Study of 2D Vibration Summing for Improved Intensity Control in Vibrotactile Array Rendering

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Abstract. 2D tactile arrays may be integrated into handheld devices or VR controllers to enhance user experience, for example, with touch communication for collaborative tasks. Multiple tactors (tactile elements) may be activated in combination to approximate a vibration point (virtual tactor) having arbitrary position and intensity. We studied the combination of intensities from multiple tactors to guide virtual tactor rendering approaches. Subjects matched perceived loudness of multi-tactor vibrations to a reference tactor. The multi-tactor vibrations corresponded to overall perceived positions halfway between tactor pairs and in the center of a 2D 4-tactor group. Results inform the relationship between tactor signal level and perceived loudness at these critical positions. The relationship leads us to propose a nonlinear 2D rendering approach, provides a basis for assessment of existing rendering techniques, and lays a foundation for further study of 2D array rendering.

1 Introduction

We consider rendering cues of arbitrary position and intensity on 2D tactile grids. Devices such as tactile-enhanced smartphones (Figure 1) might be used in a collaborative augmented reality game with geolocation constraints or as VR controllers in a data exploration application. For example, by tapping or dragging a finger across the touch surface, the sender can draw points or curves on the receiver's hand to give direction or event cues. Such applications motivated tactile grids like smartphone cradles [1], [2] and spherical controllers [3]. Prototype handheld devices [4] and palm-sized tactile grids [5], [6] have been used to develop rendering algorithms and tactile cue arrangements. Related social and interpersonal impacts of virtual tactile communication have been considered, e.g., by [7], [8], [9], [10].

Our work involves understanding perceived intensity for a varying number of contributing tactors representing a tactile grid cell. This concept has seen sparse coverage and inconsistent results for 2D arrangements [11], [12], [13], as most related work focused on 1D arrays, and rendering perceptually-consistent intensities with more than two tactors may require a formulation not found in previous studies. Previous work [4], [11], [13] suggested logarithmic or other 1D functions for adjusting tactor intensity, for example, to interpolate smoothly between two tactors. In our study, subjects matched vibrations from tactor combinations in a 2x2 cell to reference vibration levels. We recommend a 2D interpolation approach based on the experimental results and define a generalized rendering algorithm.

2 Related Work

Perception of points between tactors depends on spacing, relative amplitudes (due to amplitude inhibition), timing (due to temporal inhibition), and a funneling action (combined inhibition and summation) that integrates multiple stimulation sites into a combined phantom sensation [14], [15], [16]. Neural activity level increases when the skin receives additional stimuli from multiple tactors or increased area [17]. Onset delay between tactors can generate apparent motion, meaning a sensation appears to move along the skin (phi phenomenon) [18]. Recently, researchers focus more on tactor intensity control to interpolate sensation for adjacent tactors (e.g., [4], [5], [19]), noting this avoids perceptible taps of pulsed methods [19] and using amplitude inhibition is stronger than temporal inhibition [14], [19]. Alles [14]

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briefly mentioned the possibility of three or four tactors for interpolated 2D cues and separately noted a spacing tradeoff: wider spacing increases transmission but degrades sensation. 2D arrays with more tactors may support both good transmission and sensation.

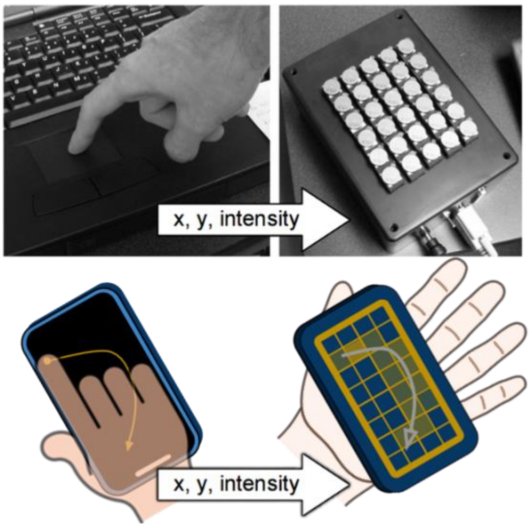

Figure 1: *Top*: Prototype using laptop touchpad and 2D tactile array to communicate touch, from [6]. *Bottom*: Smartphone with palm-facing array is used to communicate vibration patterns (conceptual illustration).

Borst et al. studied 2D rendering on the prototype array of Figure 1 using an area sampling approach with per-tactor gamma correction [20], [21], [22]. Other works deployed related systems for remote tactile communication, e.g., [9], [10]. Haans and IJsselsteijn [9] provide a review of remote “social touch” from a sociological and personal communication perspective. They address design principles impacting how remote touch can elicit a physiological response like that in a social context. Huisman et al. [10] developed a sleeve with touch sensing and tactile display components. Two users wearing the sleeves communicated pressing or poking actions.

Un-weighted area sampling [20] activated tactors based on the percentage overlap of an arbitrarily-positioned virtual tactor with each array tactor’s area. The method was equivalent to bilinear interpolation and conceptually similar to anti-aliased point rendering for visual raster displays. Subjectively-tuned gamma correction was included to consider nonlinear tactor or human response. We propose a nonlinear 2D function controlling waveform amplitudes based on a measured relationship between tactor amplitudes and desired sensation at critical virtual tactor positions. We also objectively determine how added tactors contribute diminishing amounts to sensation.

Oakley et al. [12] studied perceptual response to vibration on up to three tactors. Subjects compared pairs of tactor configurations and judged which gave stronger vibration (or indicated them as equal). Results showed perceived loudness generally increased with the number of active tactors. This was based on the mean number of times a particular configuration was judged louder. The method of comparison, however, did not allow the direct specification of amplitudes for our purposes.

Ryu et al. [3] developed a topologically-2D thirteen-tactor arrangement on a spherical handle for use as a 6-dof hand controller. It provided directional cues using multiple simultaneous vibrations. Tactor amplitudes were set by a 1D logarithmic function of distance from a desired perceived point. Parameters of device construction and psychophysical thresholds must be determined prior to effective use.

The 2D Tactile Brush by Israr and Poupyrev [11] renders vibrations according to an assumed sum of squares relationship between the intensities of physical tactors and a virtual tactor (rendered point) placed in between. Four-tactor summation was not addressed directly, as the concept was to use perceptual summation effects along one dimension and apparent motion illusions along the other. Tactile Brush is not suitable for applications suggested by Figure 1: it was limited to pre-defined stroke paths of linear segments and endpoints must fall on gridlines due to a discrete activation of tactors for the apparent motion effect. Our proposed approach instead uses only the summation effect along both dimensions, as this effect has benefits mentioned earlier.

3 Methods

The method of Manual Adjustment [23] allows subjects to produce a vibration intensity based solely on their perception. No numeric values are given to the subject for comparison, only a Reference stimulus. Two vibrations are presented, alternating between Reference (left arm) and Adjustment (right arm), until the subject completes a trial. During this time, the subject tunes Adjustment to match Reference.

Subjects: We recruited fourteen unpaid subjects (three female) from the investigator's university via e-mail and word of mouth. The median age of subjects was 28. All reported normal feeling in both arms.

3.1 Apparatus

Seen in Figure 2 (Left), five C2 tactors [24] delivered 250 Hz vibrations to a subject's inner forearms. One tactor delivered a Reference stimulus to the left arm. Four tactors aligned on a 1.5 inch grid (Figure 2, Right) delivered Adjustment vibrations to the right arm. Adjustment tactors were activated in various combinations, with active Adjustment tactors having equal signal level. Subjects varied Adjustment Intensity (signal amplitude) by turning a Griffin Powermate 1040 knob. The tactors were placed close enough together that the stimuli were perceivable as one vibration [16].

Figure 2: Apparatus. *Left*: Subjects sat between two devices, placing an arm on each. *Right*: Four C2 Adjustment Tactors labeled with per-tactor intensities I_{st} and interpolation parameters on a unit cell. The contribution of I_{00} to virtual tactor intensity I_v is determined by interpolation parameters *s* and *t*.

A half-inch-thick steel plate with four three-quarter-inch expanded PVC pads acted as a mount for the four Adjustment tactors. A separate L-shaped steel plate and expanded PVC construction acted as a mount for the remaining Reference tactor. The steel plates absorbed low frequency vibrations not transmitted to the skin. The PVC material isolated the vibrations from surrounding furniture and prevented direct contact of tactors with the steel plates. A cotton sheet reduced remaining vibrations transmitted through the mounting apparatus or the signal wires.

To isolate subjects from the audible tone generated by the tactors, they wore over-ear headphones, and the experiment software emitted a constant 250 Hz masking tone. When subjects performed an adjustment, a short 500 Hz tone was superimposed over the masking tone to provide feedback about the knob's motion.

Five audio amplifiers (LM386-based 1W Audio Amp) with adjustable input gain drove the tactors. Using an oscilloscope, the maximum sinusoidal outputs of all amplifiers were set to equal, non-clipping levels. A power source of 7VDC and signaling cables were connected to each audio amplifier, with all wiring and electronics encased in a project box. Audio driver software defined adjustment values between a normalized signal level (SL) of 0.0 and 1.0, inclusive. The software emitted 250 Hz sine waves over audio channels of a USB sound card (Diamond Xtreme Sound 7.1). The sound card's voltage response was verified to be linear with respect to commanded signal. Each tactor was signaled through one side of a stereo output. The driver guaranteed tactor activation signals were in phase and synchronized.

Experiment control software presented the visuals of Figure 3, which consisted of trial count, labels reminding subjects about the Adjustment and Reference positions, a non-binding 90-second timer bar, and an instruction for advancing trials. Subjects adjusted intensity with the Powermate knob, which has no stops or detents. It was placed near the left hand to require minimal motion, avoiding motion of the left arm away from the reference tactor. Plus and minus signs (+, -) under the adjustment text gave visual confirmation of the subject's last knob action. Tapping a computer mouse next to the knob allowed subjects to advance trials.

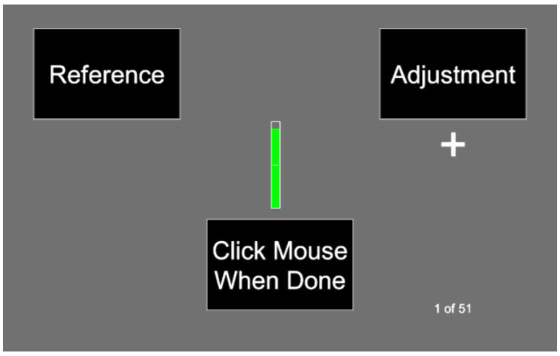

Figure 3: Experiment software with timer and Adjustment feedback.

3.2 Procedure

Once seated, the subject donned headphones and placed either arm on the appropriate tactor(s). An attendant ensured correct arm contact, explained the task, and answered any questions. A demonstration stage of three trials preceded data collection.

Each trial presented subjects with alternating vibrations at Reference (on the left forearm) and Adjustment (on the right forearm) configurations. The number of active Adjustment tactors (Tactor Count) varied between one and four. For counts of one, two, and three, there are multiple possible tactor choices, and the software randomly chose from the possible subsets, per trial, with the constraint that every possible subset appeared at least once. This was to allow averaging to avoid bias from any specific subset (e.g., due to variations in tactor response or contact pressure).

Reference Intensity varied between trials, in random order, with signal levels 0.3, 0.416, 0.577, and 0.8 (SL, i.e., normalized units). Each stimulus lasted one second, with a 100 ms pause between stimuli. Subjects altered Adjustment Intensity without time limit. A non-binding 90-second timer allowed subjects to gauge duration.

Adjustment tactors began at 0.05 SL for half of the trials and 0.95 SL for the others (randomized), ensuring half of all trials required an increase adjustment, and half required a decrease. There were three trials for each of sixteen combinations for a total of forty-eight trials, with short breaks after completing the first 1/3 and second 1/3. Our software recorded the subject's final Adjustment setting per trial.

4 Analysis

Per subject, Adjustment Intensities were averaged for each Tactor Count and Reference Intensity level, i.e., three trials were averaged for each of the sixteen Tactor Count and Reference Intensity combinations. For the single tactor Adjustment case, resulting Adjustment values should be close to the References within a reasonable margin of error. Adding a second equal-amplitude tactor increases total perceived loudness above the single-tactor level, but should not double the loudness, due to amplitude inhibition [14]. Consequently, Adjustment Intensity for the two-tactor condition should be greater than one-half the single-tactor Adjustment.

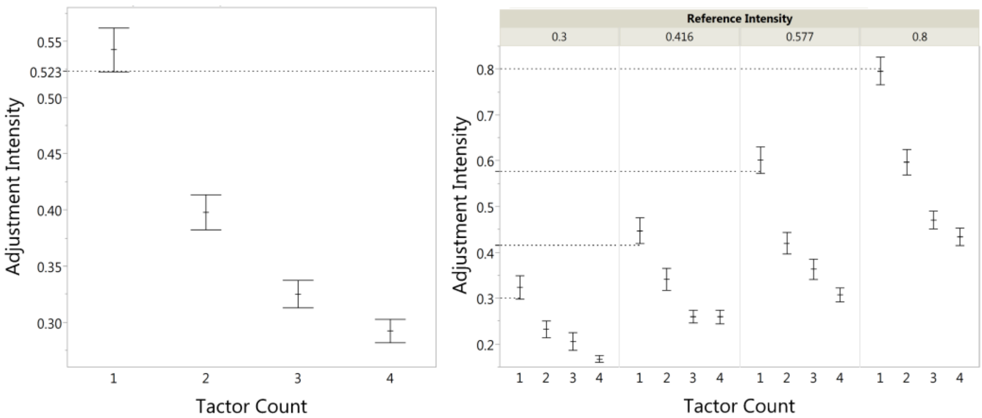

Figure 4: Means and standard errors (+/- 1 SE) for Adjustment Intensity. *Left:* Averaged per Tactor Count. *Right:* All sixteen conditions. Dotted lines indicate average (left) and individual (right) Reference Intensities.

4.1 Results and Discussion

To provide insight for rendering virtual points in 2D grid cells, the combinations of Tactor Count represented virtual tactors centered on single tactors, between two tactors, and between all four tactors. We also included 3-tactor cases that may provide additional insight into the summation beyond suggestions in [3], [12]. Tactor Count and Reference Intensity both had significant effects, $F(3, 11) = 74.9$, $p < 0.001$ and $F(3, 11) = 130.7$, $p < 0.001$, respectively (repeated-measures ANOVA). There was significant interaction between Tactor Count and Reference Intensity $F(9, 5) = 7.87$, $p < 0.018$. These ANOVA results were expected from known properties of perceptual summation and the spacing of Reference Intensities. Interaction reflected the shape changes in Adjustment Intensity for different References.

Inspection of Figure 4 shows the mean response for a single tactor was within the standard error boundaries overall (left) and within or near the boundaries for individual Reference Intensities (right). Some deviation away from Reference Intensity is expected due to random variations such as contact pressure with the Reference tactor, and does not impact our later interpretation (we are mainly interested in relative intensities between different tactor configurations). When considering Adjustments averaged over all Reference Intensities (Figure 4, left; mean Reference 0.523 SL), the mean Adjustment decreased from 0.543 SL in the single-tactor case to 0.398 SL in the two-tactor case, notably less of a decrease than the 50% decrease a linear relationship would suggest. The spacing of Adjustment Intensity between successive values of Tactor Count shows a nonlinear relationship, with a mean decrease of 26.7% between one and two tactors, a mean decrease of 18.3% between two and three tactors, and a mean decrease of 9.8% between three and four tactors. Each added tactor has less effect on total perceived loudness, both because it constitutes a lower percentage of total tactor count and because inhibition during funneling further reduces each tactor's effect when combined with others.

The Adjustment tactor configurations in Figure 5 show single tactor vibrations, pairs horizontally or vertically adjacent, and all four tactors. The proportions of means from single-tactor to two-tactor, and from two-tactor to four-tactor, are nearly equal (1.37 and 1.36, respectively). This suggests loudness may follow dimensionality: when the same percentage increase in Tactor Count occurred with the same spacing between added elements, per-tactor intensity ratio changed by an equal proportion.

While consistent with Oakley et al. [12], we contributed a quantifiable growth rate of perceived loudness. We also demonstrated conditions under which this growth occurs. Prior 1D studies suggested, to one degree or another, logarithmic growth of sensation. Our results indicate an arrangement of tactors for a proportional increase in sensation, considering a 2 × 2 arrangement not shown in those earlier works.

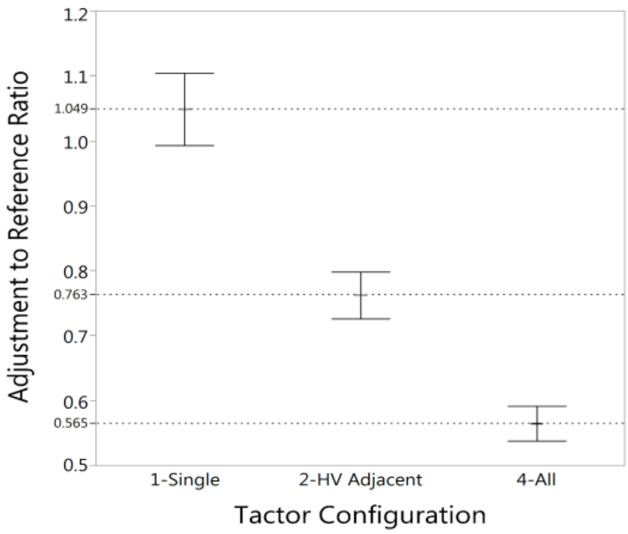

Figure 5: Means and standard errors (+/- 1 SE) for Adjustment to Reference Ratios. Tactor Configurations only considered single, horizontally or vertically adjacent, and (all) four tactors for clarity. Dotted lines indicate mean values.

4.2 Implications for 2D Tactile Rendering Algorithms

Prior work distributed vibration across multiple tactors, but did not always provide consistent perceived intensities. Extending our statement above that loudness follows dimensionality, we propose 2D interpolation-based rendering for more consistent perceived intensity of arbitrary points in a 2D grid. Note a 1D version would compute, for each tactor near the point, an intensity $I = I_v \bullet f(s)$, where I_v is desired overall perceived intensity and $f(s)$ is an interpolation function with parameter s being the distance between the tactor and point. Assuming 1-unit tactor spacing, reasonable constraints are $f(0) = 1$ and $f(1) = 0$. Linear interpolation is $f(x) = 1 - x;\ 0 \leq x \leq 1$.

2D Nonlinear Interpolation Approach. Following our results, we generalize to 2D and then discuss nonlinear aspects. For a point in a grid cell like that in Figure 2 (right), interpolation can be applied in two dimensions by computing, for each nearby tactor, an intensity $I = I_v \bullet f(s) \bullet f(t)$, where s and t are the horizontal and vertical distances between the tactor and point.

In Figure 5, 2-tactor cases correspond to points halfway along a cell edge, the 4-tactor case corresponds to a cell-centered point, average Reference level was 0.523 SL, and the plotted values are Adjustment-to-Reference ratios. For the 2-tactor results, this gives a relationship $I = 0.523 \bullet f(0.5) \bullet f(0) \approx 0.392\ SL$ for the relevant tactors, implying $f(0.5) \approx 0.750$. Substituting the 4-tactor point position gives $I = 0.523 \bullet f(0.5) \bullet f(0.5) \approx 0.294\ SL$, nearly identical to the sample mean of $0.293\ SL$.

The value at $f(0.5)$ adds a third constraint that linear functions do not satisfy. While the full shape of the ideal interpolation function is not known, 1D studies (e.g., [4], [5]) suggested logarithmic adjustment as promising. The general logarithmic form for our approach is $f(x) = a \bullet ln(b\,x + c)$. For the values given above, the specific equation satisfying the constraints is $f(x) = 0.41 \bullet ln(-10.46\,x + 11.46)$.

The midpoint value $f(0.5)$ was found from averaged Reference Intensities. Further extension could incorporate a loudness parameter into $f(x)$ if perceptual summing is found to depend on intensity. Our current data do not definitively address this – we did not detect any clear or consistent effect of this type.

Assessing Other Methods. Tactile Brush [11] uses the energy model $H^2 = I^2 + J^2$, where I and J are physical tactor amplitudes and H is a desired virtual tactor intensity. From our results, a point halfway between two tactors requires both to be activated at $I_v \bullet f(0.5) \approx 0.750\ SL$, for a normalized $I_v = 1.0\ SL$. In the energy model, $1.0 = I^2 + J^2$ and $I = J$ imply $I \approx 0.707\ SL$. While the difference between the two models is not large, it exceeds our standard error (standard error of the mean for our model is 4.72%, but the Tactile Brush result is 5.73% from the mean). Furthermore, Tactile Brush only applied the model along one dimension. It may be possible to generalize the energy model to 2D by repeated application or additional summands, but the curve shape provides little flexibility for fitting to new results.

Approaches like T-Hive [3] apply a 1D function of distance at each of up to four nearby tactors. For such an approach to fit our results, the 1D function must satisfy an additional interpolation constraint $f(0.707) \approx 0.56$, which means it should give the intensity determined by our 4-tactor case when given cell center distance (the other constraints were listed earlier for $f(0)$, $f(1)$, and $f(0.5)$). The logarithmic function of [3] and related approaches were not intended to fit four constraints. The added constraint also reduces flexibility in handling additional factors that may be determined by future studies, for example, measurements at several points along an edge.

Gamma correction [6] adjusts tactors independently after interpolation and has a limitation like that of the T-Hive approach. It may still be useful, in combination with our proposed approach, for handling nonlinear responses of less precise tactors. This would allow separated handling of tactor characteristics and perceptual mechanisms.

Limitations and Future Extensions. Differences between devices, like the prototype in [6] and our experiment cell, include location on the body, tactor type, and spacing. We preferred C2 tactors for their precision and the forearm for consistent contact, both being important for studies of this kind. The same perceptual mechanisms and class of mechanoreceptors are present for the inner forearm and the palm [17]. The main concepts should transfer, but exact parameters can be checked per configuration.

Static points rendered by multiple vibrations extend to a moving stimulus by varying s and t over time. Some 1D studies, e.g., [4], [19], coarsely evaluated interpolation methods for moving sensation between two tactors and found that interpolation function and speed influence consistency of perceived intensity.

The midpoint between two tactors and the center of four tactors were a focus of our results, and 1D work has also emphasized centers. These are the most critical points, as largest deviation occurs there. Other points of interest can include 3-tactor cases, where triangular interpolation (e.g., parametric) may allow us to render positions in an arbitrary triangulated tactor arrangement. The study of levels for additional points can also lead researchers closer to finding the ideal interpolation function shape.

5 Conclusions

Our study contributes to understanding perceived intensity for tactor combinations encountered in 2D arrays. We showed how the results motivate a 2D interpolation approach for rendering points on 2D arrays. We also showed how the results provide a basis for assessing various other proposed approaches for array rendering. Although 2D interpolation is conceptually simple, researchers developed the other approaches with a goal of exploiting or handling perceptual summation effects. Our results suggest that suitable nonlinear interpolation functions can accomplish this goal, and we gave a specific form modeling our results at the critical points in an array cell. Further research may help check for more ideal forms for sensations moving at arbitrary array positions. This is still an open problem, even for 1D arrays.

Our results may be applied to such uses as games on handheld devices, VR controllers, or navigation assistance. We expect our results to extend to stimuli over larger areas of the skin and a larger number of tactors. Future studies will investigate alternative interpolation functions for accuracy in both intensity and position and explore the need for a loudness parameter during interpolation. This will further guide smooth motion rendering throughout 2D grids.

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