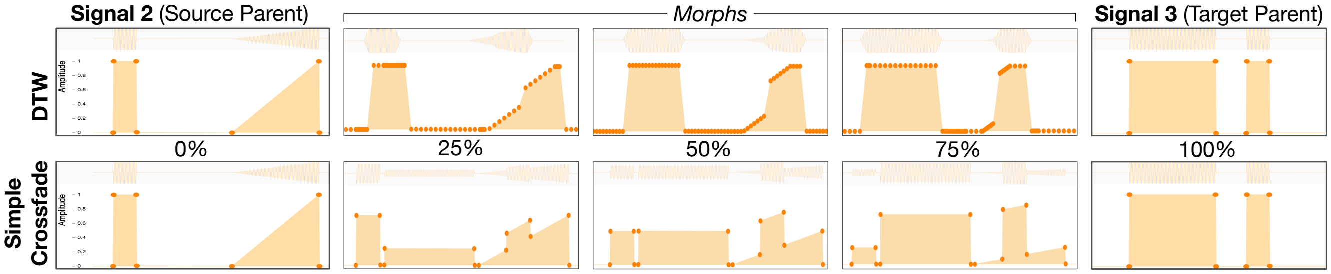


Fig. 2: The two morphing algorithms studied here, illustrated with morphs between parent signals 2 and 3. Upper: the dynamic-time-warping algorithm implemented in MacaronMix. Lower: a simple crossfade.

II. RELATED WORK

VT feedback is the most common haptic feedback mechanism today, present in mobile devices, wearables, and increasingly in laptops and virtual reality experiences. VT sensations can provide informative, invisible cues for spatial guidance [2], [17] and timing [13], [31], alerts with urgency or sender identity [3], [30], and emotional content [34].

VT Design Palette: Haptic icons are haptic sensations associated with meaning [18], also referred to as haptic notifications and tactons [3]. The VT design palette can include amplitude, frequency, and spatial location [9]. We focus here on rhythm, which addresses a large, learnable design space; users can discern at least 84 different rhythmic signals [33], and learn associations over time [30]. Rhythmic VT icons are deployable with even low-cost rumble motors, and can unintrusively illustrate ambient information [6].

Tools and Techniques: To generate the expressive vocabularies needed for these applications, designers require effective composition tools [9]; [25] overviews critical features of several tool examples. End-users also want and need to customize feedback [28], preferably with simplicity, like adjusting perceptual filters [27]. Recently, *example-based haptic design* has been enabled by large, organized online libraries [29], and an editor based on example reuse [26].

Morphing is a commonly used technique for generating and refining visual and audio stimuli. Facial morphs are used for special effects in animation [1] and to generate stimuli for studies on visual perception [4]. Morphing can be used to create new auditory timbres by manipulating frequency spectra [5], and to synthesize speech [8]. Once developed, morphing algorithms can be in a targeted way to increase control over stimuli and special effects, or integrated into design tools that generate or customize existing examples for designers and end-users, e.g., populating design galleries [14] or retargeting websites [15].

Previous Haptic Morphing and Interpolation: This work builds on past semantic interpolations between tactile endpoints. MacLean et al. introduced morphing for periodic tactile signals [19], to interpolate smoothly between high-frequency waveforms displayed on 1-degree of freedom (DOF) force display. Feel Effects [12] are meaningful links between VT sensations and semantic statements, handcrafted to interpolate between related statements (e.g., *rain* varies from *light rain* to *downpour* by varying timing, amplitude); these have been implemented in a customizable framework for adding tunable haptic effects to media experiences in FeelCraft [24]. Others have accomplished spatial interpolation using, e.g., saltation [32] or phantom vibrations [11].

To these efforts, here we add progress towards an automatic semantic interpolation method, and structure guiding concepts for future work.

III. SYSTEM DESIGN

We set out to create at least one algorithm that, given two parent VT signals, produces a child morph (Figure 2). This required (a) criteria for objectively evaluating approaches and their results on different source material, (b) a representative range of potential parent signals, and (c) a range of candidate algorithmic approaches – multiple algorithms, and valid morphable paths between parents, may exist.

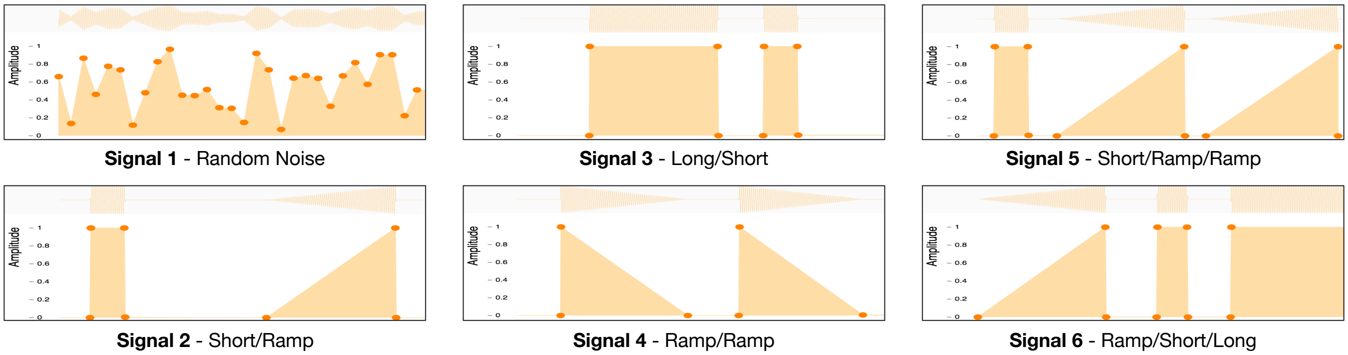
Parametric Scope: We studied rhythm morphing – i.e., signals with varying number, size, shape and placement of pulses within a fixed (three seconds) duration. We initially considered morphing of amplitude and frequency elements simultaneously, but found that both algorithm development and perceptual evaluation of this more complex situation were intractable on a first pass: while the studied algorithms trivially handle either element, morphs were not compelling without semantically aligning features between the two elements. During algorithm piloting, we found our proposed algorithm was most effective when interpolating rhythmic pulses, and thus we fixed frequency to a constant 250Hz.

A. Criteria for a Successful Morph

We propose two necessary criteria for a successful mix between two parent signals:

1. *Predictable*: The result must have some perceptual resemblance to both parents.
2. *Distinguishable*: The result must be perceptually distinguishable from both parents.

A morph which does not satisfy both of these cannot be considered a perceptual mix of the two, and is of little practical design value, offering no controllable refinement – although we note that distinguishability, in particular, may interact both with the quality of the hardware display and individual tactile sensitivity. As morphing algorithms mature, other criteria might be imagined, e.g., *linearity* to mean an even, direct path between two parents in a perceptual space



Signal 1 - Random Noise
Signal 3 - Long/Short
Signal 5 - Short/Ramp/Ramp
Signal 2 - Short/Ramp
Signal 4 - Ramp/Ramp
Signal 6 - Ramp/Short/Long

Fig. 3: VT signals (S1-6) used in studies. Shown are three-second amplitude profiles on a 250 Hz carrier frequency.

along which multiple morphs can be found, or *smoothness*, where users feel a continuous transition from one parent to the other. These properties seem to exceed a minimal standard, but can help to discriminate algorithm effectiveness.

Here, we evaluate the success of various morphing algorithms by measuring the the perceived difference of a child from each of its parents, and the degree to which parent and child are perceived as related, using two different psychophysics study techniques. Other assessment approaches could be considered – e.g., analytic methods based on inspection of temporal or frequency domain properties. Indeed, these will be promising to explore once we have measured and modeled the basis of what humans perceive as different and same along these new scales, but we must start with the metric we ultimately care about – human perception.

B. *Candidate Signals*

We developed six VT signals using existing VT libraries and editors [26], [29] to represent a variety of rhythms with different pulse lengths, amplitude profiles, and number of pulses (Figure 3). We included one signal of uniform random noise (Signal 1), three with 2 pulses (Signals 2-4, and two with 3 pulses (Signals 5 and 6). With this set, we could examine algorithm performance when mixing VT signals with the same or different numbers of pulses, and over different profiles (here, ramps or square profiles).

C. *Mixing Algorithms*

We investigate two morphing algorithms: a straightforward cross-fade (CF), and a new and more sophisticated algorithm based on dynamic time warping (DTW). Algorithm design involved rapid, iterative development using using visual and tactile inspection and user piloting prior to formal psychophysical evaluation. Both are implemented in *MacaronMix*, an open-source, online VT morphing tool available at `hapticdesign.github.io/macaronmix/`.

Cross-Fade (CF): Two signals are encoded as amplitude over time. The new "child" is created from two "parents" by taking the weighted average of their respective amplitudes for each time value. While CF is appealingly intuitive and often does sensible things at least visually, it has many failure modes; e.g., blending a 2-pulse to a 3-pulse signal.

Dynamic Time Warping (DTW): Rhythmic signals can be mixed by adapting their time-varying features. The DTW algorithm *aligns* parent time-varying features, specifically their duration and timing [20], [22]. To accommodate differences in parent keyframe numbers, we resample source signals every 75ms.

Step 1: Create $n \times n$ matrix ($n =$ number of resampled points) in which a cell at index (i, j) corresponds to the *difference* between the amplitude at time i in the first parent and the amplitude at time j in the second parent (Figure 4).

Step 2: Find a path through the matrix that begins at cell i_1, j_1, moving only through adjacent cells on the way to cell i_n, j_n. The optimal path minimizes the sum of traversed cells.

Step 3: Construct a new signal by averaging parent amplitudes at these new time-value pairings, specified by the coordinates along the lowest-cost path (i, j pairs) through the matrix. Figure 4 illustrates Step 3 (alignment), with the final result in Figure 2.

IV. STUDY 1: PREDICTABILITY

A. *Method*

We evaluated our DTW implementation's predictability compared to CF. We mapped parents and morphs onto a perceptual space using multi-dimensional scaling (MDS) [4], [18], and considered morph placements relative to their parents'. We hypothesized that DTW morphs would lie between their parents; CF morphs would be distributed less predictably.

In a series of tasks, participants sorted the six candidate signals and their pairwise 50% morphs ($6 + \frac{6 \times 5}{2} = 21$ signals) into a defined number of bins. Signals were randomly labeled (once for the study) and had randomly distributed graphical start locations (Figure 5). The first tasks required 2, 3, 4, and then 5 sort bins; then, participants were offered 6 bins but allowed to use any number. Participants first did these 5 tasks for one algorithm then the other (e.g., CF then DTW), counterbalanced for order.

We transformed these sortings into a perceptual space using MDS [4], [18], [19], [21], [33]. A 21×21 similarity matrix had cells for each signal pair. When the pair was sorted together, their cell's contents incremented by the number of bins in that task, e.g., a score of 2 for the 2-bin task; a joint sorting has more weight when more bins are available. The similarity matrix was converted to a dissimilarity matrix, then projected onto two dimensions using MDS. Residuals indicated dominance of the primary

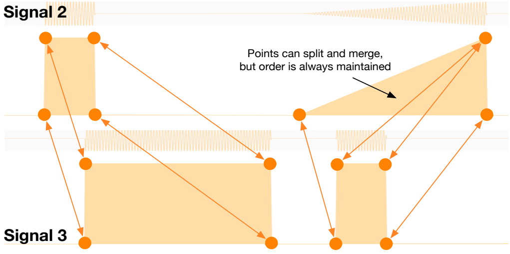


Fig. 4: Dynamic-time-warping (DTW) alignment between Signals 2 and 3.

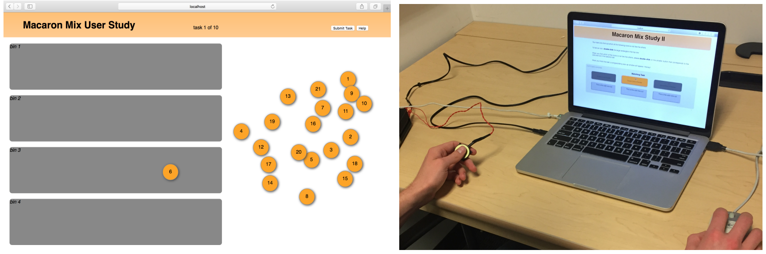


Fig. 5: Setup for Studies 1 (left) and 2 (right). In both, participants held a C2 tactor in their left hand while interacting with the study interface.

coordinate dimension; visually the second axis also played a role, so we visualize two dimensions.

B. Results

We recruited 11 participants (ages 19 to 25, 6 female) for Study 1. The CF algorithm's MDS map was dispersed but exhibited low morph *predictability* (Figure 6, Kruskal stress 13.12%). Some 50% morphs (S2/4, S2/5, S3/5) stayed near one parent; all but S2/5 were positioned randomly (S1) rather than aligning between their two parents, even when S1 was not a parent.

In contrast, the DTW algorithm revealed clustering by pulse number (Figure 7, Kruskal stress 2.90%). All morphs between two-pulse parents were clustered with those parents (S2,3,4), while all morphs with at least one three-pulse parent appeared with the three-pulse parents (S5,6). We note that the DTW algorithm will include a third, smaller pulse when morphing between a two-pulse and a three-pulse parent. All signals with an S1 parent (random noise) clustered near S1.

These results suggest that the CF algorithm becomes "muddy", producing a noisy result between most VT signals, while in the DTW algorithm, a higher number of pulses is like a "dominant" gene passed on to children.

V. STUDY 2 - DISTINGUISHABILITY

Study 1 established that the DTW algorithm can propagate signal characteristics (i.e., pulse number) from parents to children (Criteria 1: Predictable). However, MDS can only establish relative, not absolute, differences between signals, and suffers from limited resolution: a child might be sorted with its parents in most or all trials [21]. To determine whether children are *distinguishable* from their parents (Criteria 2), we conducted a one-up two-down adaptive experiment to estimate their just-noticeable-difference (JND).

A. Method

The physical setup was identical to Study 1. We employed a three-interval, forced-choice, one-up two-down adaptive procedure [16], illustrated in Figure 8. In each trial, participants were presented with three stimuli: two were identical versions of a parent (the target), and the other was a morph between the target and a second signal (the source). Participants could play each signal without limit, then click a button to select the signal that did not match the others.

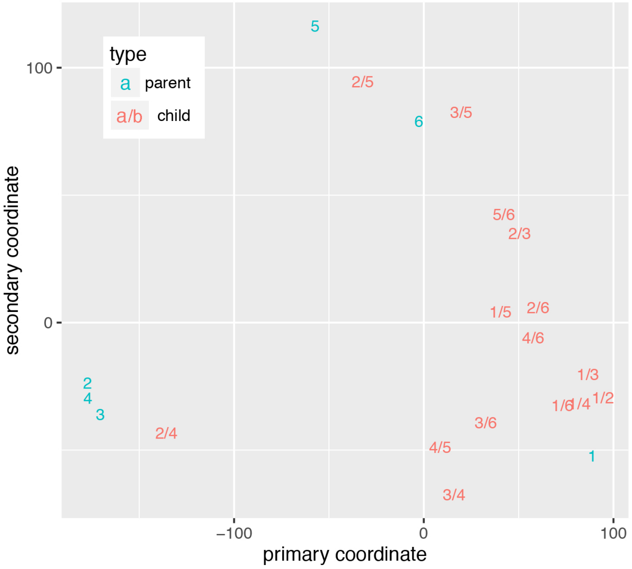


Fig. 6: MDS solution for crossfade (CF) algorithm's 50% morphs. Morphs show little relation to parents, with locations tending towards randomness.

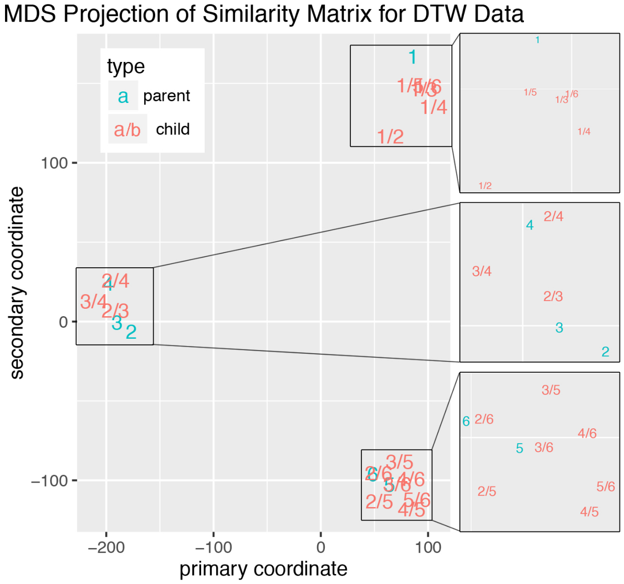


Fig. 7: MDS solution for dynamic time warping (DTW) algorithm's 50% morphs. Zoomed views are shown for concentrated regions.

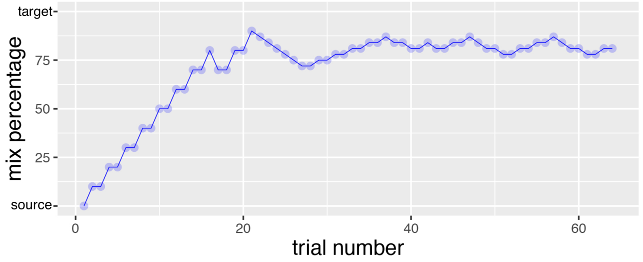


Fig. 8: Example of a one-up two-down (or as pictured here, two-up one-down) adaptive procedure for P4, S2/5.

The morph level was initially set to 0% (pure source) and adapted afterwards. Initially, the morph amount increased or decreased by a linear step size of 10 percentile points. After three reversals, the step size changed to 3 percentile points to provide a more precise estimate. The experiment terminated after 10 reversals at the smaller step size.

We studied three pairs: Signals 4/3 (both 2-pulse), signals 6/5 (both 3-pulse), and signals 2/5 (2-pulse and 3-pulse). Considering time constraints and the study's exploratory intents, we conducted one set of trials in one direction per pair, chosen randomly: S4→3, S6→5, S2→5, where SA→B means we produce SA/B starting at 0% (pure A). This study design intentionally compromised symmetric morphing tasks in favour of coverage in this initial investigation. To collect some symmetry information, we conducted a fourth set as time permitted, reversing source / target (e.g., S3→4) at the end. Each set took 20-30min, for a 3-or-4-set, 90min session. Participants were instructed to break when needed; a pop-up alert reiterated this between sets.

B. *Results*

We recruited 12 participants and analyzed P1-9, ages 19-26, 4 women. Three exclusions reported being able to hear the actuator, hands too cold to feel, and that the task was too difficult; the last also reported age >60, where tactile sensitivity declines. Thresholds from the one-up two-down procedure converged on the psychometric function at the 70.7 percentile level [16]. Initial piloting with an equivalent one-up one-down method had suggested negligible constant error.

Only 5 analyzed participants completed Set 4 in the allotted time; we thus could not study symmetry. However, a software error had reversed S4 and S3 in half the sets, so we collected S4→3 for 6 participants, two of which were reversed 4th sets, and S3→4 for 6 participants, one of which was a reversed 4th set. As visual inspection of reciprocally sampled pairs revealed no obvious differences, we aggregated them.

The average JNDs in terms of mix percentages were 57.5% (S5/6), 53.2% (S3/4), and 80.5% (S2/5).

A two-way ANOVA with the factors participant ID and signal pairing revealed a significant interaction between the two factors ($F(17, 152) = 19.24$, $p < 0.0001$). Subsequent inspection of boxplots (Figure 9) showed that most participants had a small JND (i.e., mix-percentage ≥75%) for S2/5, likely because they have different numbers of pulses. The other two pairs (S3/4, both 2 pulses; S5/6, both 3 pulses) showed more individual variance, with participants clustered roughly into those above and below 50%.

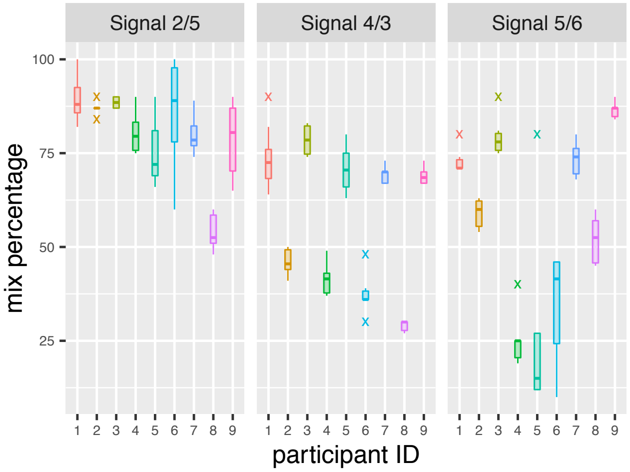


Fig. 9: Box Plots (min, 25th percentile, mean, 75th percentile, max) of Study 2 one-up two-down morph threshold estimates; higher values mean lower JND. Each pairing includes data collected in both threshold-detection directions. S2/5 morphs (which vary in pulse number) are best distinguished: most participants could consistently distinguish a 75% morph from its closer parent. A PID/signal pair interaction is significant, and so data is displayed by participant.

VI. DISCUSSION

Our results indicate that DTW is a viable morphing algorithm for rhythmic signals, in that it can produce morphs which are both predictable and distinguishable.

In the MDS predictability study, 50% DTW morphs clustered near at least one parent, and inherited the pulse number of the higher-pulse parent. That is, the morphs were seen as related to at least one parent, and further exhibited a predictable dominance effect of number of pulses. An "ideal" map might have placed morphs halfway between parents. The present result could be partly due to elicitation method (bin resolution) [21]; more likely, the perceptual meaning of "halfway" needs more study. The DTW map had more understandable pattern than did the CF algorithm, whose morphs showed little relation to either parent.

In the threshold distinguishability study, most participants could distinguish morphs from their parent signals, at $\geq 50\%$ when parent pulse number varied, and with more spread when they did not. This again points to needed clarification on perceptual salience of morph features, but is promising for this initial case involving just one feature's variation. We found no indication that direction of morph comparison matters, although data for this is sparse.

These studies were exploratory and we intentionally did not address symmetry, learning, or fatigue effects. We focused on individual differences when signals were uncalibrated for perceptual sensitivity. The resultant large inter-participant variations requires further investigation using signals at the same perceived intensities across participants.

As such, the present results provide a coarse iteration on haptic morphing over [19]'s initial approach, by addressing a more complex and highly salient element, rhythm. DTW is a promising approach to morphing rhythmic pulses, with the potential for combination with other techniques for other features (e.g., waveform [19]). Meanwhile, we have set a structure for future investigations: evaluation criteria, methods to measure algorithms against that criteria, and new questions – whether a morphing algorithm must be individually calibrated, whether an algorithm produces symmetric results, and what types of more stringent criteria, like linearity, are measurable and valuable for morphs. Methodological considerations out of our scope include complementary studies focusing on symmetry, and qualitative feedback to explore the meaning of morphs.

VII. CONCLUSION AND FUTURE WORK

Dynamic time warping (DTW) shows promise for morphing rhythmic VT signals. In our first MDS study assessing morph *predictability*, DTW outperformed simple cross-fading (CF) by behaving more predictably in the task of pulse re-alignment: child morphs were clustered near at least one of their parents. In our *distinguishability* study, we found that the DTW algorithm could produce rhythm morphs which are distinguishable from their parents, in some cases with JNDs under 25%. We also found evidence of participant individual differences, with a significant interaction effect between participant ID and signal pair.

Future work includes exploring individual differences: identifying for whom morphing algorithms will work, and tuning algorithms to individuals. More sophisticated and integrated algorithms will be able to handle additional frequency profiles, waveform or frequency spectra, and combinations of features. Finally, MacaronMix as an online tool can be further developed to support hapticians and end-users.

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