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Morphing in Periodic Tactile Signals

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Abstract

Humans naturally use both categorical and continuous structures when classifying perceptual experiences. However, design of haptic information displays is eased by the availability of design parameters that can be smoothly modulated along a continuous dimension. Taking guidance from visual and auditory media design, we identified and validated a perceptually successful "morph" function that modulates a tactile vibration between two disparate endpoints (a square and a triangle or sine wave), by varying the magnitude of the vertical (highest frequency content) component of the waveform. This finding suggests a specific psychonomic function related to frequency perception, points towards a practical utility in haptic information design, and supports reflections on further possibilities for haptic morphing.

Keywords: Perception and psychophysics; Human-computer interaction; Tactile devices and display.

1 Introduction

When we describe and mentally organize "real" textures and "naturally occurring" vibrations, humans tend to use both categorical and continuous structures. Much-studied attributes such as "hardness", "roughness," "evenness," and "harshness" refer to categorically different sensations, and themselves might be posed as continuous (and often magnitude-related) dimensions. But there is still so much parametric variability within, for example, the different forms that roughness can take, that a sampling of sensations of different roughness might not be easily classified in a perceptually linear way.

In the world of synthesized haptic sensations (whether tactile or force feedback), we have both the constraint of display hardware that is less expressive than sensations available in the real world, and the power to control the displayed sensations so they *do* naturally lend themselves to some method of perceptual organization. To leverage this power, it is necessary to understand what humans find salient about specific sensations; and to identify the *continuous parameters* whose smooth modification corresponds to a smoothly varying percept – akin to the concept of a "morph" function in the world of computer graphics. The ability to do this contributes both to a basic understanding of human haptic perception, and practical utility in haptic information display.

In this paper, we describe the search for one such morph function, specifically in the perception of a periodic vibration. We were able to identify a simple operator whose linear modification creates a smooth and nearly linear perceptual transform between two endpoint waveforms (a square wave and a triangle or sine wave; Figure 1); these intermediate points share the same base wavelength, but differ in a parameter describing one aspect of higher frequency content. As well, we demonstrate some other plausible transformations between the same endpoints that can be described in an algorithmically linear way, but do *not* achieve a smooth perceptual function. Our findings are validated through a user study making use of a Multi-Dimensional Scaling technique to visualize perceptual classification.

1.1 Perception of Continuous Waveform Transforms

What guarantee is there that a perceptually smooth transformation between two arbitrary, distinct haptic stimuli should exist? In the natural world, there are numerous continuous scales of variation, including many that do not subjectively correlate to the easily ordinal dimension of "intensity". However, many of these scales do not connect to one another so clearly; for example, while the percept of "softness" certainly varies continuously, is there a perceptual continuum between "soft" and "rough," or between "soft" and "smooth"? How would one mathematically define this movement between incongruous qualities in a textural rendering?

In visual media, it seems possible to find a convincing continuous transformation between instances of just about anything that can be represented as a geometry model, a mesh or pixels; and the process of doing so has become increasingly automatable. There are innumerable examples of improbable graphical transforms that succeed as perceptually convincing paths between two inherently unlike things ([1, 14] provide a sampling). In fact, implausible "morphs" are easier to make believable than those with which observers have experience – for example between different facial states or postures in the same person. When we see an imaged gorilla turn into a chipmunk, the path the morph takes is not critical to our assessment, since we have nothing to compare it with.

Some other relevant lessons for haptic morphing from graphical media is that (a) these transformations freely violate certain physical laws; (b) plausibility comes from obeying *other* laws, which often distill to certain parameters which must vary smoothly, e.g. the relative facial distances between markers located in consistent locations of the two key frame images.

The subject of visual morphing also raises the subtly different cases of *static* and *dynamic* morphological transformations. In haptics, what we refer to as static haptic morphs would be separate signals placed at will along a linear scale and perceived either separately or in parallel – akin to a set of static in-between visual images showed in a row. Alternatively, dynamic haptic morph functions would change "under your finger," in the same way we that we see a morphing face "melt" from one to another. In the case described in this paper, we are more focused on the static as a starting point, but see the difference as one of application more than underlying structure.

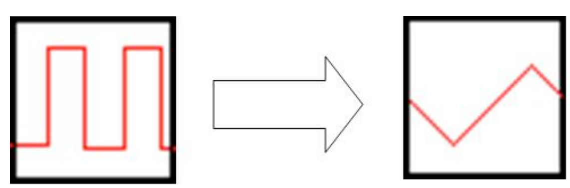

Figure 1: Finding a perceptually continuous, linear transform between two waveforms

1.2 Practical Utility

The communication of abstract information to users is an important emerging use of tactile and force feedback displays; for example, delivered through tactile-enabled mobile handheld devices, force feedback knobs in automobile cockpits or person-to-person communication in collaborative environments. We refer to these abstracted stimulus-meaning pairings as "haptic icons" [3, 16]. In designing the haptic substrate of these signals – the underlying stimuli that the user must perceive and associate with a meaning – access to continuously manipulable haptic dimensions provides two primary benefits. The first is in the potential for more natural mappings between meaning and stimulus, and the other is in ease of systematically creating perceptually differentiable stimulus sets.

In terms of usability and learnability, associations where both the target meanings and the stimuli are ordered along a naturally continuous dimension are likely to be easier to learn and remember than pairings in which one side is continuous and the other is not (e.g. in the ordinal representations described in [19] versus the categorical or mixed representations of [4-6]). For example, possible messages in a handheld device that would benefit from continuous display dimensions include message/task urgency and age; number of participants in a text discussion; length of a to-do list; time until an appointment; or contents of a portable media player, accessed through a linear list-scrolling device. In a car steering wheel, they might indicate distance/time to an upcoming suggested turn, or nearness of a car approaching in a blind spot. On the car dashboard, they could indicate radio stations, temperature settings, and many other information values. For some of these meanings, magnitude is important, and they may be best paired with a stimulus scale that reflects intensity in some way. Others are relatively flat in salience – e.g. items ordered in a list or directory. For these, stimuli that are ordered without varying in salience may be more appropriate.

To create differentiable stimulus sets that make optimal use of a display's capabilities, designers may take a dimensional approach: establish one or more axes along which stimuli may be manipulated and/or users perceive salient differences, then create a set of stimuli by choosing different points along these axes. It is difficult to move items around on such axes when their contents are categorical rather than continuous; rather, it is most efficient to employ stimulus transformations that result in perceptually continuous scales.

2 Background

Relevant background to the challenge of identifying a perceptually successful force or tactile waveform morph includes an overview of a previous study which this one builds upon; a brief description of the perceptual visualization tool used later to validate our most likely candidate morph function; and some observations and guidance taken from visual and audio media processing.

2.1 Continuous Tactile Psychometric Functions

While we are not aware of past studies focused specifically on transformation of synthetic tactile signals, there is a wealth of investigation into relevant psychometric functions, for both naturally occurring materials and textures, and renderings that mimic them. Of these, we highlight one especially apt example that deals with tactile perception of roughness through a probe [13], in which Klatzky, Lederman et al. found a relation between perceived roughness magnitude and surface geometry. Specifically, log magnitude was a quadratic function of log spacing between elements in the surface, with the function's peak location (at the probe "drop point") determined by the *relation* of probe/surface geometry. This function is the nearest we can find to the phenomenon felt in the waveform morph described here, but it is clearly not the same thing – the key element described in [13] is spacing (wavelength itself) rather than the present exploration of the perceptual role of inter-element geometry.

Illustrating a quite different approach, Ternes and MacLean discovered a potentially related phenomenon by looking at how users organized stimuli that varied by rhythm. In this study, no specific attribute was sought; but a multidimensional scaling analysis revealed that users organized stimuli by multiple dimensions of which one was found to correspond to rhythm "evenness" [20]. While the use of rhythm in this stimulus set provoked associations of music rather than natural textures, the psychonomic function employed may have been related. However, the categorical mechanism by which these stimuli were created did not lend itself to modeling them dimensionally – that is, it was not possible to identify a "rhythm evenness operator" analogous to the log(spacing) roughness operator found by Klatzky et al.

Comparing these examples gives inspiration to look for such an operator, both to better understand the psychophysical basis by which users were ordering these rhythms, and to increase control over this design parameter. In the present experiment, we began with a simpler problem.

2.2 Lessons from a Mixed-Model Stimulus Set

In a previous effort we investigated the perceptual mapping of 36 haptic stimuli created by combining three discrete wave shapes (sine, square and sawtooth) with several periodic frequencies and amplitudes [16]. In that design, we were able to treat frequency and amplitude as continuous variables; but we could not do this for waveform. The result was a "mixed model" multidimensional stimulus set, with two continuous and one categorical dimension.

Our goal in creating that first set of stimuli targeted at use in haptic icons was to spread the stimuli out "optimally" in perceptual space, with the help of a suitable visualization tool (Section 2.4). That is, we wished to make the best possible use of the display's capabilities, and ensure that the 36 stimuli were spaced as far apart perceptually as possible – thus attaining maximum distinguishability across the set. Thanks to the tool, we did succeed to a large extent. However, iterative adjustments were hindered for the categorical dimension.

We therefore took a closer look at wave shape alone, and sought to identify the "morph" function as well as the spacing of the perceptual intermediate states that would produce a continuous and linearly varying percept between a pair of "keyframe" wave shapes known to feel completely distinct.

2.3 Morphing in Film, Computer Graphics and Audio

Inspiration for morph operators can be taken from the media editing tools in the visual and auditory domains. In the earlier days of film special effects (for our purposes, before the 1990s), smooth transitions were typically accomplished through "cross-fading" or "dissolve" techniques, where in temporally progressive steps, a sequence of double exposures (taken while the object remained motionless) were controlled from frame to frame in order to transit from the end of one clip to the beginning of another. This amounted to a form of *weighted addition* of the "before" and "after" images. A similar effect is produced in video editing by interpolating image brightness levels in the video signal [7, 21]. These transitions were generally not meant to convey a sense of uniform identity (i.e., of the end-points representing altered versions of the same thing); nor did they. Rather, they made scene changes flow smoothly, without jarring.

Modern techniques in computer graphics (CG) and animation have more in common with "tweening" techniques used in traditional hand-drawn animation: the "before" and "after" images are *distorted* to move towards one another, in a structural transformation, at the same time that actual pixels are transitioned. To accomplish this, for example in morphing from one facial image to another, markers or "key points" are set at corresponding points in each face; the faces are meshed, and structurally distorted to bring the key points into correspondence (e.g. [18]). The effectiveness of these and other techniques are related to the notion of *optic flow*, by which both animals and computer vision techniques infer object motion and structure [12].

In studio sound editing, the most common morphing tool has historically been the "crossfader". A fader is a manual or digital control used to smoothly vary the level of an individual audio signal. Crossfading, akin to a film "dissolve", is used to combine or move between audio tracks, whether for mixing or transitioning. Disk jockeys employ crossfading to "beat match", where the primary adjustment is in tempo rather than other qualities of the sound (see [2] for an example of haptic tools to support beatmatching for digital audio). More sophisticated auditory techniques are based on spectral analysis, and do actually "morph." For example, in morphing between recorded utterances by different voices, algorithms encode formant shifting between spectral magnitude envelopes [10].

The operators employed across these various examples involve either *weighted addition* (film dissolves and audio crossfading) or *distortion* (computer graphics morphing, animation tweening, audio beatmatching and formant matching). Both classes of operators share the need to identify the most perceptually important degrees of freedom describing the change between the two media states, and to focus the transition along them.

2.4 MDS Visualization Tool

Multidimensional Scaling (MDS) is a visualization tool that can reveal the underlying structure of data sets [17] and is useful in analyzing perception in complex stimulus spaces. In perceptual MDS, the algorithm takes as input a "dissimilarity matrix" containing user-perceived distances between s items (here, haptic stimuli, which have been created along n design dimensions) and locates them in a Euclidean m-dimensional perceptual space, such that inter-item distances approximate the degree of dissimilarity described by the input matrix. The algorithm also delivers model "stress," indicating goodness-of-fit as a function of m: a higher-order model may provide a tighter fit (lower stress value), but at the cost of abstraction and/or clarity. Ideally a knee in the stress=$f(m)$ curve will suggest the best value for m. We take the m dimensions as the most salient aspects of the set; stimulus coordinates recovered in the scaling locate the objects.

For efficiency and stability, we have had greatest success collecting dissimilarity data by requiring participants to sort items into similar groups [11, 17] rather than make direct Pairwise comparisons. Cluster-sorts repeated by several participants on successive candidate stimulus sets therefore is the core of an iterative design technique, in which convergence towards a maximal inter-item spacing is supported by reference to the quickly-derived MDS solution [16]; validations and updates to this basic technique are recently summarized in [15]. For set sizes of up to about 30, we have found that data from about 5 users each contributing a 20-60 minute session provides enough dissimilarity data for a stable, consistent map; and thus a full iteration on a stimulus set of this size requires only 2-5 hours of participant time, depending on the set size.

3 Establishing a Perceptually Continuous Function

Although of lower dimensionality than many visual or auditory signals, a single-channel haptic stimulus can still have multiple controlled and perceived parameters. Some may be more critical to a transition between two signals than others. We make a start on understanding this space by examining one transition between a pair of signals of a given type.

Identifying a single-channel perceptual waveform transform was an iterative process that involved repeatedly testing candidate waveforms in pilot tests, prior to a more formal evaluation of the most successful candidates (described in Section 4). Candidate identification began by establishing a high-level approach and scope of investigation; this was followed by a prototyping stage where we explored a variety of mechanisms for operating the transformation.

3.1 Definition of Domain and Scope

To begin, we needed to establish an operative domain, and appropriate endpoints of our morph function. These early design decisions frame the remainder of the work.

1. Time versus frequency domain manipulation: We chose to explore the control and perceptual properties of waveforms in the time rather than frequency domain, for ease of manipulating the signals and intuitiveness of interpreting the result. In future work, it will be of interest to explore the perceptual dimensionality and salience of spectral variation more generally.

2. Choice of waveform endpoints: We used simple waveforms varying from a square to a triangle wave (Figure 1). Our earlier work had revealed that these haptic signals were the most perceptually different of all that we tried whereas a triangle and a smooth sine wave are nearly indistinguishable [8]. In the present study, we treat the triangle and sine wave as perceptually interchangeable, and the triangle was better suited to time-domain manipulations on the control side. In planned future manipulations from the frequency domain, the sine wave will likely be the better choice of this pair, because of its clean spectral content.

3. Choice of base frequency or wavelength: In some cases, features of the morph operators are subject to the overall period (time duration) of the waveform, due both to electromechanical and human sensory dynamics; for example, the usable range of the operator might be smaller for a high base frequency, or might be perceptually less discernable. This will be almost universally the case across substantial frequency ranges (e.g. from the longest practically-useful wavelengths corresponding to 1-2 Hz up to

Figure 2: Knob setup used to display waveform morph candidates.

beyond peak sensitivity, 200-300 Hz), meaning that waveform morphs are unlikely to be frequency-invariant at those ranges. Hardware dependence is also a factor. We did not examine these effects in detail here; the frequencies we investigated ranged from 3-21 Hz, chosen for reasons unrelated to morph optimization. These relatively long wavelengths allowed waveforms that seemed to be perceived consistently across the spectrum used, and which displayed some fine detail with the display hardware used.

3.2 Setup

The stimuli employed in the current study were displayed on a direct-drive actuated knob in torque control (Figure 2). The knob was rubber-covered brass with an outer diameter of 10.5 mm and a length of 16.5 mm, mounted directly on the shaft of a 20W Maxon DC motor (RE025; stall torque of 240 mNm and position frequency roll-off at 200 Hz). All signals were delivered as open-loop torque commands.

Participants sat at a table and used the knob setup (located on a slightly raised platform with a padded armrest) with the non-dominant hand. To mask auditory noise from the haptic display, participants wore headphones and listened to white noise throughout the test session. They made responses by sorting graphically displayed tiles (each associated with a different stimulus during MDS cluster-sorting) using a standard mouse with the dominant hand.

3.3 Candidate Morph Operators

Following our review of morph operators in other media domains, we considered a number of candidate operators for the relatively simple case of moving between square and triangle waves of the same base frequency and force or torque amplitude. Simultaneous transformation of multiple simple operators did not arise as an option – i.e. all the transformations we found constrained the remainder of the signal, giving rise to a one-degree-of-freedom transformation problem.

Examples of candidate transforms we considered included the following (an exhaustive list would require extensive pictorial representation without contributing much insight):

1. **Parametric** approaches:
   a) *Slope* of vertical component (Figure 3)
   (Alternatively, *width* of horizontal component)
   b) *Height* of vertical component (Figure 4)
   (Alternatively, *slope* of non-vertical components)
2. **Weighed addition** approaches:
   a)-d) At multiple *phase offsets* – e.g. 0°, 45°, 90°, 135° relative to peak-synchronization (Figure 4 shows 0° offset)

Some observations help elucidate the nature of these possibilities. First, while parametric operators such as slope and width (case 1a) follow the same transformation path, they do not traverse it at the same rate; e.g. a linear modulation of width causes a nonlinear modulation of slope. Similarly, a non-linear "inverse" relationship exists between other pairs of operators.

Secondly, phase matters in weighted addition schemes. In the time domain, addition produces different results when the sources are at different phase offsets.

Figure 3: Unsuccessful waveform transform: varying *slope* from square to triangle.

Finally, the parametric and weighted-addition approaches are in some cases equivalent. For example, case 1b) is equivalent to weighted addition at 0° offset; this in fact is the morph function was ultimately most successful (see Figure 4).

3.3.1 Unsuccessful Morph Function

To illustrate the perceptual issues involved, we examine more closely one of the *unsuccessful* morph candidates we prototyped and informally tested. It operated linearly on slope angle of the wave's rising component, to transition from the square wave (90° slope) to a triangle (down to 45°) slope (Figure 3).

In practice, this transformation was not perceived as either smooth or linear. It produced a perceptually abrupt (rather than gradual) transition between the square and triangle waveforms. Pilot testers rated these waveforms as all feeling like a triangle waveform as soon as the slope was reduced from vertical by about 5°; and found them indistinguishable from a pure square wave before this (between 90-85° slope).

3.4 Successful Morph Function

The results of the slope investigation eventually led to the supposition that participants were indeed keying on "verticalness", but in a way that the slope parameter did not capture well. Another parametric attempt was based on *extent* of the vertical component, where a square wave had a vertical extent of 100% and a triangle of 0%. We could then vary the amplitude of this vertical component in relation to the waveform peak amplitude (indicated with the wide red line in Figure 4). This parametric approach is in fact equivalent to a zero-offset weighted average, represented mathematically as:

$$\tau_{morph}(\theta, p) = (1-p)\tau_{square}(\theta - 0) + (p)\tau_{triangle}(\theta - 0), \ \ p \in [0,1] \quad (1)$$

where square and triangle waveforms are in-phase and at the same frequency; and p determines the ratio of triangle vs. square content in the result.

Two observations about potential extensions to or simplification of this relationship are in order. First, one could propose a still simpler transform in which shape itself is held constant, and *only* the height of the vertical discontinuity is varied: e.g. by modulating the square wave's amplitude without

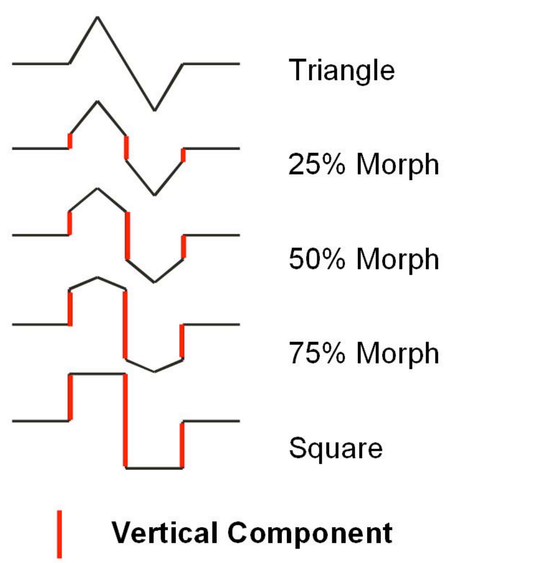

Figure 4: Successful waveform transformation: the perceptually important parameter is the vertical component amplitude relative to peak-to-peak amplitude.

adding the triangle component. Secondly, one could conjecture about values of p that are negative or >1. However, both of these cases will produce a strong confound with overall signal amplitude (in the latter, a coefficient outside of [0,1] would produce a higher-amplitude signal). This could make significance difficult to interpret.

In informal pilot experiments, subjects found that instances of this waveform spaced between the square-triangle ends of the spectrum (as illustrated in Figure 4) produced a change in perception that was approximately proportional to the value of p.

4 Perceptual Validation of Proposed Morph Function

The morphing method represented in Figure 4 was validated more formally with a multidimensional scaling study of perceived dissimilarity. In this experiment and analysis, two control parameters were varied simultaneously along continuous scales: waveform morph and the base frequency of the stimulus waveform. This experiment also served a parallel goal of refining a perceptually optimized set of stimuli for another research purpose, a two-dimensional haptic icon *association* study described in [9].

4.1 Method and Stimuli

The cluster-sorting procedure for collecting dissimilarity ratings followed the basic procedure referred to in Section 2.4 and laid out in [15, 16]. A set of 25 haptic sensations was composed of the 5 waveforms of Figure 3 (triangle, square and the 3 intermediates defined by p=0.25, 0.50 and 0.75) displayed at 5 frequencies (3, 7, 13, 18 and 21 Hz). These two-dimensional stimuli shared the same fixed torque amplitude, with a peak fixed at a single clearly-perceptible level (~5 mNm). They were delivered using the setup described in Section 3.2. 11 participants (6 male, age range from 20-35 with median 27) took part.

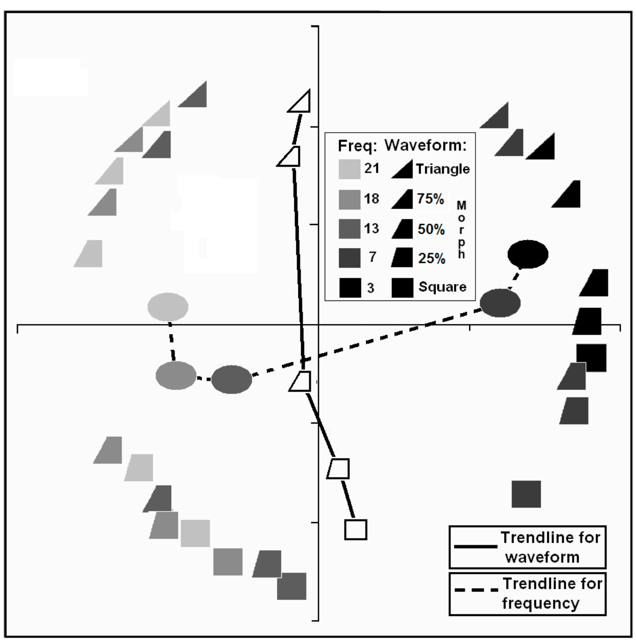

Figure 5: 2-dimensional MDS map (perceived distribution) of stimulus test set including 5 levels of the waveform transform. The two trendlines join centroids for each level of the respective control parameter; each centroid is the average of 5 values.

4.2 Results and Discussion

Figure 5 shows a graphical representation of the MDS perceptual map of these 25 stimuli, based on dissimilarity data obtained from participants' repeated cluster-sorting of the stimuli. The solution is presented in two dimensions. Further dimensional MDS solutions resulted in inconsequential reduction of stress values. In meta-analysis, trendlines for the MDS result as a function of the input control parameters are plotted on the same figure. That is, each point on the trendline is the centroid of all values containing the respective value; e.g. the top center trendline point (unshaded triangle, representing the 100% triangle morph) is the average location of the stimuli containing that morph value at all 5 tested frequencies.

The first thing to notice in Figure 5 is that the trendlines indicate a fairly consistent correspondence between the two control parameters (frequency and waveform) and the perceptual organization found by the subjects (illustrated by the two trendlines). This is seen in the orthogonality of the two trendlines. The morph trendline is quite straight and spans the MDS space in extent, indicating that this axis is accounting cleanly for one of the two dimensions varied in the stimulus set.

The next thing to look for is uniform distribution of the three morph centroids in between the extreme endpoints. This reveals good but not perfect results. The three intermediates are spaced along the straight line in the expected order – rather than on a curved trendline, e.g. as is seen for frequency. However, their spacing is not precisely uniform. While some error is anticipated with most techniques based on subjectively obtained user data, it is also possible that there is a slight nonlinearity in the perception of the morph function. Such a nonlinearity, if verified, could be easily be corrected with a minor adjustment of the transform; e.g.

$$\tau_{morph} = f(\theta, a\log(p)) \quad \text{rather than} \quad \tau_{morph} = f(p). \qquad (2)$$

The primary divergence from the ideal result of two straight, perpendicular trendlines is seen in the frequency result. While the perception of frequency itself does not concern the present waveform-focused investigation, we *are* interested in interactions in perception between the two parameters. The most likely explanation for the slightly curved frequency trendline – most pronounced for the highest (21Hz; lightest shading) and lowest (3Hz, darkest shading) frequencies used – is such an interaction, i.e. different levels of the morph transformation had a differential effect on the perception of frequency. Prior work has indicated similar interactions in perception between waveform and frequency [16].

In summary, this analysis shows that those participants tested were indeed rating different levels of these morphed waveforms as perceptually intermediate between a square and a triangle; furthermore, the degree of variability registered was comparable to the range expressed for a parameter already known to be highly salient (periodic frequency).

5 Conclusions and Next Steps

These results demonstrate the existence of a smooth perceptual path between two distinctly perceived tactile waveforms (square to triangle); without this evidence, it would be difficult to know whether the hypothesized continuum existed. Furthermore, at least one function defining this perceptual path is a simple proportionality. For a completely linear transformation of the perceptual variance along the path, a small adjustment of the proportional operator (e.g. a mild log function) may be required.

This finding provides insight into tactile perception of synthetic vibrations. For the display employed here, the most salient feature of a rendered waveform is the amplitude of its vertical components in relation to waveform peak amplitude. It was the relative amplitude of these high-frequency stimulus changes that people focused on when rating these waveforms.

In terms of practical aspects of tactile information display, this result contributes both directly and by example to the design of better synthetic haptic signals. The square-triangle continuum studied here, while a particularly useful one due to its ease of production, is presumably just one of many others still to be found. In addition, it is the only example of which we are aware of a tactile stimulus *continuum* (as opposed to collection of categories) that is not obviously confounded with sensory magnitude or intensity (as are frequency, amplitude, tempo). Further, our experience with this continuum is that it is flat in salience; while this should be confirmed experimentally, any salience asymmetry could easily be corrected with amplitude modulation. This gives it value in creating haptic icons for flat-salience lists, useful e.g. for many forms of media navigation. Along with the stimulus-meaning compatibility benefits cited earlier, the use of continuous scales in signal design also eases adaptation of stimuli across haptic displays of varying capability.

Next steps should focus on two areas, which can probably be solved in tandem. First, it will be productive to look into stimulus design in the frequency domain, by manipulating spectral content rather than temporal features of the waveform, e.g. borrowing from techniques in audio DSP (digital signal processing). Our observation that users consistently keyed on fine adjustment of the highest-frequency aspect of the temporally-defined waveform lends support to this approach. Secondly, we are not convinced that the somewhat laborious trial-and-error approach combined with extensive pilot studies used here is necessary; we seek a more systematic and perhaps automated method. It is quite likely that spectral techniques will provide a more analytical approach. However, as with the time domain approach, it will be most successful when guided by detailed insight into what users are finding perceptually salient; and user testing will remain essential.

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