Force-Sensitive Detents Improve User Performance for Linear Selection Tasks

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Abstract—Haptic technology, providing force cues and creating a programmable interface, can assist users in more accurately using an interface. This paper investigates haptic assistance in combination with auditory feedback instead of visual feedback. A user test is carried out in which participants select fundamental frequencies from a continuous range to play brief musical melodies. Two control conditions are compared with two detent-based haptic assistance conditions. The detents gently guide the users toward locations of equal tempered fundamental frequencies. Results from the user test confirm improved accuracy brought about by the detents. It is further helpful to provide regulation of the strength of haptic assistance in real time, allowing the user to remain always in control. This concept motivated the force-sensitive detent condition, which enables the user to adjust the strength of the haptic assistance in real time by changing the downward force applied to the haptic device. The work implies that users of graphical user interfaces could similarly benefit from force-sensitive detents and more generally real-time regulation of the strength of haptic assistance.

Index Terms—Haptics, haptic assistance, detents, force-sensitive detents, subject test, Theremin, haptic widgets, music

1 INTRODUCTION

When users interact with computers, they typically receive multimodal feedback to help immerse them in a virtual or augmented environment. Visual feedback, auditory feedback, and haptic feedback play important roles. This paper investigates how active haptic feedback can assist a user in completing a task more accurately.

Active haptic feedback has traditionally been more frequently employed to give a user the impression that he or she is touching virtual objects. For example, Fig. 1 depicts a user reaching into a virtual environment to interact with virtual objects via a single point on the index finger. The haptic system (not shown) exerts a force on the user’s finger depending on what the user is doing, giving the user the impression that he or she is touching virtual objects. Of course the interaction can be much more complex with multiple points of interaction, more degrees of freedom, rendering of textures, higher-frequency vibrotactile stimulation, and so on. However, for simplicity, this paper focuses on haptic assistance for force-feedback interaction at a single point.

Program code for controlling a haptic device often specifies how to compute a force that should act on the haptic device in response to the device’s current and prior positions. For simulating a simple virtual environment, the code can implement the laws of physics relating to interacting with a virtual environment. However, the haptic systems programmer has the power to invent new lines of code to simulate systems that would not readily exist in nature, including nonpassive systems, unusually nonlinear systems, or systems whose model parameters may be time varying. For example, a force can be computed in such a manner to assist a user in selecting targets, which is the focus of this paper.

Section 2 provides a brief review of some prior work in haptic assistance for graphical user interfaces. Section 3 describes haptic assistance for selecting discrete notes from a continuous range on an audio interface. Section 4 explains the user test experiment design and results, while Section 5 provides general conclusions with respect to haptic assistance.

2 HAPTIC ASSISTANCE USING DETENTS

2.1 Basic Detent

A haptic widget is a user-controllable element of a GUI that provides haptic feedback to augment the user’s interaction with the element [1], [2]. The haptic “detent” is one of the most basic haptic widgets. A detent implements an attractive force field of haptic assistance around a single point [3]. Fig. 2 illustrates the force field for a basic piecewise linear detent in a single dimension. Near the center of the detent at \( y = 0 \), the force in the \( y \)-axis behaves like that of a spring, pulling the haptic device back toward \( y = 0 \). The force level decreases back to zero when the
position $y$ moves further from the detent’s center (see Fig. 2). By expanding this concept with similar force fields, other kinds of haptic widgets and haptic assistance can be implemented for a GUI with multiple buttons, pull-down menus, windows, scroll bars, and so on.

### 2.2 Prior Work

As early as 1994, Engel et al. [5] tested a custom force-feedback mouse, which they found was relatively easy to learn to use. Furthermore, it reduced errors and completion time for users navigating through a maze when the force fields pushed the mouse away from the maze walls. Around the same time, Akamatsu and Sato designed a “multimodal mouse” with vibrotactile actuation and controllable friction. They found that vibrotactile stimulation and increased friction over a target enabled subjects to reach a single target faster on average [6]. Later, Dennerlein et al. [7] also studied the benefits of force feedback to aid a user in steering along a menu. Similar kinds of force feedback have been studied for three-dimensional CAD applications too [8], [9].

In a pilot study, Rosenberg showed that subjects had reduced task completion times when presented with attractive force fields pulling toward buttons, the centers of pull down menus, and the centers of scroll bars [10], [11]. Later, Miller and Zeleznik [1] determined some guidelines for haptic augmentation of the X Windows GUI. However, they found haptic feedback for the menus to be particularly problematic. For instance, they implemented force feedback providing guidance away from the menu target boundaries; however, they found the force feedback to be distracting when the user wanted to pass over multiple boundaries to reach a more distant target—for instance, the user could overshoot the intended target.

### 2.3 Detents Can Be Distracting

Other distracting targets can cause users to temporarily “get stuck” in an unintended target, increasing user frustration and effort required to complete tasks [12], [13]. Some researchers have suggested making the magnitude of the haptic assistance depend on the speed [14], [2]. In particular, Picon et al. [15] suggested reducing the haptic assistance to zero at low speeds and high speeds. However, they did not believe that they had chosen the best parameters for this strategy. Hwang et al. [16] found that no velocity dependence was necessary for motion-impaired users to benefit from having multiple targets.

Nevertheless, modulating the strength of the haptic assistance would seem promising, especially if the intended target could be known [12]; however, Oirschot and Houtsma [17], [18] concluded that correct target prediction depended both on the haptic device and the user. Münch and Dillmann [19] also found target prediction to be user-dependent and application-dependent.

Unfortunately, any target prediction or user intention prediction scheme will occasionally make some errors. Passenberg et al. suggested employing Hidden Markov Models (HMMs) to estimate the user’s intention; however, HMMs employ a statistical technique to make classifications, so they are subject to errors. Furthermore, Passenberg et al. [20] observed that if “the task classification does not switch back . . . fast enough, the wrong classification can even lead to instability,” implying that instability problems can even arise due to classification errors.

The errors described above could contribute to a change in the feedback control that the user could not always anticipate. Since the user employs forward control of the human motor control system for making fast movements [21], the user might not be able to completely correct for the error while making a fast movement. This drawback seems particularly problematic for the application of increasing the speed with which a user can operate a GUI, where fast movements are required.

### 2.4 User Control of Haptic Assistance

Accordingly, this paper proposes to enable the user to control the strength of the haptic assistance by himself or herself. In other words, the user should be able to adjust the strength of the haptic assistance in real time via an additional sensed quantity (see the FRC condition in Section 3.5.3).

### 3 Haptic Assistance for Fundamental Frequency Selection

#### 3.1 Selecting Fundamental Frequencies

Similar to GUI users selecting items from linear menus, musicians also commonly select fundamental frequencies on linear interfaces. For example, string instruments and trombones provide their players with the freedom to choose fundamental frequencies from a continuous range. However, given any standard tuning system as a reference, only a discrete set of fundamental frequencies is considered to be in tune. Hence, the freedom of the continuous pitch range can be troublesome, especially for beginners who have trouble playing in tune. The use of frets, dividing the fingerboard of plucked string instruments (e.g., guitars, lutes) into fixed segments, makes it much easier to achieve good tuning. However, continuously controlled fundamental frequency inflections such as glissandi or vibrato, which
can greatly contribute to the expressivity of music, can only be played to a limited extent on a fretted instrument. The use of both fretted and fretless electric basses, for instance, illustrates the tradeoff between the freedom of selecting fundamental frequencies from a continuous range and the ease of playing in tune with discrete selection.

Consequently, it would be desirable to provide a musician with haptic assistance in selecting fundamental frequencies on a continuous interface to help overcome this tradeoff, combining the advantages of instruments with discrete and continuous pitch selection. Fig. 3 depicts the metaphor of a cellist playing a real cello and receiving haptic assistance for selecting fundamental frequencies.

3.2 Relation to Learning
A system that assists a user in selecting fundamental frequencies could conceivably assume the role of a virtual teacher. Indeed, prior research has addressed the application of using force-feedback systems to teach how to play certain pieces of music [22] or more generally motor skills [23], [24], which could be used for playing a musical instrument. However, we would like to emphasize that this is not the direct goal of this work. Instead, with this research, we seek to learn how active haptic feedback can assist a user playing a musical instrument in real time. We can create more knowledge about designing new, futuristic or augmented musical instruments that are easier to play.

Theories about learning are nonetheless important because learning can affect how human subjects perform using novel musical instruments. Fitts proposed that humans progress through three phases as they learn to master a new motor skill [21], such as playing a new instrument. During the first cognitive phase, the learner focuses on understanding how to complete the task. He or she must individually consider how to complete each of the subtasks to complete the overall task. Nothing is automatic, and the learner will make many errors during the cognitive phase. The second learning phase is the associative phase, which begins once the learner has determined the best way of doing the task. During the associative phase, the learner knows how and when to complete each of the subtasks, so the learner can focus on making smaller adjustments. However, he or she still must concentrate to achieve the goal, and some errors will still occur. Finally, in the final and autonomous phase of learning, the learner no longer needs to concentrate and performs the task automatically making very few errors.

3.3 Theremin Hypothesis
As a thought experiment, it is intriguing to consider the qualities of a musical instrument that provides no haptic feedback at all. For instance, the Theremin musical instrument’s sound is controlled by the orientation of the hands when held in free space [25]. In an approximate sense, the position of one hand controls the volume, and the position of the other hand controls the fundamental frequency of the single note output. Although the player receives proprioceptive feedback regarding the position of the hands, the player receives no haptic feedback from the instrument itself.

On a technical level, one can argue that playing the Theremin accurately should be difficult because on a rudimentary level, it involves making pointing movements in free space. However, there is a well-known tradeoff between the speed of human pointing movements and their accuracy [21]. This implies that the Theremin can only be accurately played if the pointing motions are sufficiently slow, which can hamper one from playing fast melodies on the Theremin.

In general, we hypothesize that

“if a musical instrument does not provide any haptic feedback at all, it will probably be difficult to play accurately.”

We term this hypothesis the “Theremin hypothesis.” We base this hypothesis partially on experience we have in teaching a course at Stanford University on the design of novel electronic musical instruments [26]. When advising student projects, we have found it fruitful to attempt to prevent students from making instruments with continuous control of the fundamental frequency without haptic feedback, because such instruments can have a tendency to be difficult to play.

We base the Theremin hypothesis also on prior work by Sile O’Modhrain. O’Modhrain studied the accuracy with which users can select fundamental frequencies with a Theremin-like haptic interface. She compared how accurately test subjects could select fundamental frequencies given the complete absence of haptic feedback from the instrument versus several kinesthetic haptic feedback conditions such as a spring force, a viscous damping force, and a constant force. She concluded that the

“existence of force feedback in a computer-based instrument marginally improves performance of a simple musical [fundamental frequency selection] task” [27].

3.4 Theremin-Like Haptic Musical Instrument
For the purpose of evaluating haptic assistance for fundamental frequency selection, we designed an example Theremin-like haptic musical instrument using the Phantom Model T haptic device [28]. Setting up the instrument precisely according to the idealized representation in Fig. 3.
would have been challenging, so instead the musical instrument was simulated via the haptic device.

We strove to make the virtual instrument as simple as possible. Although the haptic device was designed to move in three dimensions, we restricted motion of the device to the $y$-axis and simultaneously measured the force applied normal to this axis in the vertical $z$-direction (see Fig. 4). The user’s index fingertip was connected to the haptic device by a thimble. The user could rest his or her wrist on the white piece of wood placed horizontally across the table as shown in Fig. 4. For simplicity, the user could adjust only the fundamental frequency of the sound—there was no volume control. Sound was synthesized using additive synthesis with sinusoidal components at one times, two times, and three times the fundamental frequency [29].

Due to the finite workspace of the haptic device, the horizontal position $y$ (see Fig. 4) of the user’s finger could vary over about 20 cm and was mapped to the logarithm of the fundamental frequency of the musical instrument. This mapping allowed the distance between each pair of adjacent half steps to be about 0.75 cm. Higher fundamental frequencies were further to the right, as with the pianoforte. However, in comparison with the pianoforte, each octave on the Theremin-like instrument spanned roughly half the physical distance due to the workspace constraints of the Phantom Model T.

### 3.5 Force Feedback Conditions

We developed specific haptic force-feedback conditions for the subject test, with the goal of determining which condition could most effectively assist users in selecting fundamental frequencies [28]. Because the fundamental frequency was controlled by the $y$-position, we considered force feedback conditions that exerted forces in the lateral $y$-axis as a function of the current and past $y$-positions of the thimble, as well as the downward force $p$ exerted by the user’s finger in the $z$-axis (see Fig. 4).

#### 3.5.1 Multiple Detents (DET)

The multiple detents DET condition was designed to help orient the user and assist the user in selecting fundamental frequencies from the discrete set of equal tempered frequencies. The basic detent described in Section 2.1 was extended to assist the user in playing multiple discrete notes from a diatonic scale.

Fig. 5 shows the piecewise-linear force field for the first five notes of the scale, which was employed in the subject test. A force field was centered around each note, making the corresponding $y$-position a locally stable equilibrium point, as denoted by the dashed blue circles in Fig. 5. In between each pair of notes, the forces were tapered toward one another to avoid creating any distracting discontinuities. The detents were made as wide as possible to ensure that haptic assistance was provided for the largest set of positions $y$. Since there was a semitone instead of a whole tone in between “mi” and “fa,” the force field was warped to retain the same form (see Fig. 5).

Metaphorically, the multiple detents DET condition can be thought of as corresponding to frets of a guitar. On a single guitar string, as one moves upwards along the guitar neck playing ascending tones, the frets become closer together to satisfy the physical tuning relation for a guitar string [30]. In contrast, DET was not bound by this physical constraint, so we simplified the mapping for multiple detents DET by keeping the semitones equally spaced along the $y$-axis. However, because the diatonic scale does not include some of the semitones, DET did not include detents for the unneeded semitones. Consequently, there were only two possible distances between neighboring tones of the scale (note the two possible distances in between neighboring blue dashed circles in Fig. 5).

#### 3.5.2 Calibrating DET Parameters

Only limited prior information was available on tuning the precise shape of the basic detent element upon which DET was based. For instance, Moss and Cunitz [31] employed a sinusoidally shaped detent element, but they did not compare it with other detent shapes. Other researchers conducted more elaborate tests and reported that nonlinearly altering the shape of a piecewise linear detent manifested itself psychophysically as primarily an intensity difference [9]. Discontinuities in the shape of the detent were also reported in some cases to detract from the feedback system stability [9]. Informally, we found that discontinuities could lead to sudden or jerky motions that could seem unnatural.

Consequently, we employed the piecewise linear detent element and completed a calibration procedure to help us fine tune the parameters for the basic piecewise linear detent element, upon which the DET and FRC conditions

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1. Although we did not experimentally test other force fields for related detent conditions, we believe that they could be equally valid, particularly if they are similar. For instance, DET could simply be shifted left or right for assistance in playing the other seven modes of the diatonic scale. Alternatively, assistance could be provided for the chromatic scale by warping DET so that the distance between all detents centers (then 12 per octave) would be the same as the distance between ”mi” and ”fa” in Fig. 5, or the whole tone scale could be rendered by making the distance between all detent centers (then six per octave) the same as the distance between ”do” and ”re,” as shown in Fig. 5.

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Fig. 4. User’s finger inserted into the thimble of the Phantom Model T.
either side of the detent was independent of
in real time. In other words, rather than trying to infer from
the user could regulate the strength of the haptic assistance
2.3) [2], [13]. We proposed a new approach, in which
presence of multiple detents could be problematic because
Past experiments by other researchers indicated that the
energy change
maximum force level (see Fig. 6). Note that the potential
for any horizontal position
 depended. The element was described mathematically as

\[ F_{DET}(y) = -\text{sign}(y) \cdot \begin{cases} 
\frac{|y| D}{\rho W} & \text{if } |y| < \rho W \\
(1 - \rho)W & \text{otherwise.} 
\end{cases} \]  

(1)

\[ W = \frac{\text{half of the width of the detent}, D \text{ described the}}{\text{maximum absolute value of the force, and the parameter}} \]
\[ \rho \in (0, 1) \text{ adjusted the } y\text{-position corresponding to the}
\]
\[ \text{maximum force level (see Fig. 6). Note that the potential}
\]
\[ F_{DET}(y) \text{ required to move the thimble through}
\]
\[ \text{either side of the detent was independent of } \rho:
\]
\[ E_{DET} = \int_0^W F_{DET}(y)dy = -\frac{WD}{2}. \]  

(2)

\[ W = 0.375 \text{ cm was already fixed approximately due to the}
\]
\[ \text{workspace size and the desire to allow subjects to play over}
\]
\[ \text{a range of about two octaves. We employed a simple test}
\]
\[ \text{with an ascending diatonic scale and descending continuous}
\]
\[ \text{glissando to initially choose } D = 0.41 \text{ N and } \rho = 0.3.
\]
\[ \text{For more details, see Section 7.7.3 of Berdahl’s doctoral}
\]
\[ \text{dissertation [32]. There was a clear tradeoff in choosing}
\]
\[ \text{if } D \text{ was too large, then the haptic assistance was so strong}
\]
\[ \text{that it prevented the user from being able to play smooth}
\]
\[ \text{glissandi with DET. On the other hand, if } D \text{ was too small,}
\]
\[ \text{then the haptic assistance did not clearly aid the user in}
\]
\[ \text{selecting fundamental frequencies.}
\]
\[ \text{During later pilot tests with the melody excerpts, we}
\]
\[ \text{made the parameters slightly more focused by reducing } \rho \text{ to}
\]
\[ 0.2. \text{This slightly more aggressive parameterization worked}
\]
\[ \text{well when tested by the first author for the excerpts shown.}
\]
\[ \text{We had the impression that reducing } \rho \text{ may have lessened}
\]
\[ \text{the tendency to get stuck in unintended detents, but we}
\]
\[ \text{made no attempt at verifying this formally. In informal}
\]
\[ \text{testing, altering } \rho \text{ also changed the way the detents}
\]
\[ \text{“felt”—in some sense, it changed their texture. The basic}
\]
\[ \text{detent element with the finalized parameters } \rho = 0.2, W =
\]
\[ 0.375 \text{ cm, and } D = 0.41 \text{ N is shown in Fig. 6.}
\]

\[ \text{3.5.3 Force-Sensitive Detents (FRC)}
\]
\[ \text{Past experiments by other researchers indicated that the}
\]
\[ \text{presence of multiple detents could be problematic because}
\]
\[ \text{users could “get stuck” in interfering detents (see Section}
\]
\[ 2.3) [2], [13]. We proposed a new approach, in which}
\[ \text{the user could regulate the strength of the haptic assistance}
\]
\[ \text{in real time. In other words, rather than trying to infer from}
\]
\[ \text{whether the user required assistance [2], [13], [14], [15],}
\]
\[ \text{[16], the user could specify directly how much assistance he}
\]
\[ \text{or she should receive. The simplest approach was to allow}
\]
\[ \text{the user to control the degree of haptic assistance with the}
\]
\[ \text{downward force he or she applied to the thimble. The FRC}
\]
\[ \text{condition was configured so that the user only received}
\]
\[ \text{assistance when he or she requested it by pressing}
\]
\[ \text{downward with force } p > 0. \text{ If the user instead pulled the}
\]
\[ \text{thimble even slightly upward (i.e., } p < 0), \text{ then no haptic}
\]
\[ \text{assistance was provided, allowing the user to easily glide}
\]
\[ \text{over any otherwise possibly distracting intermediate}
\]
\[ \text{detents. Mathematically, } F_{FRC}(y, p) \text{ was defined as follows:}
\]
\[ F_{FRC}(y, p) = F_{DET}(y) \cdot \alpha(p), \]  

(3)

so that the strength of the detents was modulated by \( \alpha(p) \),

\[ \text{as shown in Fig. 7, in which the constants } l > 0 \text{ and } M_0 > 0
\]

\[ \text{[28], [32]. The parameter } M_0 \text{ scaled the maximum detent}
\]
\[ \text{strength to prevent the detents from becoming unreason-
\]
\[ \text{ably strong if the user ever pressed down particularly hard.}
\]

\[ \text{3.5.4 Spring Force (SPR)}
\]
\[ \text{For comparison with O’Modhrain’s experiment, we included}
\]
\[ \text{the SPR condition, with } F_{SPR}(y) \text{ describing a spring}
\]
\[ \text{with stiffness } k_y:
\]
\[ F_{SPR}(y) = -k_y(y - y_0). \]  

(4)

The spring rest position \( y_0 = -5 \text{ cm placed the virtual spring}

\[ \text{center near the left edge of the workspace. This caused the}
\]
\[ \text{spring with relatively small stiffness } k_y = 0.07 \text{ N/cm to exert}
\]
\[ \text{a force to the left over the entire range of the discrete notes}
\]
\[ \text{that subjects should play during the subject test.}
\]

\[ \text{3.5.5 No Feedback (NOFB)}
\]
\[ \text{We further introduced a control condition, in which the}
\]
\[ \text{force in the } y\text{-dimension was set to zero to model the}
\]
\[ \text{original Theremin:}
\]
\[ F_{NOFB}(y) = 0. \]  

(5)

\[ \text{4 Subject Test}
\]
\[ \text{To verify the efficacy of haptic assistance in this application, we}
\]
\[ \text{conducted a formal subject test. Human test subjects}
\]
\[ \text{were asked to play simple melody excerpts on the haptic}
\]
\[ \text{interface. We hypothesized that subjects would be able to}
\]
\[ \text{select fundamental frequencies more accurately with the}
\]
\[ \text{DET and FRC force-feedback conditions than with the SPR}
\]
\[ \text{2. Since earlier work [28], [32], Passenberg et al. [33] have apparently}
\]
\[ \text{independently developed a similar equation for controlling the strength}
\]
\[ \text{of haptic assistance although the application is different.}
\]
and NOFB conditions, while DET would contribute to significant bumpiness of the frequency trajectories in contrast with the other conditions. We selected six simple melody excerpts for testing all of the subjects. Hence, the independent variables for the experiment were the force-feedback condition and the melody excerpt number, and the dependent variables were the mean absolute error (MAE) of the fundamental frequency trajectories (MAE, see Section 4.2.1) and the bumpiness (see Section 4.2.2). To verify that haptic assistance did not necessarily prevent subjects from playing smooth fundamental frequency inflections, as is characteristic to the Theremin’s instrumental practice, each melody excerpt also contained a continuous glissando in addition to a series of discrete notes (see the online supplementary material, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/ToH.2012.55).

4.1 Design

The experimental design was motivated primarily by the desire to obtain data that could be compared across subjects, even if some learning effects could possibly be observed in the data (see Section 3.2). Seven subjects were recruited from the Stanford Symphonic Orchestra and nine subjects were recruited from the M.S. and PhD programs at the Center for Computer Research in Music and Acoustics (CCRMA) at Stanford University. Of the 16 subjects total, one was left-handed and five were female. The total time commitment required of each subject was about one hour, on average, and each subject was compensated with $20 for his or her efforts.

Each subject was presented with a sheet containing the seven simple excerpts. One excerpt was for training, while the remaining six excerpts were for testing (see the online supplementary material). All of the subjects played the same seven excerpts total. To help the subject learn the excerpts before being tested, the subject was asked to initially play them twice on a standard piano keyboard-based instrument.

During training, the subject was also introduced to the haptic musical instrument described in Section 3.4. The subject was asked to feel each condition using his or her right hand, while the operation of the condition was explained. The subject was instructed to try to employ the following strategy when using the FRC condition:

- press down slightly when playing small intervals and lift up slightly or maintain a neutral hand weight when playing larger intervals or continuous glissandi.

Then, the subject went through a training process with the haptic musical instrument, in which the subject learned how to record his or her performance of the single training melody excerpt for each of the four conditions. The entire training process took about 15 minutes for each subject.

Finally, during the test phase, the subject experienced each of the four force conditions. To minimize the ordering effects of the subjects’ being tested on one condition before another, the conditions were presented across subjects according to a balanced Latin square. For each force condition, the subject recorded himself or herself performing each of the six test melody excerpts. If the subject was dissatisfied with any performance, he or she could immediately rerecord the performance. We employed this process because of its similarity to the process of recording a piece of music in a studio, in which a studio musician can rerecord a part in a piece until he or she is satisfied. Hence, for each of the 24 condition-excerpt pairs per subject, only the data from the last performance were retained.

4.2 Data Analysis

The fundamental frequency trajectories played by the test subjects were analyzed to evaluate the tuning of their performances. To employ a unit approximately reflecting how humans perceive the tuning, we represented the fundamental frequency using MIDI note numbers. The MIDI note number for “middle C” is 60. Since each unit of the MIDI scale represents a half step, the first C# above middle C has the MIDI note number 61, the first D above middle C 62, and so forth.

Let \( F_s(m, c, t) \) be the fundamental frequency trajectory played by subject number \( s \), where \( m \) indicates the excerpt, \( c \) indicates the condition, and \( t \) is time in seconds. To obtain an estimate of the discrete note sequence that a subject intended to play, we quantized the measured MIDI note trajectory to the nearest MIDI notes from the C major scale (for example, see the red dash-dotted trajectory in Fig. 8a and note that it never takes on the values 68, 70, or 73 because these notes are not included in the C major scale). There was a tendency to detect some spurious notes, especially at transitions between distant notes. For this reason, all detected notes with durations shorter than 0.2 sec were eliminated, starting with the longest of these spurious notes first. As each spurious note was eliminated, it was replaced by its neighbors, where the transition time between neighboring notes was chosen to minimize the fundamental frequency error measure. The output from the quantization algorithm was named Estimated Intended Notes, or EIN.

4.2.1 Mean Absolute Error

The MAE between the EIN trajectory and the actual performed fundamental frequency trajectory was employed to evaluate the tuning accuracy for each melody performance. This error measure was selected because it did not emphasize the inevitably large error contributions stemming from note transitions, but rather it focused more on the typically more constant error contributions from within notes (for example, visually inspect the difference between the solid blue and dash-dotted red trajectories in Fig. 8a). Mathematically, the MAE of the fundamental frequency trajectory from time \( T_1 \) to time \( T_2 \) is

\[
MAE_s(m, c) = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} |F_s(m, c, t) - EIN(F_s(m, c, t))| dt.
\]

(6)

\( T_1 \) and \( T_2 \) denote the segmentation time boundaries of the discrete notes played prior to the glissando during the excerpt. The segmentation was carried out manually for each performance to minimize the influence of slight timing differences on the MAE.

4.2.2 Bumpiness

We wanted to study to what extent detents caused the user to play bumpy or jagged fundamental frequency inflections
rather than smooth fundamental frequency inflections. To this end, the portion of each performance corresponding to a continuous glissando was manually segmented, for instance corresponding to the thick green trajectories in Fig. 8. The bumpiness was estimated using the root-mean-squared (RMS) estimated acceleration of the fundamental frequency trajectory \( \tilde{F}_s(m, c, t) \) during each continuous glissando, where \( [T_3, T_4] \) denoted the segmentation time interval of the glissando:

\[
Bumpiness_s(m, c) = \sqrt{\int_{T_3}^{T_4} \tilde{F}_s^2(m, c, t) \, dt}. 
\]  

4.3 Qualitative Results

The fundamental frequency trajectories for subject seven and excerpt five are shown in Fig. 8. These trajectories illustrate some behavior typical of the test subjects. Of course, the performances differed among the subjects and excerpts, but the statistical analysis in Section 4.4 confirms important trends in the data.

Fig. 8a shows the trajectory for the NOFB condition, for which no haptic feedback was provided. The subject’s trajectory is shown in blue, while the EIN are shown in dash-dotted red. Finally, the continuous glissando portion is indicated by the especially thick green line. The subject was able to perform the melody; however, the performed and intended discrete notes do not match up well together. As a consequence, the \( MAE_S(5, NOFB) = 0.43 \) was relatively large. In other words, the mean absolute fundamental frequency error was about 0.43 half steps, or 43 cents. The performance was similar in the case of spring SPR feedback (see Fig. 8b). We believe that the NOFB and SPR conditions resulted in large fundamental frequency MAE because NOFB and SPR provided no physical indication guiding toward the tuned note locations.

In contrast, the multiple detents DET condition caused the performed fundamental frequency trajectory to match the intended note sequence much better as evidenced by the decreased \( MAE_S(5, DET) = 0.23 \) (see Fig. 8c). However, the detents were strong enough that the glissando was somewhat jagged or bumpy (see the thick, green line in Fig. 8c). The relative elevation of the \( Bumpiness_S(5, DET) = 37 \) indicated the same tendency.

The performance for force-sensitive detents FRC is shown in Fig. 8d. The test subject modulated the strength of the detents appropriately. The discrete notes were selected accurately with the help of haptic assistance, while the glissando was smoother than for DET because the test subject was able to decrease the haptic assistance when desired.

4.4 Results

We performed a statistical analysis with the data to verify the significance of the findings across all subjects and excerpts. Due to the small number of test subjects, no attempt was made to remove outliers from the data set. Since the MAE and Bumpiness values for each condition were
neither normally distributed nor homogeneous in variance, the nonparametric Friedman test was performed, which showed that the both the MAE ($p_{\text{MAE}} < 0.001$, Kendall’s $W_{\text{MAE}} = 0.81, 3 \text{ df}$) and Bumpiness ($p_{\text{Bump}} < 0.001$, Kendall’s $W_{\text{Bump}} = 0.42, 3 \text{ df}$) depended significantly on the force-feedback condition. In addition, posthoc Wilcoxon signed-rank tests were performed to check the significance and effect size of differences between all pairs of conditions (see Tables 1 and 2). The effect sizes were determined by dividing the corresponding Wilcoxon signed-rank $Z$-values by the square root of the number of samples.

### 4.4.1 Analysis of MAE

Fig. 9 shows a box plot of the MAE for selecting the fundamental frequencies of discrete notes according to the four different conditions, indicating medians and interquartile ranges (IQR). The whiskers indicate the lowest/highest datum within 1.5 IQR of the lower/upper quartile, while the red plus signs represent outliers. The paired comparison tests showed that the MAE was significantly different for all pairs of conditions except for (NOFB, SPR) and (DET, FRC) (see Table 1). We believe that the NOFB and SPR conditions resulted in relatively large fundamental frequency MAE because they provided no physical indication guiding toward the tuned fundamental frequency locations. In contrast, subjects performed significantly more accurately with the detent-based conditions FRC and DET, as indicated by the significantly decreased MAE represented in Fig. 9. Subjects seemed to perform more accurately with FRC than DET, presumably because they less frequently got distracted by or stuck in interfering detents; however, this result was not statistically significant (see Table 1).

### 4.4.2 Analysis of Glissando Bumpiness

The analogous results from the bumpiness analysis of the continuous glissandi are depicted in Fig. 10. Two of the outliers (one for DET and one for FRC) were cropped away from the box plot to aid the reader in focusing on the remaining data. The paired comparisons showed as expected that DET caused significantly bumpier dynamics than NOFB and SPR. Obviously, the detents, which helped the test subjects select the fundamental frequencies of discrete notes accurately, interfered with playing continuous fundamental frequency inflections such as glissandi. In other words, the detents affected the dynamics of the subject coupled to the feedback system. However, Fig. 10 suggests that the force-sensitive detents FRC condition resulted in a decreased (although not statistically significant) bumpiness compared to DET. Since the test subjects were able to modulate the strength of the detents for the FRC condition, the haptic assistance did not cause them to play excessively jagged or bumpy glissandi.

In theory, the glissando bumpiness for NOFB and SPR could have been approximately the same as for FRC if the subjects had learned to optimally adjust the strength of the haptic assistance. We would expect that the bumpiness of FRC could have been reduced relative to the other conditions with more rigorous training, which would however risk further fatiguing the subjects prior to testing (see Section 4.1).

### 4.4.3 Residual Learning

The experiment aimed to test subjects only after they progressed beyond the first phase of learning (see Section 3.2) so that they would not record a large number of errors due to their limited experience with the setup.
performed an analysis to verify that any additional learning occurring during testing had only a small effect on the recorded data. The analysis studied the dependency of the MAE on the test trial index, i.e., the chronologically ordered number of the satisfactorily recording performance by the test subject. We performed an affine regression of the MAE as a function of the test trial index across all subjects. The affine regression model showed that subjects improved by 0.01 half steps (i.e., 1 cent), on average, over the course of the entire testing procedure. This learning was, however, dwarfed by the much larger task MAE (see Fig. 9). We conclude that, on average, the subjects’ continuing to learn during testing had only a negligible effect on the experimental data over the course of the test.

4.4.4 Questionnaire

The 16 subjects were asked to order the conditions from the most preferable (“4”) to the least preferable (“1”) for playing continuous glissandi as well as for playing discrete notes. The corresponding rank distributions are represented in Figs. 11 and 12, which incorporate the median ranks, IQRs, standard whiskers, and outliers. The Friedman test showed that the rank orderings depended significantly on the force-feedback condition for playing both notes ($p_{Notes} < 0.001$, Kendall’s $W_{Notes} = 0.53$, 3 df) and glissandi ($p_{Gliss} = 0.002$, Kendall’s $W_{Gliss} = 0.31$, 3 df). Differences in rank order were analyzed using a Wilcoxon signed-rank pairwise difference test with Bonferroni correction, the results of which are shown in Tables 3 and 4.

For playing notes, only the (FRC, NOFB), (FRC, SPR), and (DET, NOFB) differences in rank were significant, indicating that the subjects tended to prefer the FRC and DET conditions for selecting notes (see Fig. 11). This result implies that even with minimal amount of training for a nonphysical and unusual condition such as FRC, subjects can prefer this kind of haptic assistance. For playing glissandi, DET was the only condition that was preferred significantly less than all of the other conditions (see Fig. 12 and Table 4). In particular, subjects significantly preferred to play glissandi with the FRC condition over the DET condition, implying that the subjects tended to prefer the ability to modulate the haptic assistance strength.

5 Conclusions

This work showed that carefully designed haptic assistance can help users perform significantly more accurately with an electronic musical instrument. In the framework of a subject test, we demonstrated that haptic detents (DET and FRC) can improve the accuracy with which users select fundamental frequencies over a linear range. Informally, we do not believe that our results would be especially sensitive to the parameterization of the basic detent element (see Section 3.5.2), although the strength of the detents are of particular significance, and generally speaking, we believe that detents need to be parameterized such that users find them to be comfortably calibrated for a given application.

In particular, force-sensitive detents FRC, which enable regulating the strength of haptic assistance in real time, can be significantly superior to a simple spring force SPR or no haptic feedback at all NOFB. By exerting more downward force, users can receive stronger haptic assistance from FRC, for instance when honing in on a specific note fundamental frequency or when playing a small interval. Conversely, FRC allows users to decrease the strength of haptic assistance, such as when playing large intervals or

![Fig. 11. Preferences for playing notes.](image1)

![Fig. 12. Preferences for playing glissandi.](image2)

<table>
<thead>
<tr>
<th>TABLE 3</th>
<th>p-Values and Effect Sizes from Applying Posthoc Wilcoxon Signed-Rank Tests of Preference Rankings for Playing Notes (See Also Fig. 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of preferences for playing notes</td>
<td>p-value</td>
</tr>
<tr>
<td>(SPR, NOFB)</td>
<td>0.09</td>
</tr>
<tr>
<td>(DET, NOFB)</td>
<td>0.006</td>
</tr>
<tr>
<td>(FRC, NOFB)</td>
<td>0.001</td>
</tr>
<tr>
<td>(DET, SPR)</td>
<td>0.054</td>
</tr>
<tr>
<td>(FRC, SPR)</td>
<td>0.002</td>
</tr>
<tr>
<td>(FRC, DET)</td>
<td>0.027</td>
</tr>
</tbody>
</table>

The comparisons for which the significance level did not satisfy the Bonferroni-corrected level of $p_{0.05/6} = 0.0083$ are grayed out.

<table>
<thead>
<tr>
<th>TABLE 4</th>
<th>p-Values and Effect Sizes from Applying Posthoc Wilcoxon Signed-Rank Tests of Preference Rankings for Playing Glissandi (See Also Fig. 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of preferences for playing glissandi</td>
<td>p-value</td>
</tr>
<tr>
<td>(NOFB, SPR)</td>
<td>0.96</td>
</tr>
<tr>
<td>(NOFB, DET)</td>
<td>0.002</td>
</tr>
<tr>
<td>(NOFB, FRC)</td>
<td>0.94</td>
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<tr>
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</tr>
<tr>
<td>(SPR, FRC)</td>
<td>0.56</td>
</tr>
<tr>
<td>(FRC, DET)</td>
<td>0.007</td>
</tr>
</tbody>
</table>

The comparisons for which the significance level did not satisfy the Bonferroni-corrected level of $p_{0.05/6} = 0.0083$ are grayed out.

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3. For more details, please consult Berdahl’s doctoral thesis [32, pp. 205-206].
continuous glissandi. While other researchers have previously suggested allowing the strength of haptic assistance to be automatically optimized [33], [20], we have demonstrated benefits of allowing the user to directly control the strength of haptic assistance in real time.

In the case of DET and FRC, the user is always in control, which is important for fast motions in which the human motor control system operates in a feedforward mode and cannot fully compensate for unexpected dynamics [21]. Fast motions are important not only for the expressive performance of music. For instance, we believe that FRC-type force feedback could effectively assist users in selecting items from menus in GUIs because users could temporarily reduce the strength of assistance, allowing them to glide over unintended menu items rather than inadvertently getting stuck [12], [13]. Furthermore, this work implies that valuable additions to force-feedback mice designs would include measurement of downward force, pressure, or other easily sensed parameters, which could be employed for adjusting haptic assistance strength in real time. The application of a force-feedback mouse could indeed turn out to be particularly beneficial because by some accounts, GUI users spend as much as half of their time with the mouse [34], [35].

Our experiment focused on playing melodies on the diatonic scale, but we believe that closely related force fields could be helpful for playing many other melodies and pieces. Future work could involve testing to what extent musicians can cope with detent positions that are dynamically moving, disappearing, and reappearing with time for assisting in playing very specific melodies. An instrument could even be imagined that learns over time how to respond haptically. Nevertheless, we believe that it is probably important not to present typical musicians with too many possible detent force fields because we believe they need to precisely understand the effect of the detents and they need time to learn to benefit from them. Nonetheless, dynamically changing detents could form an intriguing basis for composing and/or performing a modern and complex piece of avant-garde music.

In contrast to O’Modhrain’s suggestion that, for instance, “spring” haptic feedback SPR might help subjects perform more accurately than no haptic feedback NOFB (see Section 3.3), we did not observe a significant difference between the two conditions. However, several differences between the experimental setups could have contributed to this difference. While in both experiments the horizontal position along the edge of the table was mapped logarithmically to fundamental frequency [27], the 3-cm-long workspace for O’Modhrain’s experiment was considerably smaller than our workspace of approximately 20 cm. Second, in O’Modhrain’s experiment, each subject received haptic feedback at the hand only by touching the active part of the force-feedback device. O’Modhrain’s subjects usually did not even rest their elbow on the table. In contrast, in our experiment, each test subject could rest his or her wrist as desired upon a piece of wood placed horizontally at the edge of the table (see Fig. 4). Informally, we found the piece of wood necessary to prevent fatigue from the subject constantly holding his or her arm in mid-air to touch the haptic device; however, the piece of wood presented a passive haptic cue at the hand for our NOFB that was absent in O’Modhrain’s experiment. The complete absence of any other, even passive haptic cues, may have made the no force-feedback condition particularly challenging for test subjects in O’Modhrain’s experiment.

Haptic assistance has the potential to open up new application areas for haptics. Haptic assistance should be designed carefully, and users require sufficient training to learn how to benefit from it. In particular, effective haptic assistance does not necessarily correspond to systems found readily in nature, so haptic assistance, such as the FRC condition, may seem initially unfamiliar to subjects.

The best type of haptic assistance will certainly depend on the task and will, thus, have to be designed just as one designs a human-computer interface for a specific application. The current investigation suggests that user-regulated, force-sensitive detents can serve as an important new tool in the haptic designer’s tool chest.

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REFERENCES

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