JuxtaMIDI: Using Data Visualization to Pinpoint Mistakes in MIDI Practice Recordings

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Abstract— When a musician wants to practice their instrument, they often have to rely on their peers or an instructor to help them isolate mistakes in their technique. As an alternative solution, we are proposing a system to answer the following question: how can we leverage data visualization to pinpoint mistakes in music data? For the sake of scope, we have chosen to focus on MIDI recordings.

Index Terms—Music, Data Visualization, MIDI.

1 Introduction and Motivation

Music is a profession and hobby enjoyed by many people. Unfortunately, the field hasn't received a lot of attention from the technology community. To this day, musicians still practice their instruments with little to no benefit from technology.

One area of music that could really benefit from a technological upgrade would be practice. After all, practice is usually something that occurs alone without a lot of feedback. Without access to an instructor, musicians may find it difficult to self-assess their abilities. They could all benefit from some sort of tool to help pinpoint their mistakes.

In this project, we built a data visualization dashboard which can be used to compare practice MIDI files with professional MIDI files. The goal is to isolate areas in the practice file which are most unlike the professional file for the sake of improvement.

2 Related Work

While there was plenty of motivation for the project, we still needed to lay the ground work for the project. In particular, we had to come up with some research questions, design goals, tasks, and metrics which we could use to map out our implementation.

2.1 Research Questions

As mentioned previously, the major research question we looked to address is the following: how can we leverage data visualization to pinpoint mistakes in MIDI practice recordings?

Naturally, this question raises several underlying questions such as:

- What are practice areas and quantifiable data (pitch, tempo, etc.) that we can gleam from MIDI recordings?
- What are the most effective ways of visualizing those practice areas?
- What are our options in analyzing MIDI files to visualize MIDI events in a useful manner for musicians?
- How useful is comparing MIDI recordings via velocity, sustain, and note frequency over time graphs
- Can we algorithmically generate useful automated feedback from analysis of these MIDI recordings and graphs

In an effort to pinpoint mistakes, we wanted to find the best ways to represent our musical data, so the user would see value in the tool.

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2.2 Design Goals

At a high level, our goal was to construct a dashboard split into two panes: the file pane and the graph pane.

The file pane should contain a list of active MIDI files which are each given a color for encoding purposes. That means the dashboard should be able to support about 20 simultaneous MIDI files due to the limits of color perception. This should be more than enough considering the practicality of comparing that many recordings.

Each file in the file pane should be able to be selected for viewing purposes in the graph pane. When unselected, the file's background color should be neutral. When selected, the file's background color should mirror its color in the graph pane.

Meanwhile, the graph pane should contain several graphs:

- Notes versus Time (master graph)
- Notes versus Frequency
- Velocity versus Time
- Sustain versus Time

As a stretch goal, each graph should be connected with the master graph for filtering purposes. When a section of time is selected in the master graph, all other graphs should be updated to reflect the new subsection of data. This would allow a user to hone in on specific mistakes.

In addition, graphs should contain tooltips which will highlight areas with the highest amount of mistakes. These tooltips should include high level notes to assist the user in understanding the data.

Finally, the dashboard should be extended to include realtime recording and sheet music comparison.

2.3 Tasks and Metrics

In order to verify the success of the project, we tracked several tasks in GitHub:

- MIDI File Upload
- MIDI File Pane
- Notes versus Time Graph
- Notes versus Frequency Graph
- Velocity versus Time Graph
- Sustain versus Time Graph
- Mistake Analysis for Tooltips
- Realtime Recording
- Sheet Music Rendering and Comparison

Each of these tasks were broken down into smaller tasks as they all need to be designed, prototyped, and tested.

As for verifying that our design is good, we tested it on users of varying musical abilities. For less experienced individuals, we had them watch us interact with the tool through a demonstration where we collected feedback. For experienced musicians, we had them play a song to generate a MIDI file, then we asked them to indicate any mistakes they felt they made. Finally, we compared their personal insight to the tool.

2.4 Implementation

Ultimately, JustaMIDI ended up being a web-based tool built entirely as a static website using just JavaScript, CSS, and HTML.

2.4.1 Dashboard Overview

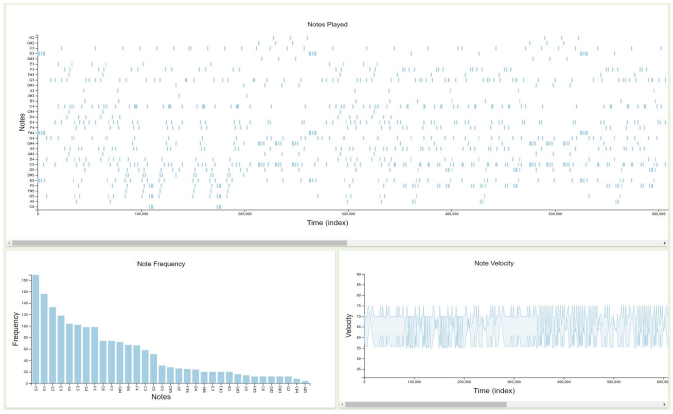

Fig. 1. The dashboard gives an overview of the music data in three forms.

In terms of general design, we went with a dashboard approach using CSS grids as seen in figure 1. In other words, we divided the space into four columns by percentage of screen width from left to right: 9%, 43%, 43%, and 3%. Likewise, we divided the space into two rows by screen height from top to bottom: 60% and auto.

Each dashboard element was then assigned some range of grid points that they could occupy. For example, the MIDI selection interface was given the entire first column. Likewise, the pane selection interface was given the entire last column. Meanwhile, the note graph was given the center two columns of the top row while the remaining graphs split the bottom row of the same columns.

2.4.2 MIDI Selection Interface

As mentioned, the entire first column was dedicated to the MIDI selection interface as seen in figure 2. This interface consisted of a single MIDI upload button and any number of MIDI file items.

The upload button works just like any file upload interface. When a file is uploaded, a callback function is executed. In this case, we parse the midi file, and pass that data to the respective graphs panes to be rendered. At the same time, we generate a MIDI file list item which allows us to interact with the loaded file in various ways such as:

- Changing its name
- Toggling it on/off
- Deleting it
- Playing/pausing it

In addition, it is at this point that we assign the file a color for encoding purposes in each graph. To aid in encoding, we color the background of the file element, so it matches any data associated with the file in the various graph panes.

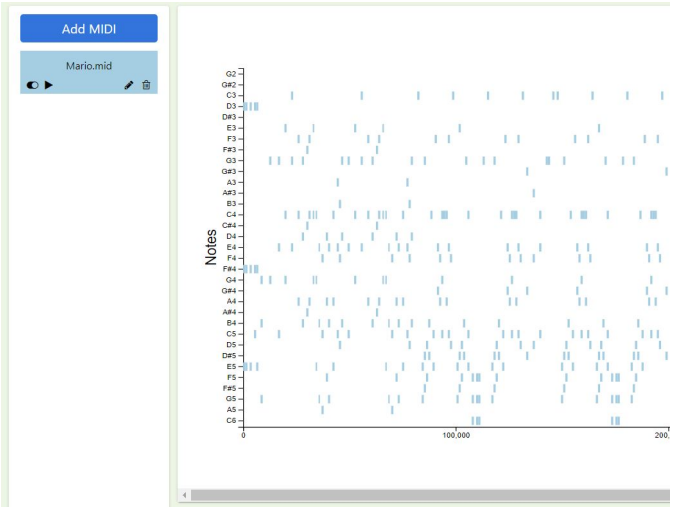

Fig. 2. The MIDI selection pane allows a user to interact with the music files.

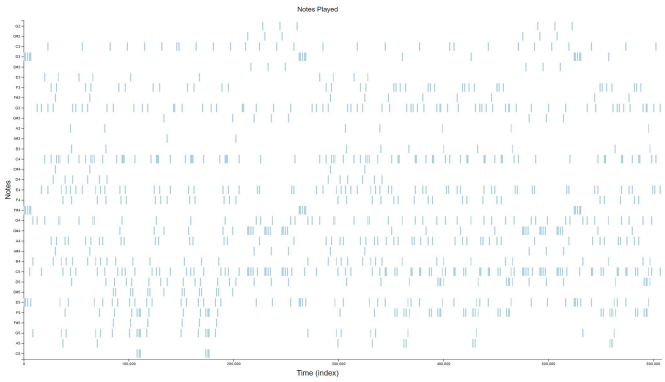

Fig. 3. The notes played pane shows the notes played over times.

2.4.3 Notes Over Time Pane

In the top pane, we render the notes over time graph as seen in figure 3. Each note is encoded in three visual channels: color, position, size. The color gives us the track mapping, so it should match whatever color the file was assigned in the MIDI selection pane. Meanwhile, the position encodes two pieces of information: note and time. Finally, the size encodes note duration.

When looking at this graph, it is helpful to imagine a piano along the y-axis. Lower pitches are near the top of the graph while higher pitches are closer to the bottom of the graph. Meanwhile, the x-axis gives us the duration of each note from the time it begins to the time it ends. Time is given as generic time units which gain meaning given a tempo. Finally, each note has a tooltip which gives information like note, start time, duration, and velocity.

To generate these features, we use a combination of open-source libraries, but the primary tool is D3 which allows us to create graphs from Scalar Vector Graphics (SVG). In particular, the notes over time graph is generated by extracting the note information from all active MIDI files and plotting the results against the axes as rectangles with the appropriate color.

2.4.4 Note Frequency Pane

In the bottom left pane, we render the note frequency graph as seen in figure 4. Here, we filter the MIDI file data, so we end up with a collection of notes. Each note corresponds to a number which we dynamically map to their respective letters using a lookup table (LUT). Using this mapping, we're able to generate a histogram of notes.

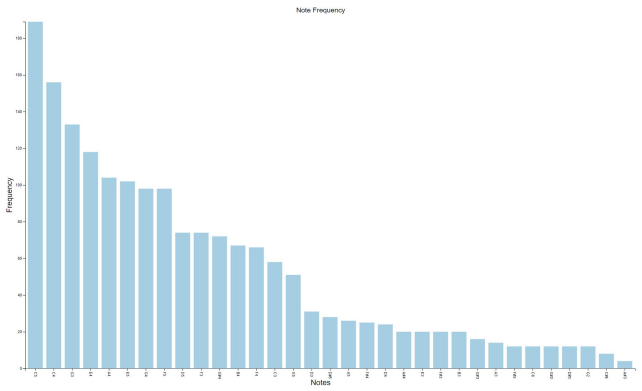

Fig. 4. The note frequency pane shows the occurence of all notes in each song.

Just like the notes over time plot, we also use D3 here to handle the bulk of the heavy lifting. At a high level, we use the note counts to plot rectangle against two axes: frequency and note. The frequency axis is scaled by the maximum note frequency over all active tracks. Meanwhile, the x-axis contains a direct mapping of all unique notes over all active tracks. We then sort that axis by the note frequency of the primary track.

2.4.5 Note Velocity Pane

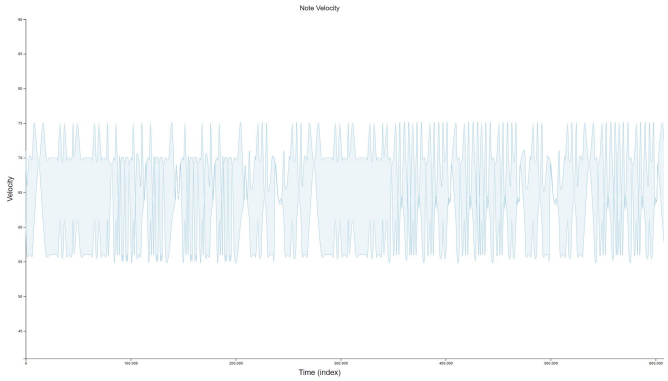

Fig. 5. The note velocity pane shows the range of note velocities over time.

While the other two plots were relatively straightforward, we had a lot of trouble deciding on the note velocity plot as seen in figure 5. Ideally, what we would like to be able to capture in this plot is dynamics. In other words, how can we show the ebb and flow of volume over time to the user. As it turns out, it is harder than it seems.

Initially, we tried summing the velocity of all the notes at each time step and plotting the results. Unfortunately, the resulting curve was pretty eratic. In fact, we noticed we few bizarre artifacts in the results like a downward slope over time which didn't make a lot of sense for a nearly constant volume song. Fortunately, someone pointed out that summing the velocities at each time step is bad practice because we aren't guaranteed to have the same number of key presses at any given time. In other words, the maximum volume is entirely dependent on the maximum number of keys played simultaneously.

To accomodate for this problem, we decided to try plotting the velocity range over time. The result contains two lines for each track where the space in between is colored based on the file color. As expected, the x-axis is in the same units as the notes over time plot, and the y-axis is raw velocity.

2.4.6 Plot Filtering Pane

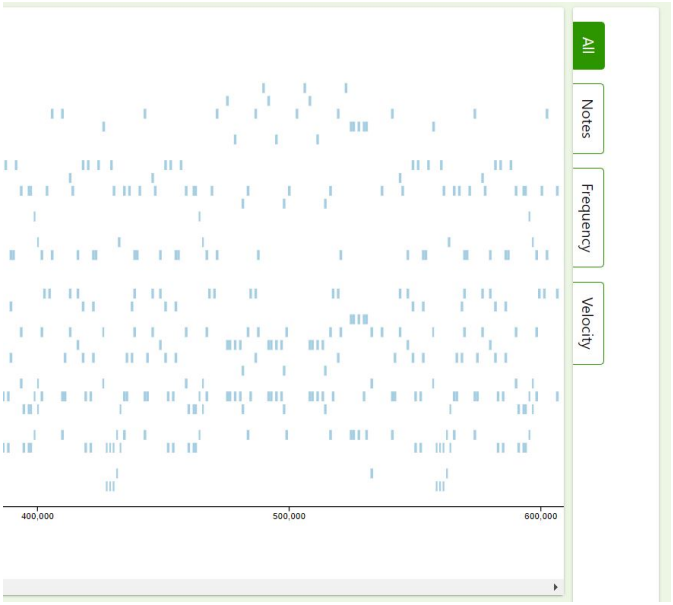

Fig. 6. The plot filtering pane allows a user to expand each plot for viewing.

Finally, we added a plot filtering pane which gives us control over which pane we can see at any given time as seen in figure 6. There are four options:

- All panes as described in the dashboard overview
- The notes over time pane alone
- The note frequency pane alone
- The note velocity over time pane alone

When a pane is selected alone, we fill the entire center two columns with that pane. For example, selecting the note frequency pane makes the other two graph panes disappear while the note frequency pane is expanded to fill the space.

2.4.7 Interactivity

Most of the interactivity elements are in the MIDI selection pane. However, we haven't discussed exactly how that interactivity works up to this point. To reiterate, there are four main ways to interact with each file: toggling, renaming, deleting, and playing.

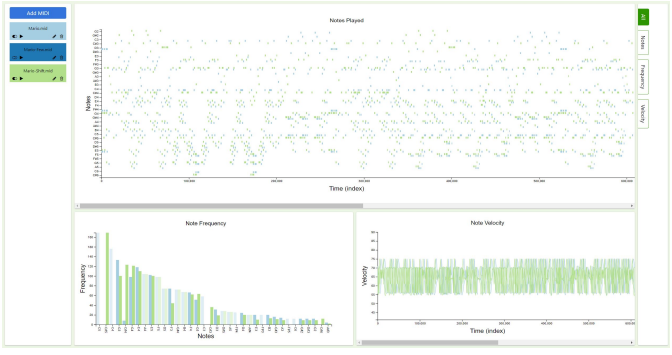

Fig. 7. An example of the dashboard with three music files–two active.

When we toggle a file, the state of that file changes based on its previous state. In other words, if we were originally showing a file in

all three graphs, toggling it would remove it from the graphs as seen in figure 7. Toggling it again would render in all three graphs once again. Meanwhile, deleting a file will remove the file from the program completely, and renaming a file updates all the tooltips.

In addition, users can play each file as well. When a file is playing, a marker is added to each time-domain graph (i.e. notes of time, velocity over time, etc.) along the x-axis. In addition, the marker is encoded with the color of the track currently playing. This is all handled through a callback function that hooks into the MIDI playback utility.

Likewise, users are able to filter by which graph they want to see as mentioned previously in the Plot Filtering Pane section. Finally, there are a few minor interactivity features like the ability to scroll along the x-axis of the time-domain graphs and the ability to hover over graph elements to show tooltips.

2.5 Environments

To complete this project, we required the following software:

- JavaScript: a web-based programming language
- D3.js: a data visualization library
- MIDI.js: a MIDI processing library
- GarageBand: a MIDI editing tool
- GitHub: a version control and project management tool
- Travis CI: a continuous integration tool for testing

With this software, we were able to build and test the entire system.

3 Design Method

Now that we have had the chance to discuss the background and related work, let's talk about our design choices and how we believe they effectively accomplish our tasks.

3.1 Data Abstraction

For our project, we were working with MIDI files which are event-based music files. In other words, we were not dealing with audio signals. Instead, we took a file format which stores music information like tracks, notes, velocities, and durations, and made sense of it visually.

Despite the fact that the MIDI file format already abstracts music signals, there still is a case to make to further abstract the data. For example, MIDI files are entirely in binary which means that they are not easy to read as a user. As a result, we used a utility to parse the MIDI file into a JavaScript object.

While the object itself was a bit easier to work with, the data still wasn't meaningful to our end user. For example, the resulting JavaScript object contained a lot of nested information about tracks and events but almost no clear information on how that data maps to musical notes, rhythms, and dynamics. To make matters worse, MIDI files store events using numeric codes, so the data is not easy to read. For example, how are we supposed to know what the following means:

- Type: 9
- Note: 47
- Velocity: (90, 0)
- Duration: 120

To do with this, we had to go up another level of abstraction using LUTs. For instance, it may be nice to know that a type 9 event indicates onset which marks the beginning of a note. It might also be helpful to know which note 47 is and exactly how to make sense of the velocity tuple.

Ultimately, we wanted the user to interact with the music in a way that they think about it on a daily basis: notes, rhythms, dynamics, chords, etc. To get there, however, we had to work I way up from binary MIDI files.

3.2 Task Abstraction

Typically, when musicians practice, they have two options: practice alone or practice with an instructor. When practicing alone, musicians don't really have a lot of options for getting feedback. In other words, there is only so much practice a student can do alone before they hit their potential limit. That limit is usually set by how well they can judge their own abilities. Meanwhile, practicing with an instructor is usually the best case scenario. Instructors can accurately pinpoint areas of improvement which the musician can focus on in their private studies.

Naturally, we wanted to fit somewhere in the middle with an automated visualization solution. In other words, the goal would be to allow a student to practice alone with a system which could provide some general feedback about their abilities.

To accomplish this, we had abstract some of the tasks of self-assessment like listening to self-made recordings and analyzing the results relative to a profession recording. The less experienced the musician, the more difficult the self-assessment task becomes.

As a result, we decided to build a visualization system which abstracts the self-assessment task. In other words, how do we take some of the cognitive overhead of making and comparing recordings and shift it to automation. The result was our JuxtaMIDI tool which allows a user to upload MIDI recordings and compare them visually, rather than aurally.

3.3 Design Considerations

Unfortunately, we have no way of perceiving sound at a global level. In other words, we can't hear an entire song at one time. Luckily, we can see the big picture, so if there is any way to demonstrate the global features of music visually, we would have an excellent tool for self-assessment. For example, a student may find it useful to compare their dynamics relative to a professional recording. Without being able to visualize a global feature like dynamics, the user would have to listen to both tracks and do their best to gauge the dynamic range for themselves.

As a result, a lot of consideration went into looking at global features of music like dynamics and note totals. These features are not easily extracted when listening to music, but they can be very easily detected in a visual format. Ultimately, we settled on visualizing the components we felt were the most difficult to track during practice.

4 Results and Analysis

Evaluation was done in two phases, an initial prototype on March 7, 2019 and an updated prototype on April 6, 2019. Feedback was gathered from both phases to evaluate and improve the product.

For the updated prototype evaluation, we shared the tool with one of our advisors. Unfortunately, they hadn't gotten around to the tool in time due to vis paper deadlines. As a result, we decided to review the tool ourselves.

4.1 Prototype Design

The initial prototype aimed to accomplish several of the major tasks mentioned previously. In particular, the following tasks were implemented:

- MIDI File Upload
- MIDI File Pane
- Notes versus Time Graph
- Notes versus Frequency Graph
- Velocity versus Time Graph

In addition, we added a few extra interactivity features during our own iterative process:

- MIDI File Color Mapping

- MIDI File Playback
- MIDI File Renaming
- MIDI File Toggling

With the prototype read to go, we began the evaluation process by presenting it to the class.

4.2 Peer Feedback

In general, feedback was positive. However, there were a few things that needed improvement in the original prototype. The following list contains the feedback from our peers:

- Colors
  - Too closely related (light blue and dark blue)
  - Yet, calming
- Velocity plot
  - Difficult to see differences in curves
  - Plot may not be capturing appropriate data (summing velocities)
  - Look into normalization
- Target audience
  - Musicians don't care about time steps - they want beats and measures
- Interactivity
  - Playback should animate graphs

4.3 Musician Feedback

In addition to the in class feedback, we also chose to evaluate the JuxtaMIDI platform ourselves. In particular, Stephen leveraged his intermediate piano playing abilities to generate the following list of comments:

- Inherent limitations:
  - Online, generated MIDI files are often lacking when compared to an actual song:
    - Song may have a constant velocity for every note.
    - Key signatures, tempo, and sustain may be missing.
  - Recorded MIDI files have some of these issues and more:
    - Velocity is obtained, but this is not exactly reflective of playing on an acoustic piano, which is what would be typically used in performance. Keyboards, especially cheaper ones, are simply less expressive than acoustic pianos.
    - If the user is off-time by even a beat, the whole song gets offset. If the user corrects their time and becomes on-time, this issue is resolved. This means the user needs to be playing to a metronome and correct any time lost, which adds additional requirements on their playing.
  - Preprocessing:
    - Key signatures and tempo need to be manually added if needed for tool (it isn't in the current stage).
    - The MIDI file also needs to be edited to remove any wait in the beginning.
- Benefits:
  - Where this tool thrives is helping identify insights that can't be simply heard or seen in a recording.
  - Users can upload and play their recordings.
  - The velocity curve is probably the most novel item, since other tools (like GarageBand) provide the features of the Master Note graph.
    - Users can follow the sheet music and quickly see how they played different sections, e.g. if they played one forte section louder than another, or if they mistakenly played one forte section as piano.
- Potential:
  - This tool would greatly benefit from adding measure count. Since sheet music often comes with measure numbers, users could cross-reference their playing with the measure number.
  - Exploring and solving the tempo offset issue would make this tool much more useful.
  - Some additional outlier detection or analysis would also help.
  - Since musicians are used to sheet music, having a sheet music overlay with different colored notes per track would be immensely helpful.
    - This would require key signature, tempo, and a really good sheet music generator

4.4 Design Changes

To address some of the feedback, we decided to look into the following changes:

1. Adding a time marker to show where the user is in the song
2. Changing velocity plot to be more expressive
3. Reordering the color array so additional tracks have drastically different colors
4. Adding option for user to specify tempo, changing time to measure

For the final implementation, we completed #1 and #2 for the updated prototype.

4.5 Production Implementation

Ultimately, the final production dashboard was extended to include a marker to illustrate playback. The marker was composed of a colored circle and a vertical line segment where the compound structure encodes both the current time of playback and which track is playing.

In addition, we implemented a handful of fixes for the following issues:

- File playback continued even after files were deleted.
- Axes labels were missing.
- Data abstraction techniques were slow.

For the most part, we fixed these issues. However, the tool is still fairly slow, and that issue scales as songs are added.

Finally, we also made each SVG responsive, so they would properly fill any screen size. The drawback of this approach is text skewing. Now, text can seem inconsistent between graphs.

5 Discussion

For musicians, practicing an instrument has long been a feedback loop between student and instructor. Naturally, we felt there was an opportunity to add a new feedback option through data visualization.

Currently, the JuxtaMIDI solution is very limited. The only people who could take advantage of this tool are musicians who play MIDI-compatible instruments or musicians who are interested in comparing MIDI tracks. Even then, the tool itself is a bit limited. For example, time offsets are a major problem when comparing tracks. If a student were to get off by a beat, their notes over time plot and velocity over plot would be shifted.

Regardless, we still believe the JuxtaMIDI tool is excellent for observing global traits of music. For example, the tool may be handy for determining the key of a track based on the note histogram. Likewise, the tool does a great job of giving an overview of velocity which may be useful for understanding a song's dynamic trajectory.

6 Conclusion

Overall, JuxtaMIDI turned out to be a solid tool for visualizing differences in MIDI files. In particular, the tool highlights errors in note frequency, dynamics, rhythm, and pitch. As a result, JuxtaMIDI may be helpful for students learning a MIDI-compatible instrument like the piano.

In the future, we would like to expand JuxtaMIDI to allow for content filtering. For example, it would be nice to be able to select a region of the master graph and filter out all data not in that region on all three plots. Likewise, we were also interested in adding some feedback through automated error detection. For instance, if a user played quiet in a loud section, we would like to highlight that error for the user.

It may seem odd to want to think of music in a visual way, but we feel our system will have a positive impact on musicians who want to improve their practice sessions.