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The University of Osaka

Doctoral Thesis

Exploration of ergonomic visuo-haptic interface for efficient sensorimotor learning

感覚運動学習を効率化する人間工学的な視触覚インターフェースの探求

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Abstract

Being able to play a musical instrument is one of the most complicated sensorimotor learning. Many beginners give up practicing piano or guitar because it requires a long time practice to overcome the difficulties: reading sheet music, touch-typing, motor control, getting feedback on their own for learning. I fundamentally rethought how the device and software should be, and tested the hypothesis that a new interface "ParoTone" with one-to-one correspondence between 5 lanes, 5 fingers, and 5 rows of buttons could solve these difficulties. I found that compared to Piano, ParoTone enables beginners to acquire playing approximately 3 times faster for melody, 5 times faster for chord. Taking advantage of efficient sensorimotor learning based on readability of operation instruction display and on touch-typing, ParoTone interface in the future may be useful for learning to operate multiple commands in a timely manner. The ParoTone interface also has the potential to be useful for solving the problems in measuring brain activity in MRI during playing musical instruments in a more natural and flexible manner.

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Contents

1. General introduction

1.1. The value and utility of playing musical instruments

Playing a musical instrument is useful for many aspects such as stress relief (Toyoshima et al., 2011), development of children's cognitive ability (Thompson et al., 2004; Moreno, 2009; Moreno et al., 2009), and music therapy for autism (Reschke-Hernandez, 2011) and dementia (Verghese et al., 2003; Moreno-Morales et al., 2020). Regarding stress relief, playing the piano reduces the cortisol level more than other creative art activities such as calligraphy or molding a piece of clay (Toyoshima et al., 2011). As for development of children's cognitive ability, 8-year-old child improves reading and pitch discrimination skills after 6 months of music training (Moreno, 2009). Many therapeutic treatments, including music-based techniques, have focused on the key features of autism, such as development of communication skills and social interactions of children (Reschke-Hernandez, 2011). Regarding prevention of dementia, playing a musical instrument can reduce the onset of dementia by 69% (Verghese et al., 2003).

1.2. Problems of giving up learning to play musical instruments

Being able to play a musical instrument is one of the most complicated sensorimotor learning. In order to enjoy playing musical instruments such as piano and guitar, we need to practice for a long time to overcome the difficulties. Many beginners give up practicing during learning. Although more than 60% of people in the world want to play a musical instrument, only about 12% actually play a musical instrument (Yamaha Music Promotion Association, music lifestyle web questionnaire, 2006; Ministry of Internal Affairs and Communications, Social Life Basic Survey, 2016). Among 800 people who have experience of playing musical instruments outside of education, 87.7%

want to play musical instruments, but 76.6% quit playing the instruments. 34.4% among the 76.6% answered that the main reason they quit playing the instruments is they couldn't improve their skills (IID, Inc., 2013). Even though there are music classes in elementary and junior high schools, many students finish their compulsory education before they reach the joy of playing and expressing all the 3 basic elements of music (rhythm, melody, and harmony) as they like. The enjoyable part of playing music is to express what they want to express as they like, to show their expressions to others, to be empathized and praised by their listeners, and to get new discoveries through communication with other players.

1.3. Problems in measuring brain activity during playing a musical instrument

In order to elucidate the mechanism of sensorimotor conversion during playing musical instruments, or to elucidate the mechanism of the brain during creating music and interactively exchanging music with someone else naturally, the researchers need to measure the brain activities of subjects during playing musical instruments. However, it is difficult for the subjects to do so in a natural situation in MRI scanners. Piano-type interfaces (such as midi keyboards) have been mainly used in previous studies (Limb & Braun, 2008; McPherson & Limb, 2013), but there are technical restrictions. It is physically impossible to bring a horizontally long piano with many keys into an MRI, so the available number of keys and the octave movements are limited in these kinds of experiments. Parallel movements of the palms are required for playing the piano, but if the subject moves his or her arms too much, noise will be added to the brain activity measurement, and the measurement itself will become difficult. It is also difficult to play with both hands with a limited number of portable midi piano keyboard interfaces. Due to these restrictions, it is only possible to measure with a limited degree of freedom in playing in a considerably different situation compared to playing in a natural state. It is necessary to devise a mirror in the MRI scanner so that the subject can see the hands ((Limb & Braun, 2008). In addition, the piano-type interface is difficult to learn, so the number of subjects who can participate in the experiment is limited. To measure brain activity while playing an instrument in a more natural and flexible manner, there is a need for a new musical instrument interface that is portable, octave-movable, minimizing palm and finger movements without adding noise to brain measurements, easy for many people to play with.

1.3. Flywheel of active musical experience

The big goal of my research project is to continue rotating the "flywheel of active musical experience" (Figure 1) without giving up starting to rotate it and without getting bored. Flywheel is difficult to turn at the beginning, but once it starts turning, it keeps turning for a certain amount of time due to inertia. In reality, the flywheel does not keep spinning forever and slows down gradually, so it is necessary to apply force regularly. The "flywheel of active musical experience" consists of 4 stages - practice, acquire a new repertoire, show, and get praised and motivated. It is important to give the experience that when you practice and improve, you want to show your performance to someone, and when your performance is praised, you want to try a new song the next.

1.4. The need for a new interface that balances the two elements

In order to keep rotating the flywheel of active musical experience, a new interface balancing easiness for beginners (without giving up) and a wide range of expressions (without getting bored) is necessary (Figure 2). The interface should not only be able to be acquired without giving up but also be able to express all 3 basic elements (rhythm, melody, harmony) and other nuances (staccato, legato, trill, strength and vibrato, etc.) as they like. Many existing musical instruments such as piano and guitar have a wide range of expressions, but are difficult to learn. Existing studies on how to support the learning and practice are limited to using existing musical interfaces (Hackl & Anthes, 2017; Trujano et al., 2018; Mochizuki, 1982; Dannenberg et al., 1990). Existing rhythm games are easy to learn but lack the freedom to play melodies and harmonies (Sagawa et al., 1999).

1.5. How to reduce giving up

At the stages from "practice" to "acquire a new repertoire" in the flywheel, many people give up practicing before they can enjoy playing because of the difficulty of reading sheet music and controlling their fingers. Regarding this issue, existing approaches such as music game style sheet music notation (Sagawa et al., 1999; Hackl & Anthes, 2017; Trujano et al., 2018) and key lighting piano keyboards (Mochizuki, 1982) have been proposed, improved to some extent, but remain unsolved. I fundamentally rethought how not only software but also hardware interface should be. At first, in my prototyping process (Supplemental figure 1a, b), in order to simplify motor control, I devised an array of 5 × 3 states in which 5 notes that are statistically frequently used are arranged side by side in the middle row, and a chord that can be pressed with a single button. Then, in order to simplify the reading of the sheet music, I made a prototype of a numbered musical notation that corresponds to the five buttons and the numbered numbers. After that, I faced problems of difficulty in touch typing, pushing the thumb, moving octaves. Therefore, in order to solve these problems, I drastically reviewed the interface of device and musical score (Supplemental figure 1c); A game-style musical score that corresponds to the arrangement of 5 lanes, a button that transitions to 3 states in the direction of finger flexion, a radial button arrangement that fits the thumb, and a sliding octave shift. Whether this new interface can address the difficulty of reading sheet music and controlling their fingers is the hypothesis to be tested in this research.

At the stages from “show” to “get praised and motivated”, the lack of listeners and friends to enjoy with, and the lack of feedback from them prevent many people from keeping motivated to try a new repertoire. How to share the performance and how to connect with their listeners are important questions at this stage.

1.6. How to keep motivation without getting bored

In order to keep rotating the flywheel without getting bored, finding a new goal, learning, and feeling growth are important. To learn after listening to new inspired music contents, you need to be able to analyze, discover the patterns, and imitate them. People with absolute pitch are often very good at doing this, so they can accumulate and learn various musical vocabularies. However, people with absolute pitch are very limited to about 5% of the population, which is estimated from university students majoring in non-music in Japan (Miyazaki et al., 2012). For those who do not have absolute pitch, the platform to share sheet music in the form of easily readable for everyone may be a solution to this problem.

1.7. The main purpose of this research

In this study, I invented and prototyped a new interface “ParoTone” (Mita & Sato, 2021, patent) to rotate the flywheels of active music experience, and verified the effectiveness of the interface to solve the problems of giving up at the stage from “practice” to “acquire a new repertoire”.

2. Verifying the effectiveness of a new interface “ParoTone”

2.1. Introduction

Playing a keyboard instrument is a kind of complicated sensorimotor transformation learning consisting of a series of processing from cognition through action to getting feedback (Emond & Comeau, 2013; Wolf, 1976; Nakahira & Kitajima, 2017). I diagramed the series of processing consisting 4 steps (Figure 4a):

- [Step 1] Deciding which key to be pressed by reading sheet music
- [Step 2] Grasping the current finger positions
- [Step 3] Generating a motor command
- [Step 4] Getting feedback on whether you pressed the correct keyboard position

At each step, there is difficulty, which disturbs the learning process. Regarding [Step 1], reading sheet music (e.g. staff notation) requires a high cognitive load on learning how to read. Complexity of the visual information is too high for beginners. The cost for learning the correspondence between sheet music and keyboard position is high. As for [Step 2], touch-typing requires grasping the position of fingers only by tactile presentation without visual clues. Since there are too many keys in piano, the cognitive load to find the key position to press is high (Ohsawa et al., 2017). Since vision is used not only for [Step 1] but also for [Step 2], there is competition (cannot be processed in parallel), and the cognitive load becomes too concentrated on visual processing, which results in frequent eye movement between hands and sheet music. As for [Step 3], motor learning difficulty consists of 2 causes. First, it is not possible to uniquely determine which finger should be used to press the target key because the number of keys is too large for the number of fingers (Sloboda et al., 1998). Second, holding chords requires simultaneous complicated multi-finger muscle control for pressing multiple keys at the same time. As for [Step 4], getting feedback for corrections (whether the correct key is pressed) only by the sense of pitch or touch is difficult for beginners, requiring visual feedback.

By explicitly diagramming the process of sensorimotor transformation in playing keyboard instruments (Figure 4a), we realized that past studies have approached only part of the steps in a whole process. Existing approaches are not enough to solve the difficulties (Figure 4b). Regarding [Step 1], approaches such as music game style sheet music notation (Sagawa et al., 1999; Hackl & Anthes, 2017; Trujano et al., 2018) and key lighting piano keyboards (Mochizuki, 1982) have been proposed, improved to some extent, but there are unsolved problems. Game style sheet music notation has the same number of lanes as the number of keys, and musical notes fall on the lanes. The keyboard should be pressed when musical notes reach the line representing the hitting point. Since there are many keys in piano compared to the number of fingers, it is difficult to recognize instantly which lane corresponds to which key. Lighting keyboard is an approach in which the next keys to be pressed are lighted up. This approach still has the problem of not being able to look ahead for more than one note, and not being able to know the duration of the note. As for [Step 2] and [Step 3], only improving software is not enough to solve the problems. The basic piano interface has not been updated for more than 300 years and is still the most common musical interface. We are now living in the digital era, it is necessary to fundamentally review how the digital hardware device should be fit for humans beyond the limitation of analog acoustic instruments. As for [Step 4], an existing approach that gives feedback to the player by moving the cursor on the digital sheet music on the PC monitor to the next note when the correct key is pressed (Dannenberg et al., 1990) works well.

I fundamentally rethought how the device and software should be for efficient sensorimotor learning, and tested the hypothesis that a new interface “ParoTone” with one-to-one correspondence between 5 lanes, 5 fingers, and 5 rows of buttons (Figure 3; Supplemental videos 1, 2, 3, and 4) could solve these difficulties.

2.2. Materials and methods

2.2.1. About “ParoTone” interface

Figure 3 and supplemental videos 1, 2, 3, and 4 show the ParoTone interface (Mita & Sato, 2021).

2.2.1.1. One-to-one correspondence between 5 fingers, 5 buttons, and 5 lanes

The most characteristic point of the ParoTone interface is one-to-one correspondence between 5 fingers, 5 buttons, and 5 lanes of sheet music (Figure 3c). The reason why there are 6 buttons is to be compatible both for the left hand and right hand. The rightmost button is inactive when using the right hand, and the leftmost button is inactive when using the left hand.

2.2.1.2. Three states transition in each button

Each button makes 3 states transition (top, middle, and bottom) smoothly in the flexion and extension directions of each finger (Figure 3c; Supplemental video 2). Users can feel the boundary between the 3 states by touch. 3 colors of musical notes in sheet music notation correspond to the 3 states.

2.2.1.3. Radially arranged buttons

Buttons are radially arranged to ergonomically fit 5 fingers including the thumb.

2.2.1.4. Switch between melody mode and chord mode for each hand

There are 2 playing modes: melody mode and chord mode. Users can choose which mode to play for each hand, e.g. melody mode for both hands (Figure 3d), chord mode for both hands (Figure 3e), and chord mode for left hand and melody mode for right hand (Figure 3f). In the case of melody mode, the 5 most frequently used sounds (C, D, E, G, A; major pentatonic scale) are arranged in the middle states (Figure 3c, d). Top states are semitone higher than middle states. Bottom states are semitone lower than middle states. These arrangements can cover all the 12 semitones of the octave from B to B flat. When playing a melody with both hands, by default, the right hand is one octave higher than the left hand. In the case of chord mode, users can play chords with one state in the button without the need for simultaneous control of multiple fingers. Frequently used chords are placed in the middle states, and frequently progressing pairs of chords are arranged next to each other (Figure 3e).

2.2.2. Experiment 1: Comparison between Piano (staff notation) and ParoTone.

The purpose of experiment 1 was to compare learning speed between Piano (staff notation) and ParoTone. Figure 5a and Supplemental video 5 show the example scenes of experiment 1. There were 17 subjects (15 adult males, 2 adult females). 11 persons were beginners (less than 1 year of keyboard instruments experience outside compulsory education) and 6 were experienced people (1 year or more of keyboard instrument experience outside compulsory education). Experiment sessions on Piano and ParoTone were done. 8 subjects did Piano session first, and 9 subjects did ParoTone session first. For 1 minute at the beginning of each session, the subjects looked at the correspondence table between the sheet music and the keyboard positions to understand the notation rules and played as they liked to practice. In the main part of the experiment, I measured how long it took for the subject to play the song “Jingle bells" chorus 4 bars 3 times, for 3 patterns of playing modes: (1) Melody only, (2) Chord only, (3) Melody and chord. Visual feedback about whether the correct keys were pressed was given to the subjects during playing. In the Piano session, the cursor moved to the next note when the correct key was pressed and did not move when the wrong key was pressed. In the ParoTone session, the musical notes stopped at the hitting point until the correct key was pressed. In both sessions, the correctness was judged only by whether the key with the correct pitch was pressed. The note duration was not used for correctness judgment. Metronome sounds with a target tempo of 120 beats per minute were played as the background sound. The ideal fastest clear time was when the subject succeeded in playing all the notes without mistakes at the target tempo without delay. The number of times the subjects moved their line of sight from the screen to their hands during the performance were counted (Figure 5e).

2.2.3. Experiment 2: Comparison among 4 types of notation

There are 2 purposes in experiment 2. First, to examine to what extent which steps contribute to the improvement of learning speed of ParoTone when compared to Piano (staff notation). Second, comparison of learning speed between Piano (game style sheet music notation) and ParoTone. There were 10 subjects (9 adult males, 1 adult female). 6 persons were beginners (less than 1 year of keyboard instruments experience outside compulsory education) and 4 were experienced people (1 year or more of keyboard instrument experience outside compulsory education). Experiment sessions on Piano and ParoTone were done. 4 subjects did the Piano session first, and 6 subjects did the ParoTone session first. Subjects played 4 kinds of sheet music notation (Figure 7a):

- [Notation X] Piano (staff notation)

- [Notation Y] ParoTone (ParoTone notation)
- [Notation Z] Piano (indicating positions to be pressed on keyboard diagram, similar to music game style notation)
- [Notation W] ParoTone (indicating positions to be pressed on ParoTone diagram)

I measured how long it took for the subjects to play a random 5-tone sequence for 2 patterns of playing modes: (1) Melody, (2) Chord. Visual feedback about whether the correct keys were pressed was given to the subjects during playing (the same way as in Experiment 1).

2.2.3.1. How to analyze for first purpose

Compared to [Notation X] and [Notation Y], [Notation Z] and [Notation W] exclude the difficulty of [Step 1] in learning the correspondence between sheet music and keyboard position (Figure 7a). Therefore, by comparing the learning speeds of [Notation X] and [Notation Y], it is possible to understand to what extent all the factors including [Step 1], [Step 2], [Step 3], and [Step 4] affect the learning speed difference between the Piano (staff notation) and ParoTone. By comparing the learning speeds of [Notation Z] and [Notation W], it is possible to understand to what extent only [Step 2], [Step 3], and [Step 4], excluding [Step 1], affect the learning speed difference between Piano (staff notation) and ParoTone.

2.2.3.2. How to analyze for second purpose

By comparing [Notation Z] and [Notation Y], I can investigate whether there is a difference in the learning speed between the Piano (music game style notation) and ParoTone.

2.3. Results

2.3.1. Experiment 1: Comparison between Piano (staff notation) and ParoTone.

2.3.1.1. Comparison result of learning speed

Figures 3b, c, d, and Table 1 show learning speed comparison results. The learning speed of the ParoTone was faster than that of the Piano (staff notation) ($p < 0.01$ in each case, Wilcoxon signed-rank test, 2.3 times faster on average for playing melody (Figure 5b), 3.8 times faster on average for playing chord (Figure 5c), 3.6 times faster on average for playing both melody and chord (Figure 5d)).

2.3.1.2. Comparison result of the number of gaze movement

Figures 3f, g, and h show comparison of how many times the subjects moved their line of sight to their hand during performance. In the case of ParoTone, the number of times the line of sight moved to the hands during the performance was less than that of the Piano ($p < 0.01$ in each case, Wilcoxon signed-rank test, as for melody in Figure 5f, chord in Figure 5g, both melody and chord in Figure 5h). This result shows that ParoTone is superior to Piano in touch-typing. In other words, by actively using the sense of touch to grasp the position of fingers without visual clues in [Step 2], the load of visual information is reduced. This enables the players to process parallelly reading sheet music in [Step 1] and grasping the current position of fingers by touch-typing in [Step 2].

2.3.1.3. Comparison between beginners and experienced people

Figure 6 and Table 1 shows the detailed comparison of learning speed between groups with and without more than 1 year of keyboard instrument experience. Especially in the beginner group (less than 1 year of keyboard instrument experience outside compulsory education), the difference in learning speed between Piano (staff notation) and ParoTone was remarkable. In the case of beginners' group, learning melody performance was 2.8 times faster on average, chord performance was 4.8 times faster on average, both melody and chord performance was 4.2 times faster on average than Piano (staff notation) ($p < 0.01$ in each case, Wilcoxon signed-rank test). As for the experienced group (more than 1 year of keyboard instrument experience outside of compulsory education), there was a significant difference in the learning speed of chord performance ($p < 0.05$, Wilcoxon signed-rank test), but there was no significant difference in melody performance and both melody and chord performance.

2.3.2. Experiment 2: Comparison among 4 types of notation

2.3.2.1. Purpose 1: To what extent which steps contribute to the improvement of learning speed of ParoTone when compared to Piano (staff notation)

Figure 7b and Table 2 shows the investigation of which steps in sensorimotor transformation contribute to improve learning speed of melody performance. The learning speed of [Notation Y] was 2.7 times faster on average than [Notation X] ($p < 0.05$, Wilcoxon signed-rank test). There was no significant difference in learning speed between [Notation Z] and [Notation W] ($p = 0.55$, Wilcoxon signed-rank test). From these results, in the case of learning melody performance, ease of reading sheet music in [Step 1] contributed to improve the learning speed of ParoTone compared to Piano (staff notation).

Figure 7c and Table 2 shows the investigation of which steps contribute to improving learning speed of chord performance. The learning speed of [Notation Y] was 13.3 times faster on average than that of [Notation X] ($p < 0.01$, Wilcoxon signed-rank test). The learning speed of [Notation W] was 4.6 times faster on average than [Notation Z] ($p < 0.01$, Wilcoxon signed-rank test). From these results, it was possible to improve the learning speed only by ease of touch-typing in [Step 2] and motor control in [Step 3], but the main factor that contributed was the ease of reading sheet music in [Step 1].

2.3.2.2. Purpose 2: Comparison of learning speed between Piano (game style sheet music notation) and ParoTone

Figure 7d and Table 2 shows the result of comparing learning speed between Piano (music game style notation) and ParoTone. There was no significant difference in the learning speed of melody performance ($p = 0.44$, Wilcoxon signed-rank test). Regarding the learning speed of chord performance, ParoTone was 4.1 times faster on average than Piano (music game style notation) ($p < 0.01$, Wilcoxon signed-rank test).

2.4. Discussion

The main purpose of this study was to test whether the new interface "ParoTone" is faster to learn than the existing Piano interface. The concrete ideas to improve the efficiency of sensorimotor transformation learning were as follows:

- One-to-one correspondence between 5 fingers, 5 buttons, and 5 lanes
- Radially arranged buttons
- 3 states transition buttons in the direction of finger flexion and extension
- Being able to feel the boundaries of the 3 states by touch
- Playing chords with 1 button

To test these ideas, I implemented the hardware and software, conducted the 2 experiments, and got results. ParoTone was faster to learn than Piano (staff notation) in melody performance and chord performance (Figure 5b, c, d, and Table 1, in experiment 1). ParoTone was faster to learn than Piano (music game style notation) in chord performance (Figure 7d, in experiment 2). ParoTone was better in touch-typing because the number of line of sight movements during performance was smaller than Piano interface (Figure 5f, g, and h, in experiment 1). Compared to the Piano (staff notation), ParoTone's ease of reading in [Step 1] contributed to improving the speed of learning melody performance (Figure 7b, in experiment 2), not only the ease of reading sheet music in [Step 1] but also touch-typing in [Step 2] and motor control in [Step 3] contributed to improve the speed of learning chord performance (Figure 7c, in experiment 2). From these results, I conclude that the new ParoTone interface improves the efficiency of sensorimotor transformation learning compared to existing Piano interface, which leads to improvement of the learning speed.

ParoTone is faster to learn than existing Piano interfaces by addressing the difficulties at each of the four steps of sensorimotor transformation. By explicitly diagramming the process of sensorimotor transformation in playing keyboard instruments (Figure 4a), I came up with the hypotheses that can streamline the [Step 2] and [Step 3] that could not be dealt with in past studies, and [Step 1] that were poorly dealt with. I realized that the cognitive load on vision was too concentrated in [Step 1] and [Step 2]. I came up with an interface for reducing the visual cognitive load of [Step 1], and further considered a hypothesis that [Step 1] and [Step 2] can be processed in parallel by substituting tactile sensation for visual perception in [Step 2]. These thoughts have made it possible to streamline the whole sensorimotor transformation process. From the experiments, I got the result that ParoTone was faster to learn than Piano (staff notation) in melody performance (2.3 times faster) and chord performance (3.8 times faster) (Figure 5b and c, in experiment 1). I also got the result that ParoTone was faster to learn than Piano (music game style notation) in chord performance (4.1 times faster) (Figure 7d, in experiment 2). From these results, I consider that our hypotheses were valid. In addition, in our experiment, the conditions for [Step 4] were the same for the Piano and ParoTone. Nevertheless, it is noteworthy that there was such a difference in learning speed. Therefore, if comparing ParoTone (including [Step 4] assistance) with Piano (traditional sheet music without feedback assistance for [Step 4]), the learning speed will be more different than the results of our experiments.

2.4.1. The mechanism of how the new interface is effective

Ease of reading sheet music in [Step 1] contributes to improving the melody performance learning speed. Not only ease of reading in [Step 1] but also ease of touch-typing in [Step 2] and motor control in [Step 3] contribute to improving the chord performance learning speed.

2.4.1.1. How ease of reading sheet music in [Step 1] can be improved by the new interface?

The interface, which has a one-to-one correspondence between 5 lanes, 5 row buttons, and 5 fingers, makes it clear at a glance the correspondence between the sheet music and the keyboard, which reduces the visual cognitive load and makes reading easier.

2.4.1.2. How effective use of tactile sensation and reduced cognitive load on vision in [Step 2] can be improved by the new interface?

Subjects looked at their hands less often during learning ParoTone than Piano (Figure 5f, g, and h, in experiment 1). This result means the ParoTone is superior to Piano in touch-typing. I interpret this result as thanks to the characteristics of 5 lanes, 5 rows of buttons and 5 fingers in a one-to-one correspondence, radial button arrangement, 3 states transition buttons in the direction of finger flexion and extension, and being able to feel the boundaries of the 3 states by touch. Thus, ParoTone makes it possible to effectively utilize the sense of touch and reduce the cognitive load on the visual sense, which contributes to the improvement of learning speed.

2.4.1.3. How ease of motor control in [Step 3] can be improved by the new interface?

First, the interface with 5 lanes, 5 rows of buttons and 5 fingers in a one-to-one correspondence uniquely determines the solution with which finger to press which button. Second, the chords can be played with one button, eliminating the need for simultaneous control of multiple fingers. These factors make the subjects' motor control easier.

2.4.1.4. To what extent each step streamlines the sensorimotor transformation learning?

As for melody performance, in Figure 7b, the learning speed of [Notation Y] was 2.7 times faster on average than [Notation X], but there was no significant difference in learning speed between [Notation Z] and [Notation W]. From this result, in learning to play a melody, [Step 1] is effective in improving the learning speed. As for chord performance, in Figure 7c, the learning speed of [Notation Y] was 13.3 times faster on average than that of [Notation X], and the learning speed of [Notation W] was 4.6 times faster on average than [Notation Z]. From this result, in learning chord performances, [Step 1] contributed mainly, but [Step 2] and [Step 3] also contributed (4.6 out of 13.3) to the improvement of learning speed. In both cases, regardless of melody or chord, the [Step 1] contributes most to the improvement of learning speed.

2.4.1.5. Why did the ease of touch-typing in [Step 2] and motor learning in [Step 3] have a stronger influence on the learning of chord performances compared to those of melody?

First, compared to playing melodies, playing chords on the Piano requires the movement control of multiple fingers. I guess that the reason why [Step 2] and [Step 3] contributed more to the learning of chord performance than to melody performance was based on the effect of playing chords with one button. Second, since the visual cognitive load in [Step 2] is higher in chord performance than in melody performance, touch-typing seems to be more effective in chord performance. In experiment 1, in Piano performance, the subjects looked at their hands more often in chord performance than in melody performance ($p < 0.05$, Wilcoxon signed-rank test, comparing the Piano of Figure 5f and Piano of Figure 5g). The fact that subjects often look at their hands during performance means that the visual cognitive load on [Step 2] is increased accordingly in chord performance compared to melody performance. I guess that touch-typing was more effective in improving the learning speed of chord performance because the visual cognitive load on [Step 2] was higher than playing melody.

2.4.2. Is the interface effective for both beginners and experienced people?

From the result of Figures 4a and b, when comparing the learning speed of ParoTone with the Piano (staff notation) in the beginners' group, ParoTone is 2.8 times faster on average for melody performance and 4.8 times faster on average for chord performance. In the case of subjects with keyboard instrument experience, there was no significant difference in melody performance, and 2.2 times faster on average for chord performance. These results show that the ParoTone interface is more effective for speeding up learning for beginners (both melody and chord) than experienced people (only chord).

2.4.3. Limitations

I acknowledge there are several limitations in this study. First, in this study, I conducted an experiment using a melody that fits within a range of two octaves. This study holds for many songs because the melody of many songs fits within two octaves. Whether or not it holds true even when playing a song containing a melody of 3 octaves or more needs to be examined in future research. Second, in this study, I did not compare the learning speed between a lighting keyboard and ParoTone. Lighting keyboard is an approach in which the next keys to be pressed are lighted up. This approach has the problem of not being able to look ahead for more than one note and not being able to know the duration of the note. At least, as for these points, it's obvious that the ParoTone interface is superior to the lighting keyboard.

2.4.4. Future applications

2.4.4.1. For music

The ParoTone interface makes it possible to deliver the joy of performing music to more people (beginners of musical instruments, children in developing countries, etc.) in a portable and low cost manner. Taking advantage of efficient learning of touch-typing, ParoTone also has potential as a barrier-free musical device for the visually impaired people in the future.

2.4.4.2. For other fields than music

Taking advantage of efficient sensorimotor learning based on readability of operation instruction display and on touch-typing, ParoTone interface may make it easier for learning to adjust multiple commands in a timely manner. For example, in effective video production and distribution, operators need to learn how to switch and adjust multiple camera angles, lighting brightness, sound levels, etc. in a timely manner.

2.5. Conclusion

From all the discussions above, I conclude that 5 lanes 5 fingers touch-typing interface enables efficient sensorimotor learning, which leads especially for beginners to acquire musical performance much faster than Piano. Taking advantage of efficient sensorimotor learning based on readability of operation instruction display and on touch-typing, ParoTone interface in the future may be useful for learning to operate multiple commands in a timely manner.

3. General conclusion

The big goal of this research project was to turn the “flywheel of musical experience” (Figure 1). In order to solve the problems, a new interface balancing easiness for beginners and a wide range of expressions (Figure 2) is necessary.

In this study, I invented the new interface “ParoTone” and worked mainly on solving the problems to turn the flywheel in the introductory period. I verified the effectiveness of the new ParoTone interface compared to the existing piano interface, staff notation, and musical game style notation. Through the experiments, I confirmed that ParoTone can solve the difficulty of reading sheet music and controlling the fingers. Thus, I conclude that the ParoTone interface is effective for solving the problems.

Compared to piano midi keyboard devices, ParoTone is more portable, octave-movable, minimizing palm and finger movements without adding noise to brain measurements, easy for many people to play with. In the future study, the ParoTone interface also has the potential to be useful for solving the problems in measuring brain activity in MRI while playing musical instruments in a more natural and flexible manner.

What I am going to tackle next is to continue rotating the flywheel without getting bored. I have a hypothesis that a platform on which users can share sheet music (Supplemental figure 2) is effective in solving this problem. Since the ParoTone style sheet music is easy to read, users can enjoy the played contents deeply while understanding and analyzing the contents, can imitate and play them, can learn and incorporate them as their own expressions. Sharing the sheet music may promote communication between users. I will verify whether ParoTone is effective in solving the problems by actually spreading ParoTone interface and a platform for sharing sheet music to the society.

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Figures

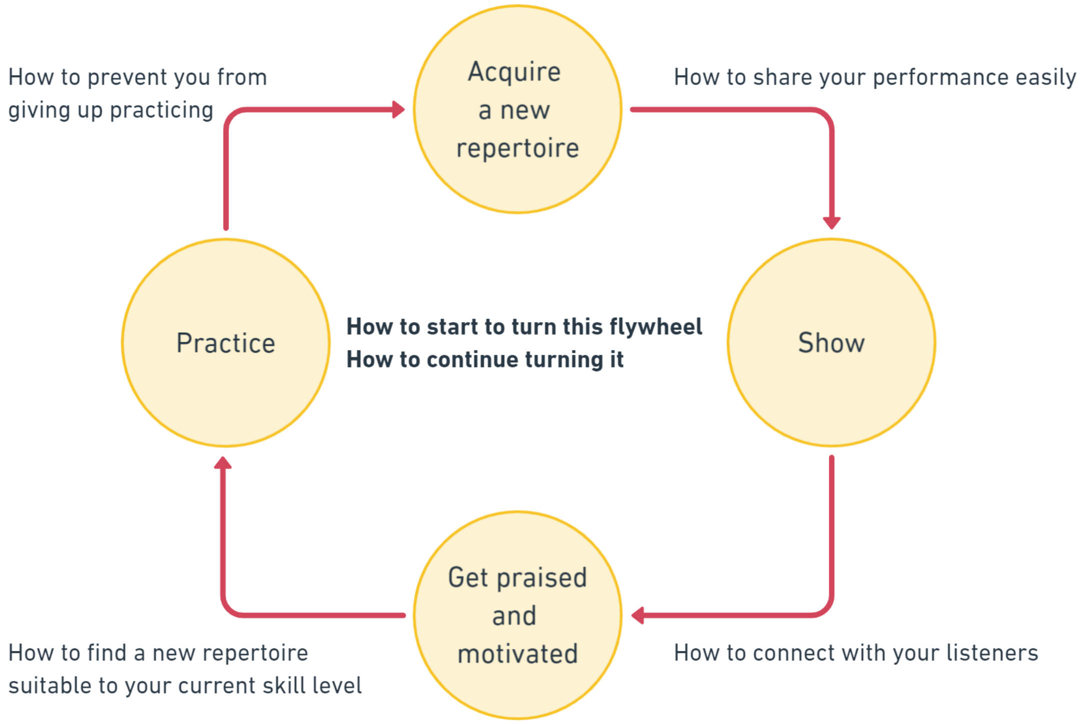


Figure 1. "Flywheel of musical experience"

The whole picture of this project. The big goal is to keep turning this flywheel.

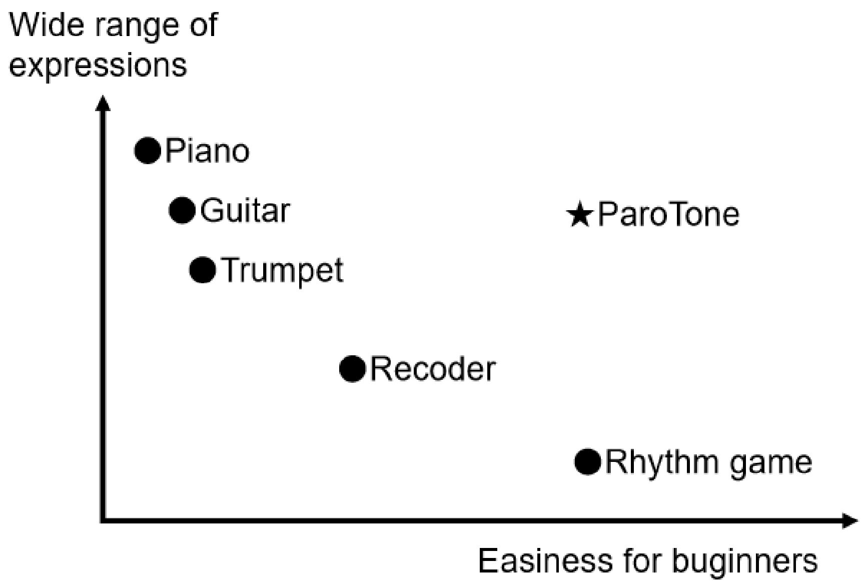


Figure 2. ParoTone balances between important 2 factors compared to the existing musical instruments

Conceptual diagram about the design philosophy of the new interface (★) compared to the other existing musical interfaces (●).

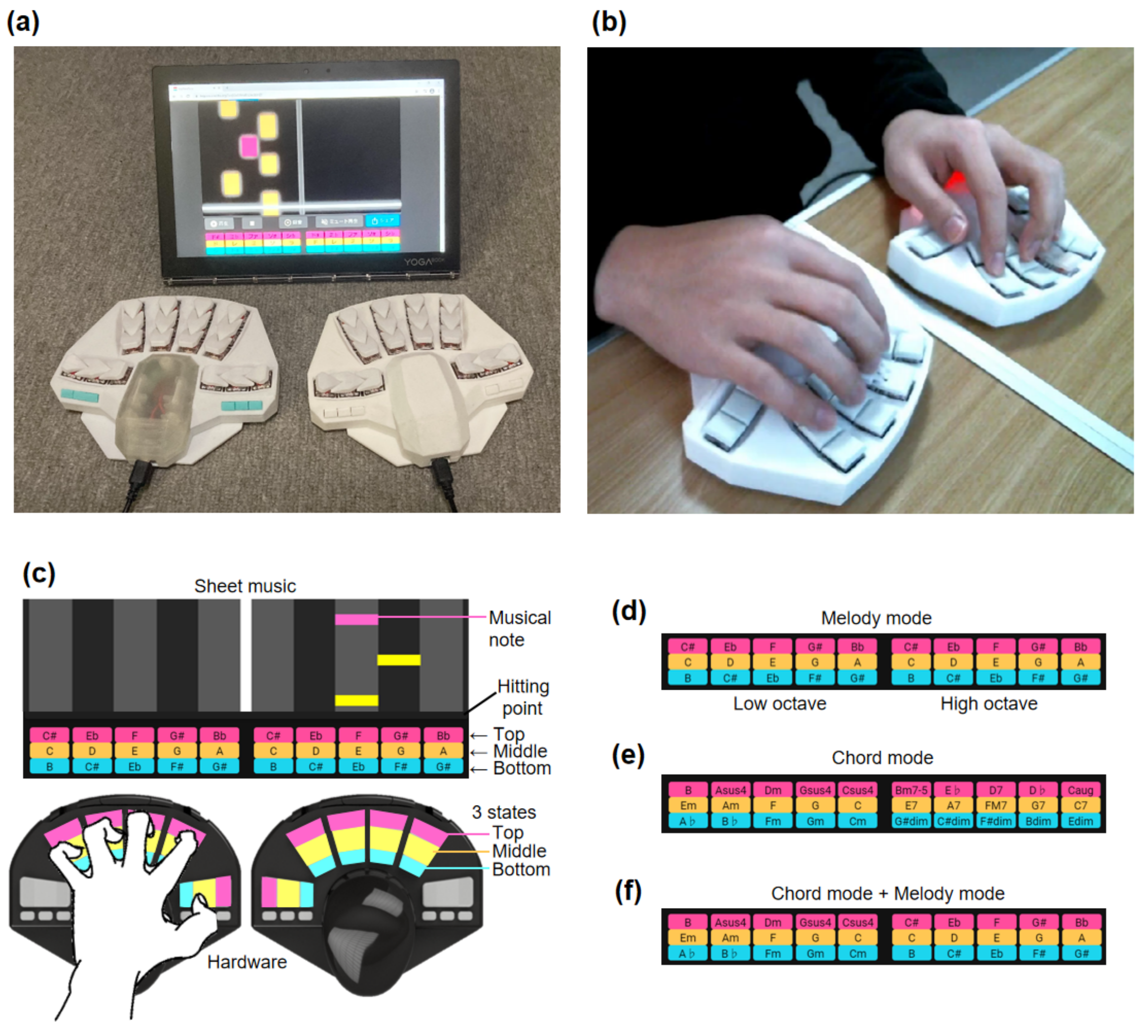


Figure 3. 5 lanes 5 fingers touch-typing interface "ParoTone"

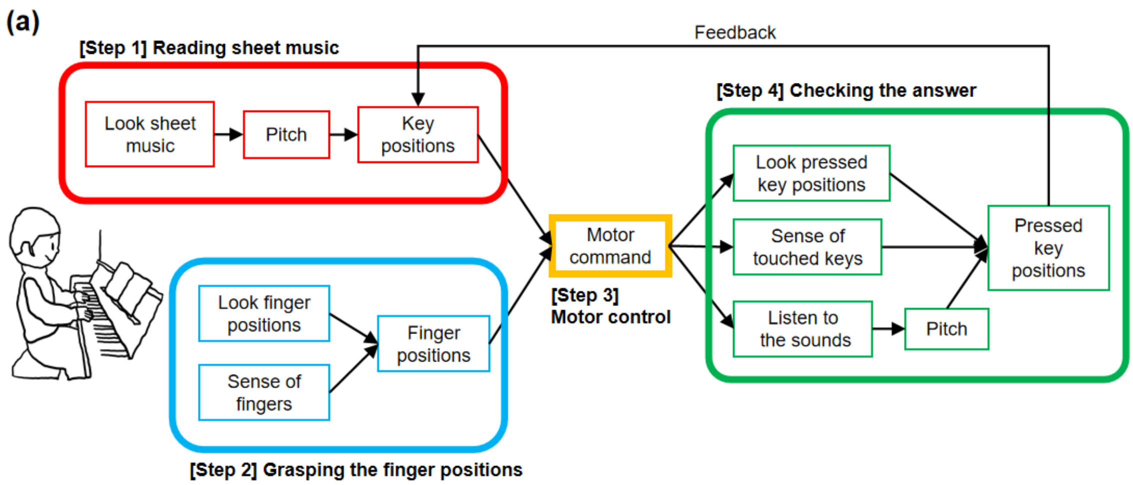
(a) Prototype of the ParoTone interface including sheet music display and hardware devices.

(b) About how the hands fit into the actual hardware devices.

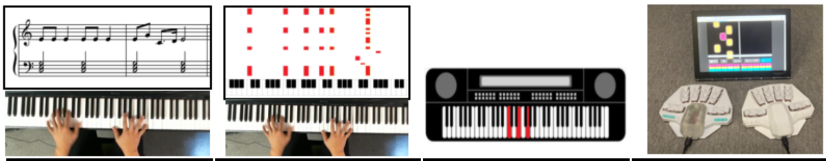
(c) Detailed correspondence between the musical notes in sheet music and buttons of the hardware devices.

(d) (e) (f) ParoTone can switch 3 kinds of playing modes (melody, chord, chord+melody). Spatial arrangement of the musical tones in each mode.

(a)



(b)



Difficulties in existing approaches	**Piano (staff notation)**	**Piano (music game style notation)**	**Piano (key lighting)**	**Proposed method "ParoTone"**
[Step 1] Reading sheet music	Unsolved	**Partly solved** High cognitive load (Too many lanes and keys)	**Partly solved** Impossible to know the duration of the note, impossible to look ahead for more than one note	**Solved**
[Step 2] Grasping the finger positions	Unsolved	Unsolved	Unsolved	**Solved**
[Step 3] Motor control	Unsolved	Unsolved	Unsolved	**Solved**
[Step 4] Checking the answer	**Solved**	**Solved**	**Solved**	**Solved**

Figure 4. 4 kinds of difficulties of sensorimotor transformation in keyboard instrument performance and existing solution approaches

(a) Whole series of processing in learning to play keyboard instruments

(b) Comparison between ParoTone and existing sheet music interfaces and Piano.

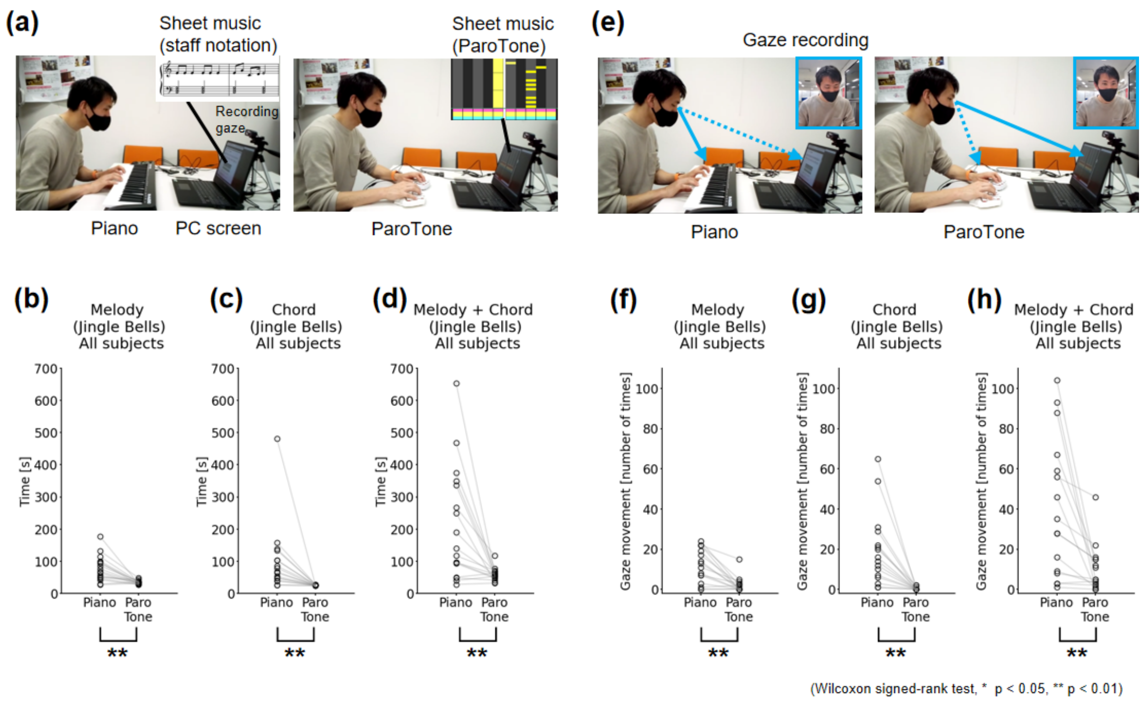


Figure 5. Experiment 1: Comparison of learning speed and the number of gaze movement between Piano (staff notation) and ParoTone

(a) The experiment setup to compare the learning speed between Piano and ParoTone

(b) (c) (d) Comparison of the time to play the the song “Jingle bells" chorus 4 bars 3 times correctly, for 3 patterns of playing modes (melody, chord, and melody+chord)

(e) Gaze recording to count how many times the subjects moved their line of sight to their hand during performance

(f) (g) (h) Comparison of the number of gaze movement during playing, for 3 patterns of playing modes (melody, chord, and melody+chord)

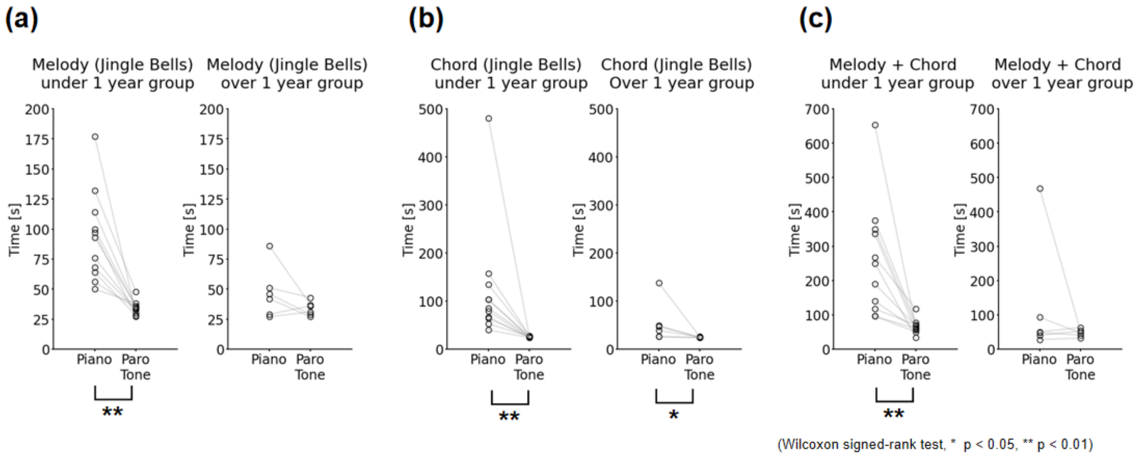


Figure 6. Detailed comparison of learning speed between beginners and experienced groups.

(a) The data in Figure 5b was divided into two groups.

(b) The data in Figure 5c was divided into two groups.

(c) The data in Figure 5d was divided into two groups.

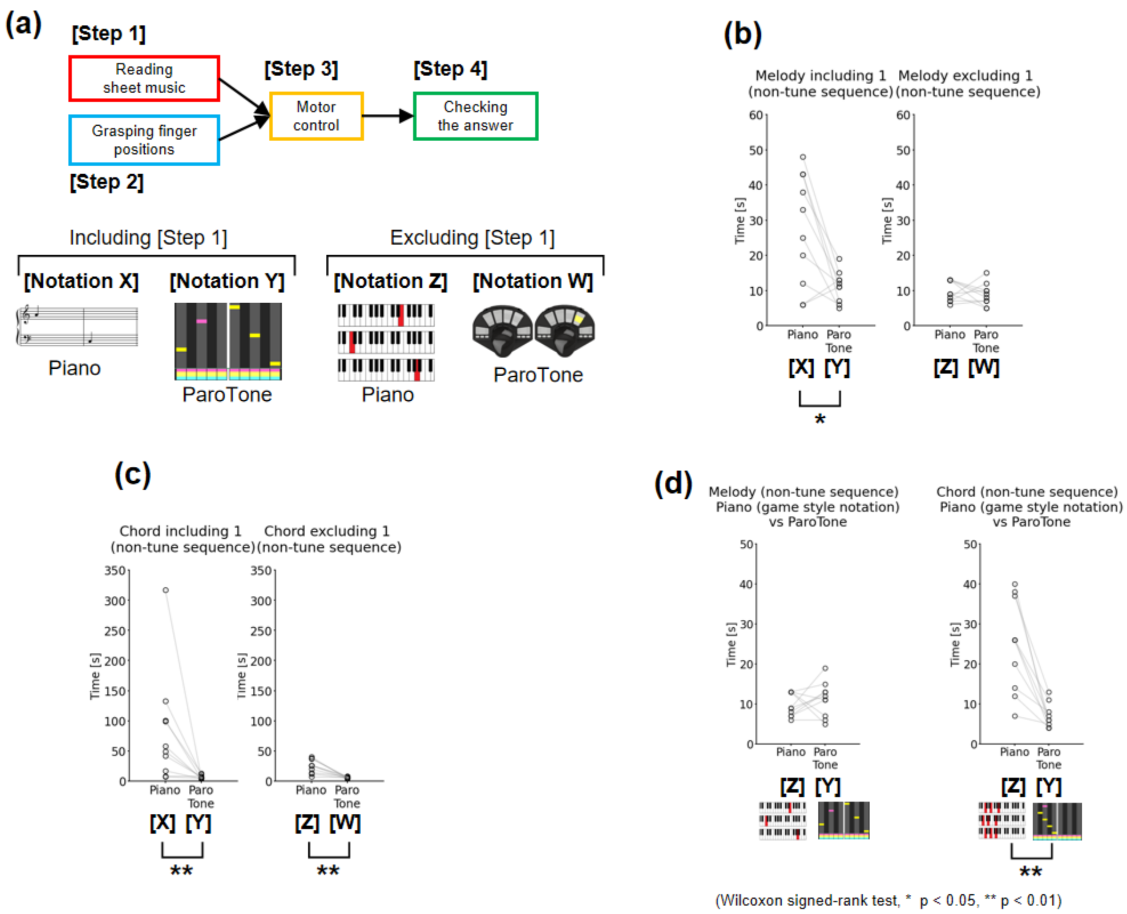


Figure 7. Experiment 2: Which steps contribute to speed up learning, and comparison between Piano (music game style notation) and ParoTone

(a) Abbreviated diagram of Figure 4a, and 4 types of notations used in experiment 2

(b) Comparison of the time to play the assigned melody tone sequences correctly among 4 types of notations

(c) Comparison of the time to play the assigned chord tone sequences correctly among 4 types of notations

(d) Comparison of the time to play the assigned tone sequences correctly between the notation [Z] and [Y]

Tables

	Beginners' group (n=11)	**Experienced group (n=6)**	**All subjects (n=17)**
Melody	2.8**	-	2.3**
Chord	4.8**	2.2*	3.8**
Melody + Chord	4.2**	-	3.6**

Table 1. How many times faster to learn ParoTone than Piano (staff notation)

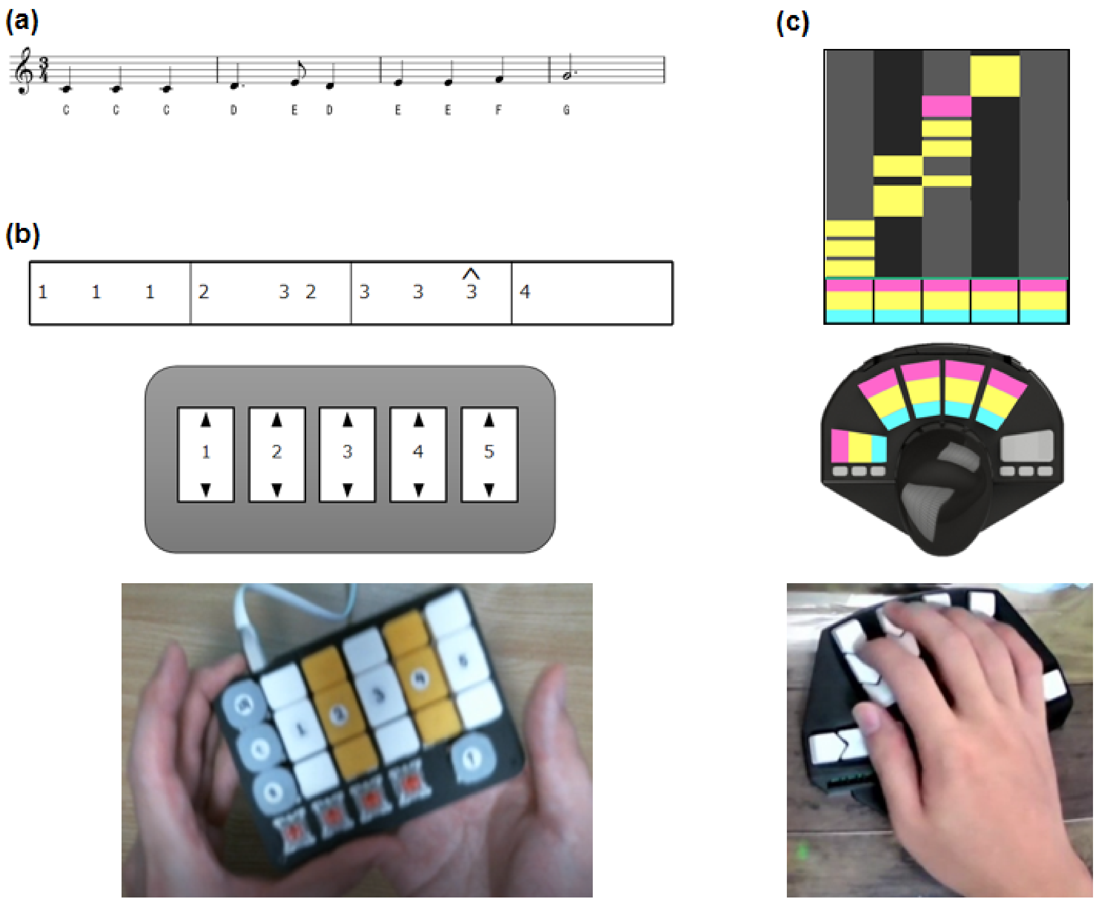
** p<0.01, * p<0.05, - no significant difference (Wilcoxon signed-rank test)

	[X] vs. [Y] (n=10)	**[Z] vs. [W] (n=10)**	**[Y] vs. [Z] (n=10)**
Melody	2.7*	-	-
Chord	13.3**	4.6**	4.1**

Table 2. How many times faster to learn ParoTone than Piano

** p<0.01, * p<0.05, - no significant difference (Wilcoxon signed-rank test)

Supplemental figures

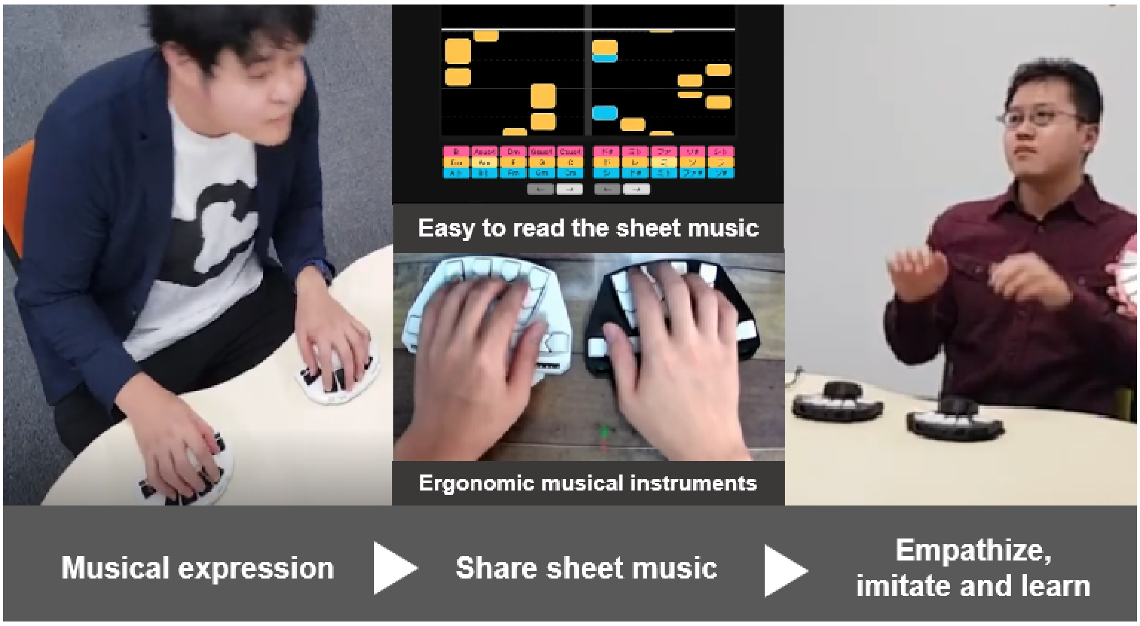


Supplemental figure 1. Prototyping history

(a) Existing sheet music of staff notation.

(b) First prototype : Sheet music of number notation. Straightly arranged buttons.

(c) Second prototype : Sheet music of music game style notation. Radially arranged buttons fitting into the shape of the hand.



Supplemental figure 2. Conceptual diagram of a platform to share sheet music

A platform on which users can share sheet music and communicate through the sheet music.

Supplemental videos

Supplemental video 1. Demo performances.

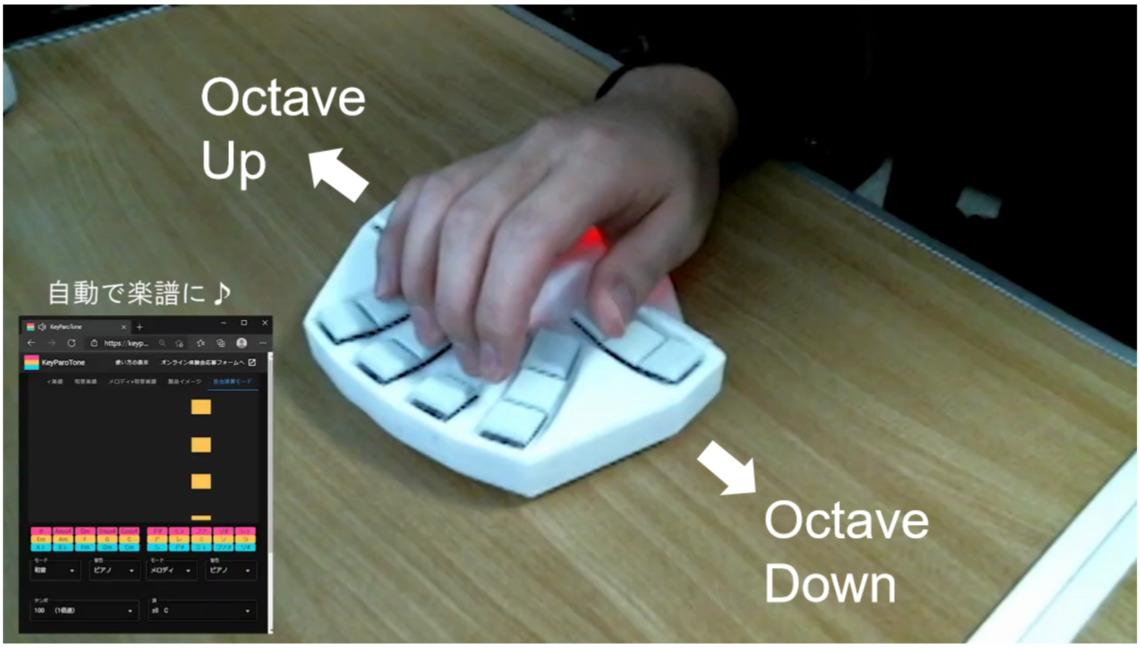
“For Elise” (L.V. Beethoven), and “La Campanella” (F. Liszt).

https://drive.google.com/file/d/1teE7cEnej77OS5LHjOENTi4-Bs4wfFKk/view?usp=sharing

Supplemental video 2. Three states transition.

Each button makes 3 states transition (top, middle, and bottom) smoothly in the flexion and extension directions of each finger.

https://drive.google.com/file/d/1Fb8MBxoHP7qp_kDVi5pzyiN5fKUDY3Ql/view?usp=sharing



Supplemental video 3. Octave shift

Switching octave by sliding the hardware device to the right (octave Up) or left (octave down).

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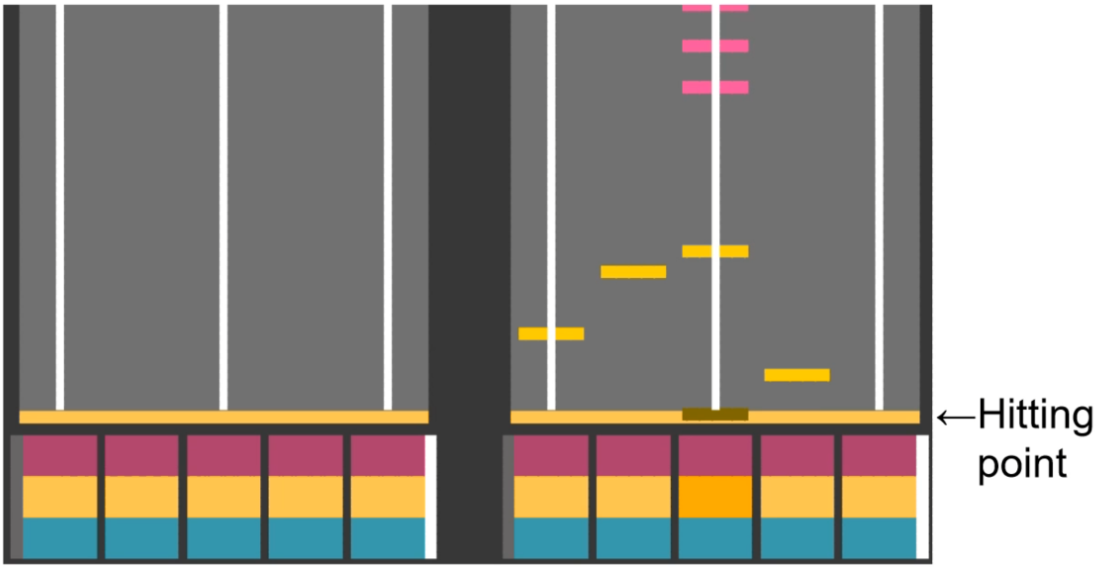
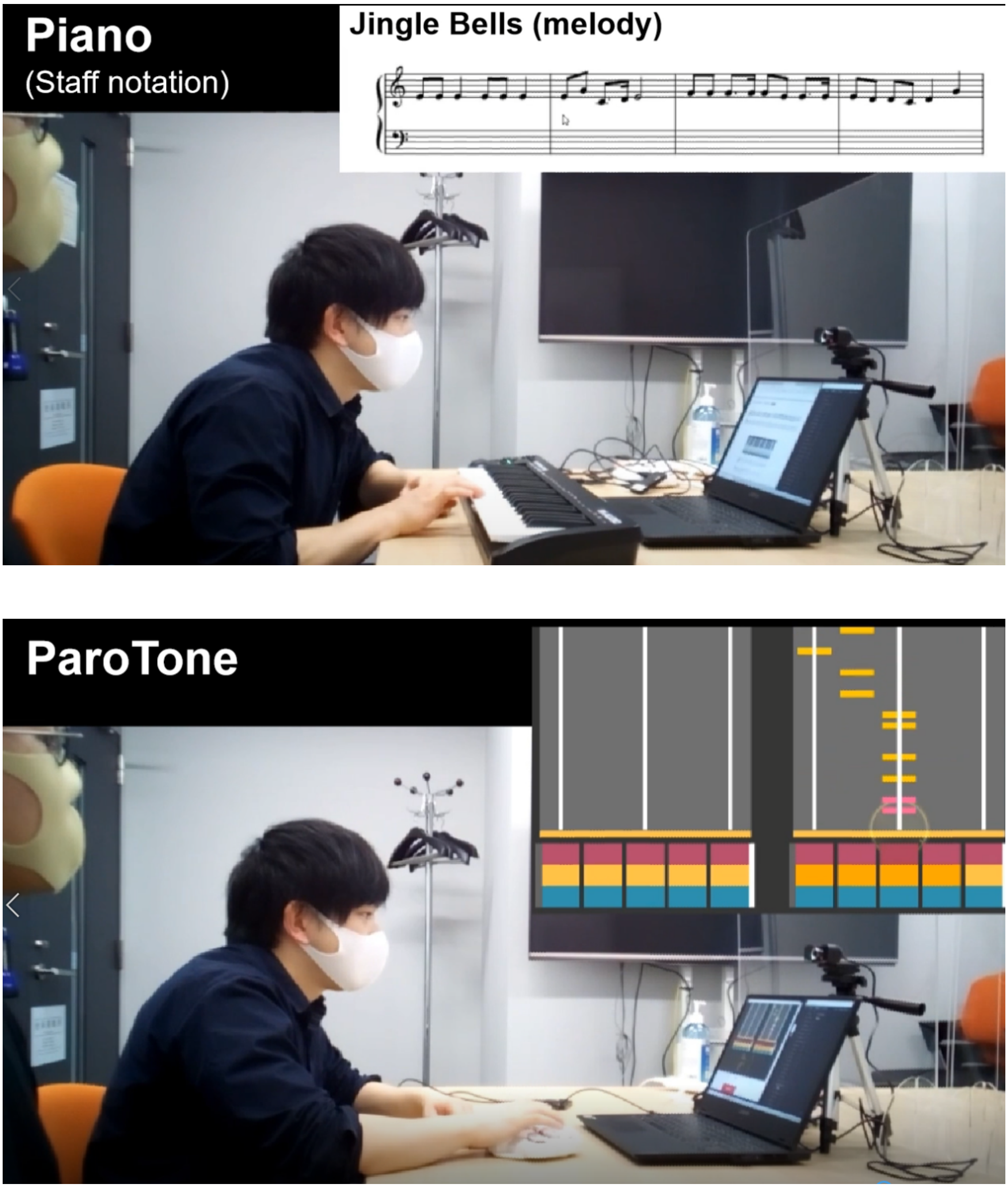


Supplemental video 4. Stopping notes at the hitting point.

Until the correct key was pressed, the musical notes stopped at the hitting point.

https://drive.google.com/file/d/1EZ8CRCIzYCgqRWeOsVJr-hWuxqD3eRID/view?usp=sharing



Supplemental video 5. Example video clips in experiment 1

https://drive.google.com/file/d/1_63poFCAWwxAaD2Knd-D1s_DcLAtTN8B/view?usp=sharing

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Bibliography

1. Achievements directly linked to this doctoral thesis

Publication (international)

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2. Other achievements

Publication (domestic)

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