Professor Plucky

Expressive body movement in human–robot musical ensembles

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ABSTRACT

When people play music together, they move their bodies, and that movement plays an important role in the activity of group music making. In contrast, when robots play music with people, the robots are usually stiff and mechanical in their movement. In general, it is not well understood how the movement of such robots affects how people interact with them, or how the robot movement should be designed in order to promote certain features of interaction. As an initial exploration into these questions, we built a prototype guitar plucking robot that plucks the strings with either a) kinetic plucking mechanisms that are designed to have visually appealing movement, or b) control plucking mechanisms that do not visually move. In a pilot study we found that when guitarists play with the robot, they move their hands more and look at the robot more when it uses the kinetic mechanisms as opposed to the control ones. However, they do not report preferring the kinetic mechanisms. These preliminary findings suggest some very clear hypotheses for future followup studies.

CCS CONCEPTS

• **Applied computing → Sound and music computing**; • **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

music, robots, musical robots, movement, gesture, mocap, eye-tracking, plucky, professor plucky, guitar, MOCO, NIME, interaction, expression

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Figure 1: Professor Plucky, prototype guitar plucking robot, with six kinetic plucking mechanisms mounted between the sound-hole and bridge, and a control plucking mechanism housed in a black box spanning the neck.

1 INTRODUCTION

Robots, including those that play music, are stereotypically stiff in their movement. Many of the world's most sophisticated musical robots scantly move at all. These include the Waseda Flute robot [26], the WABOT 2 [22] organ robot, Dr. Squiggles [16], dozens of pipe-organ robots at the Logos Foundation [17], and many solenoid-based robots for instance in the Karmetic Machine Orchestra [14] and by LEMUR [24]. Others, including many percussion robots employing drumsticks or mallets, do display some movement, although the primary focus is on the mechanics of playing and not the visual appeal of the movement itself. Human musicians by contrast use a wide variety of expressive movements, gestures, and signals when they play together. These include both rehearsed and spontaneous ones; conscious and subconscious ones, sound-producing and non sound-producing ones; and include nodding, body swaying, foot tapping, gaze direction, hand movements, and others. From this

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perspective it seems that many musical robots are missing an entire layer of important musical behaviour.

In this paper we ask broadly: How does a musical robot's movement affect the way people interact with it when they play with it? In particular, do a robot's musical partners move more, look at the robot more, or prefer it more when the robot moves in a visually appealing way? To explore this, we built a prototype guitar plucking robot called Professor Plucky, shown in Figure 1, which is designed to have visually appealing movement, even at the expense of mechanics. We then let human guitarists improvise music with the robot in a motion capture and eye-tracking studio, and then analyzed their movement and interviewed them about their experience.

2 PREVIOUS WORK

Musicians' expressive body motion has been studied extensively, in both solo and ensemble settings. The literature distinguishes between body motion that is essential for sound production and ancillary body motion, which is not directly involved in sound production and reflects musicians' individualized understanding of the music [10]. When musicians play with others, their ancillary motion tends to be more predictable (i.e., show less entropy) than when they play alone [9]. In ensemble playing, musicians exchange visual signals (e.g., exaggerated nods or breaths) that facilitate sound synchronization [4]. Gestures that are smoother and larger in magnitude make for more effective synchronization signals [5][29]. Musicians coordinate aspects of their periodic ancillary motion [11], sometimes demonstrating leader/follower relationships [7]. This coordination strengthens over time for ensembles who rehearse together and is also stronger between musicians who have a direct view of each other [3]. Ensemble musicians spend more time watching each other and depend more on visual synchronization signals when musical timing is irregular than when the timing is regular [2]. As in other forms of human interaction, gaze that is directed towards a musical partner is social in that it communicates the gazer's intention to interact [6]. Thus, gaze between ensemble members serves both to obtain information from others' expressive motion and to communicate intentions.

Regarding musical robots, less has been done. Seminal work on movement was done by Guy Hoffman and Gil Weinberg with the marimba robot Shimon [12]. The robot's striking gesture is thoughtfully designed, with preparation and follow-through. Moreover, the robot's movement plays a key role in how it improvises music. For example, in one mode of operation, the robot moves the mallets back and forth across the instrument roughly in time with the music, and only strikes a note when a mallet happens by serendipity to be in the right place at the right time. When people play music with the robot, they synchronize better when they have visual contact with it, especially during slow or changing tempi. This visual contact also makes the audience think the robot is more responsive, human-like, and better at playing. Later, a head was added to Shimon, and its movement has been used in a variety of ways. For instance Richard Savery et al [23] use the robot in rap battles, where it moves its mouth, eyebrows, and head position in time with the beat and lyrics as it raps. Other musical robots have also made use of expressive movement. In [21], a different marimba robot improvises with a human. One plays accompaniment while the other plays a solo, and they use eye-contact to trade roles. The company Toyota, as part of their ongoing work on robot dexterity, developed robots that play trumpet and violin, which can be seen performing with expressive body movement in several videos on the internet[1][2]. The same can be said for the piano robot TeoTronico, developed by the eponymous Italian company[3]. Social human-robot movement-based interaction has been studied somewhat more in the context of dancing robots [1, 19, 28], although it is not clear how well the same principles apply in the context of playing music.

Despite all of this previous work, there is still a considerable gap between the work done with humans and that done with robots. It is still generally unknown how a musical robot's movement affects how people synchronize with it, how they exchange information with it, how much they enjoy it, their creativity, and other aspects of the musical interaction. The primary purpose of this paper therefore is to serve as an entry point for a more detailed programme surrounding these questions in the future. As such, it contains a relatively exploratory pilot study that suggests that guitarists do move their hands more and look at the robot more when it moves in a visually appealing way, but they do not in general prefer the visually appealing movement. It remains to be seen whether the robot movement has any affect on the music that the guitarists produce. These findings evoke a number of potential followup studies that could provide more direct insight into the broader questions.

3 ROBOT DESIGN

The robot designed for this research, Professor Plucky, is shown in Figure 1. It consists of a guitar equipped with kinetic plucking mechanisms that move in a visually appealing way, and control plucking mechanisms that do not visually move. In the context of this paper, 'visually appealing' means that the movement follows several well-know principles of animation [13], such as exaggerated motion, lead in, moving along curves, and varying velocity. It is left as future work to validate the extent to which each of the principles contributes to user-ratings of the appeal of the movement. Both mechanisms are described in detail below. Professor Plucky is not a complete guitar robot and has no way of fretting the strings or damping them.

3.1 Kinetic Plucking Mechanisms

Each string of the guitar is equipped with its own kinetic plucking mechanism. One of these pluckers is depicted in Figure 2. The pluckers' visual design is based loosely on the animation seen in the video Resonant Chamber by Anamusic.[4] The mechanical design is based loosely on the characters presented in [8]. The pluckers consist of a 4-bar Grashof linkage in a crank and rocker configuration. The distal end of the rocker arm holds a guitar plectrum. The crank is driven by a small DC servomotor through a series of gears. When the crank moves at a constant angular velocity in the intended forward direction, the plectrum plunges slowly down next to the string and then plucks it with a rapid upward flicking

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[1] https://www.youtube.com/watch?v=PijbSFmzuUc
[2] https://www.youtube.com/watch?v=UC0ZJHtxNDE
[3] https://www.youtube.com/watch?v=EitorsOS9Vo
[4] https://www.youtube.com/watch?v=toXNVbvFXyk

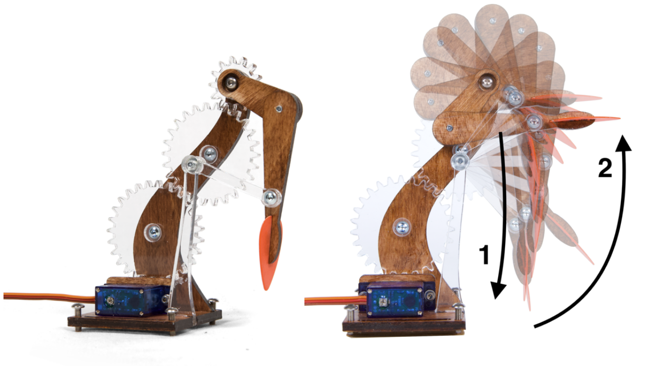

Figure 2: Left – One of the kinetic plucking mechanisms. Right – A composite image showing how the mechanism moves. The guitar pick (1) slowly plunges down next to the string, and then (2) rapidly plucks it with an upward flicking motion. The crank moves clockwise.

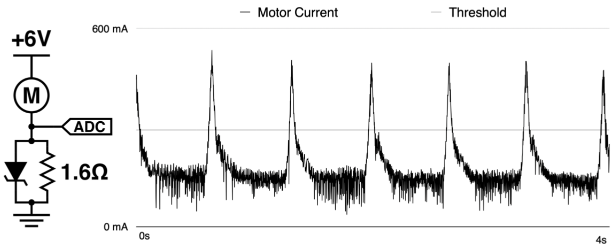

Figure 3: Left – The circuit used to measure current through a servomotor, M, using a 1.6Ω shunt resistor and an ADC pin on a microcontroller. The (Zener) diode provides transient protection for the ADC pin and has a forward voltage of about 0.7V and internal resistance of about 1.5Ω. Right – The current drawn by the motor while spinning at full speed for 4 seconds, sampled at 1kHz, with the spikes occurring when the plectrum is in contact with the string. The gray line is the threshold for determining when the string has been plucked.

motion. The mechanism follows several of the famous 12 Principals of Animation [13], such as exaggerated motion, lead in, moving along curves, and varying velocity. This suggests that the motion does have at least some visual appeal.

In order to pluck a string once reliably and stop, the servomotors in the pluckers need positional feedback. Additionally, the Grashof linkage requires that the servomotors rotate continuously through 360 degrees. Inexpensive servomotors either have positional feedback or continuous rotation, but not both.[5] To resolve this, the pluckers use continuous rotation servomotors, and achieve partial positional feedback in the following way. A small-value shunt resistor is placed in series with the motor, as depicted in Figure 3 (Left). The voltage drop across, and consequently the current flow through the resistor is measured by an ADC pin on a microcontroller sampled at 1kHz. As the motor turns, when the plectrum comes in contact with the string, the motor stalls slightly and draws more current for a few milliseconds before plucking it. Thus a spike in current locates the string. Initially, a calibration routine is performed in which each motor is run freely for 4 seconds, and the mean current is calculated. Then, during normal operation, in order to pluck a string, the motor is first turned on, and later off when the current rises past a threshold 1.5 standard deviations above the mean current. The motor will actually stop moving a few milliseconds later immediately after the string has been plucked, and will come to rest in the position seen in Figure 1. Data from an example calibration routine and the resulting threshold is plotted in Figure 3 (Right).

These pluckers as described have poor timing. This is because the crank needs to rotate all the way around before plucking the string, but the motors all move at slightly different speeds. A second calibration step was used to correct this. During this calibration, the robot plucks a string with a given plucker 10 times, pausing briefly between each pluck. The robot measures the average time between starting and stopping the motor across the plucks. This average ranges from roughly 500 ms to 700 ms across the various pluckers. Then during normal operation, when the robot receives a command to pluck a string, it waits a while before starting the motor, such that the total time from receiving the command to plucking the string is 1000 ms for each plucker. Further analysis of the efficacy of this is presented in Section 3.3 below.

Although this plucker is visually pleasing, it has some mechanical drawbacks. First it should have been designed with stepper motors, such that the plectrum can be stopped just before plucking the string instead of just after, thereby obviating the calibration steps. Second, the motors are loud, especially when placed on the soundboard. The particular guitar used has a built-in electric pickup that barely picks-up the sound of the motors. So during the user studies the guitar was amplified through a hemispherical speaker to increase the guitar-to-motor ratio. Finally, these pluckers have a repeat rate of only 1 Hz, which makes them impractically slow for real guitar music. However, as stated, the purpose of this is to study the visual aspects of the robot's movement, not the mechanics of guitar playing, so improving the repeat rate, motor noise, and other drawbacks is left for future work.

3.2 Control Plucking Mechanisms

Along with the kinetic pluckers, the guitar was also equipped with a second set of plucking mechanisms to serve as an experimental control. These have little visual appeal in their motion, and are depicted in Figure 4. They are based loosely on the pluckers used in the LEMUR GuitarBots [25], and MechBass [20]. The cited mechanisms are probably better and leave little to be desired from a mechanical perspective, but are somewhat too large to fit compactly on an actual guitar. Therefore the control pluckers used here consist of a guitar picks mounted directly on the horns of standard hobby servomotors. There is one for each string. They pluck the respective string by moving back and forth ±10 degrees from the center position. The movement is small and mostly obscured by the plywood that houses these pluckers.

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[5] Since continuous rotation servos lack positional feedback, they are arguably just gear motors in servo housings and not actually servos by definition, yet they are marketed as servos and I am retaining that nomenclature here.

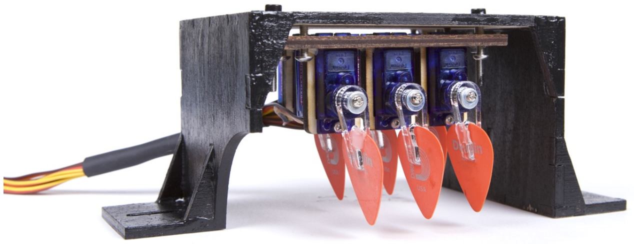

Figure 4: The control plucking mechanism, showing guitar picks mounted directly onto the horns of servomotors.

Figure 5: Top – The music used to measure Professor Plucky's timing. Bottom – Waveform of Professor Plucky playing the same, with the onsets, shown as overlaid vertical lines, labelled algorithmically.

These pluckers are overall much quieter than the kinetic ones, since the motors are only on very briefly for each pluck. To standardize this during the user study, one additional continuous-rotation servo was attached to the soundboard of the guitar. During the study, the motor was run continuously while the control pluckers were in use so as to mimic the sound of the kinetic pluckers.

3.3 Timing

The control pluckers have slightly better timing than the kinetic ones, since they need to travel a shorter distance in order to pluck a string. To standardize this during the user study, the notes to be played by the control pluckers needed to have their timing slightly randomized in advance. To determine the needed amount of randomness, Professor Plucky played the sequence depicted in Figure 5 (Top) with the kinetic pluckers. The sequence consists of 160 isochronous notes with inter-onset intervals of 300 ms. The direct output of the guitar was recorded into an audio file. Note onsets in the recording were automatically labeled with an onset detector[6] that has previously been shown to have zero mean error [16]. After the parameters were fine-tuned, the algorithm labeled virtually all of the onsets exactly once. Each label was manually confirmed to be in a plausible location, and one or two false positives and false negatives were corrected manually. The result of the labeling is partially shown in Figure 5 (Bottom). The mean interval across the 159 intervals was 300 ms as expected, and the standard deviation was 27 ms (average across five trials). This was repeated with the control pluckers instead of the kinetic ones, and the standard deviation was 20 ms (across five trials), indicating slightly better timing.

In order to increase the standard deviation of the control pluckers, all of the notes in Figure 5 (Top), were nudged backward or forward in time by a small random amount using the 'Humanize' function in Reaper (Digital Audio Workstation). This is is controlled via a slider ranging from 0%-100% humanization, but the exact statistics of the function are not known. To find out, 22 variants of the musical sequence were produced by applying varying levels of humanization from 2%-40%. For each variant, the standard deviation was again measured as described. Performing a linear regression on the resulting standard deviations σ as a function of the corresponding humanization percentage h showed that $\sigma = 0.791h - 13.21$ (R=0.98). Thus, applying 17% humanization to the control pluckers yields a standard deviation nearest to that of the kinetic pluckers (27 ms) and consequently 17% humanization was applied to the control pluckers in the user studies.

4 EVALUATION

To test whether people interact differently with the different pluckers, we invited human guitarists into a motion-capture lab individually to improvise duets with Professor Plucky. Based on music psychology literature showing that human musical partners mutually increase their body motion when they see each other moving [3], we hypothesized that participants would move more when improvising with the kinetic pluckers than when improvising with the control pluckers. We also hypothesized that participants would spend more time watching Professor Plucky when the kinetic pluckers were playing.

The guitarists were outfitted with motion capture suits and reflective markers on their head, arms, and hands. A 10-camera Qualisys system was used to collect motion capture data at 240 Hz. The guitarists also wore eye-tracking headsets from Pupil Labs [15], which collected gaze data at 200 Hz. They were given a guitar and asked to improvise while Plucky played pre-programmed music. The setup is shown in Figure 7.

4.1 Participants

We recruited 6 participants, all of whom were graduate students or postdocs at our university. Their level of guitar proficiency ranged from beginner to semi-professional, and three had extensive previous experience with improvisation. Two of the participants had direct experience working with different music technologies (e.g., musical robots or virtual agents; developing musical interfaces); three others worked in a lab where music technology is a focus, and therefore had some knowledge in the area.

4.2 Tasks

During the experiments, the participants were given three separate tasks. In all tasks, Professor Plucky played the music shown in Figure 6.[7] The first was a warm-up task in which a 2-minute recording of Professor Plucky playing the music in Figure 6 sounded through a hemispherical speaker underneath the robot. The participants were asked to play along and improvise with the music, building on the pattern played by Plucky. This gave the participants a chance to familiarize themselves with the musical material. Data were not

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[6] https://github.com/michaelkrzyzaniak/Beat-and-Tempo-Tracking

[7] The robot can be heard playing this pattern with both plucking mechanisms in a video. https://www.youtube.com/watch?v=atR9dJ-z1K0

Figure 6: The music played by Professor Plucky during the user study. The guitar is in an alternate tuning such that this was played entirely on open strings.

Figure 7: Photo showing the setup of the evaluation task. Photo by Annica Thomsson.

collected during the warm-up. The other two tasks were the main tasks. In one, the robot played Figure 6 for three minutes with the kinetic pluckers while the participant improvised. In the remaining task, the robot played for three minutes using the control pluckers while the participant improvised. Half of the participants were exposed to the control pluckers before the kinetic ones. After the tasks, the participants were asked several debriefing questions about their experience playing with the robot. These questions focused on what differences they noticed between the plucking mechanisms, which mechanism they preferred to play with, and what kinds of visual communication they normally find useful when playing with other people.

4.3 Analysis and Results

4.3.1 Body motion. Our analysis of body motion focused on participants' heads and hands and was carried out in R. Motion data were smoothed using a Savitzky-Golay filter (window size = 5; polynomial order = 3; using the library "prospectr" [27]) and differentiated to obtain velocities. The norms of 3D velocity data were then computed. As an indication of quantity of motion, we took the cumulative sum of velocity values per second.

Given the small sample size, we do not report inferential statistics. Quantity of head motion was marginally higher during improvisations with the kinetic plucker (M = 73.3 m/s, SD = 107.7) than during improvisation with the control plucker (M = 69.9, SD = 82.3). Quantity of head motion was also higher in the second improvisation (M = 84.2, SD = 110.4) than in the first (M = 59.0, SD = 76.8). Figure 9 shows the distributions of quantity of head motion values (log transformed for ease of viewing).

Quantity of hand motion, summed across left and right hands, was slightly higher in the improvisation with the kinetic pluckers (M = 111.3, SD = 68.6) than in the improvisation with the control pluckers (M = 102.5, SD = 70.5), and higher in the second improvisation (M = 120.1, SD = 76.4) than in the first (M = 93.7, SD = 59.4).

In summary, participants tended to move more in their second improvisation than in their first, and more when playing with the kinetic plucker than with the control plucker.

4.3.2 Gaze. Gaze data were manually annotated using the video recordings that were captured by the eye tracker. These videos comprise footage from a world-view camera with a visual overlay of moment-to-moment gaze position. Two participants were excluded from the analysis of gaze data because their eyes were not well-tracked (e.g., due to interference from corrective lenses). We calculated the time that participants spent looking at the guitar as a percentage of total playing time. As for head and hand motion, we do not report any inferential statistics, given the small sample size. This percentage was higher for the kinetic plucker (M = 25%, SD = 37%) than for the control plucker (M = 20%, SD = 31%), although variability between participants was high in both conditions. Counterintuitively, the lack of visual movement in the control condition may have piqued the curiosity of some participants, causing them to look more in an attempt to discover the hidden sound source.

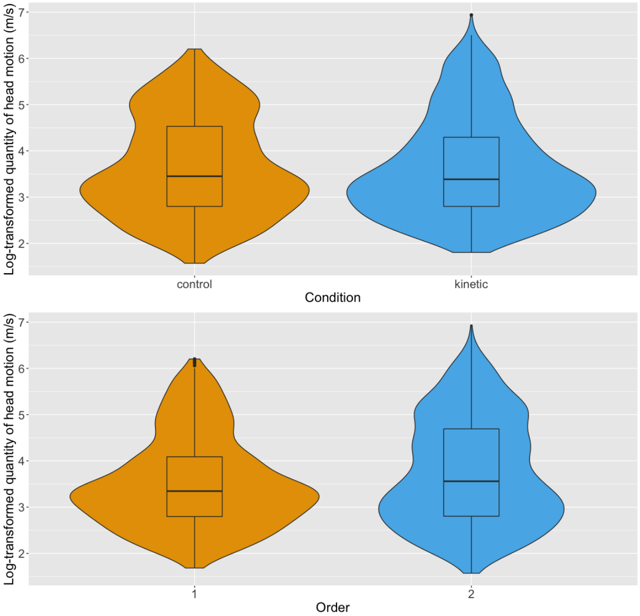

Figure 8: Quantity of head motion across conditions (control and kinetic) and improvisations (1 and 2).

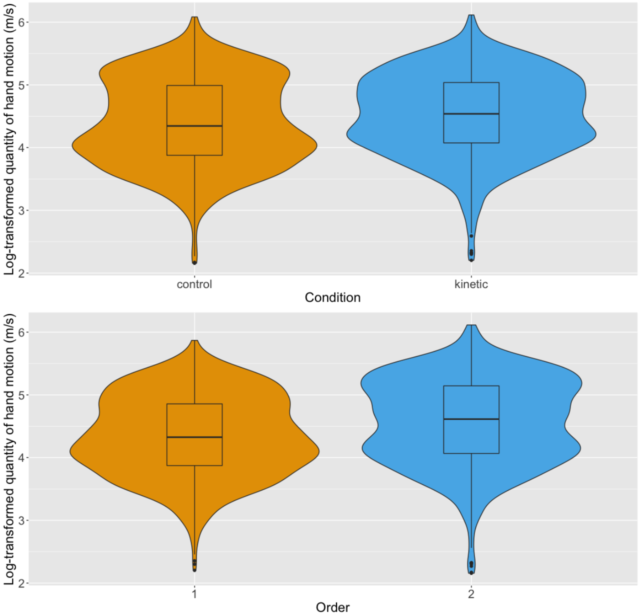

Figure 9: Quantity of hand motion across conditions (control and kinetic) and improvisations (1 and 2).

4.3.3 *Debriefing interviews.* Debriefing interviews were transcribed from audio recordings, and subjected to a thematic analysis. The main themes that were identified included participants' preferences for the two plucking mechanisms, their perception of how the mechanisms sounded, and their usual use of body motion cues during ensemble playing with other people. Their discussions on these themes are summarized below.

Participants differed in their preferences for the plucking mechanisms. Two preferred the control pluckers and four reported no clear preference between kinetic and control. Of these four, two surprisingly did not notice that different plucking mechanisms had been used in the two main tasks. Those who preferred the control pluckers reported that the motion of the kinetic pluckers was distracting, especially during the first moments of the improvisation. One participant ("P1") described the contrast between the mechanisms:

P1: "The first time, I found them a bit distracting but that could be also because I'm not that comfortable with improvising, and so I concentrated more on how to play... but then the second time I had to kind of look for where they were so they were kind of opposite, the one time it almost felt too much but then the other time I had to look for it."

There were some positive responses to the kinetic pluckers. Some participants described them in terms of "liveness" ("more alive"; "bit more like human activity"; "had some personality") or referred to them using biological terms ("arms" or "tentacles"). One participant (P6) said that the overt motion of the kinetic pluckers offered cues to timing and motivated him to synchronize:

P6: "When you see the movement I guess you can have a more precise understanding of the timing or the rhythm or what is going on...you can synchronize and at the same time you can feel the force or feel the motivation to follow the movement or you feel something is moving so you need to go alongside it. I guess that is another thing, so it is not just the timing, it makes you move with itself."

However, this participant may have been expressing prior knowledge of the project aims. In general, preference for the plucking mechanisms appeared to go with confidence in the improvising tasks, with less confident players preferring the control pluckers, and more confident players being indifferent.

Most of the participants reported focusing mainly on Professor Plucky's sound during the improvisations. All but one complained about the loud sound of the motors, which were distracting at times and prevented some participants from hearing their own audio. Two participants referred to the pitched component of the motors, and one perceived that the motor were out of tune relative to the guitar. The only participant who spoke positively about the sound of the motors said that it "incorporated more of a percussive element" which facilitated timekeeping. P4 described Professor Plucky's sound as "neat":

P4: "It is quite neat playing. There aren't any big timbral or dynamic surprises. So you kind of sense that throughout, I think that is why you feel the impulsion to try to do some of that stuff when you are playing along...I was concentrating on trying to think of things to play along and be responsive in a way. So slightly distracted I think..."

Some participants perceived differences in the sounds of the kinetic and control pluckers (e.g., control pluckers had "more rhythm"; kinetic pluckers were "more noisy"). A couple of participants heard differences in the sound quality that related to where on the strings the plucking took place (*sul tasto* versus *sul ponticello*).

When asked to reflect on how they normally use visual communication when playing with other people, participants said that they normally focus on the face of their human musical partners and get cues from full-body motion and posture. They suggested that seeing others' body motion makes them more predictable in terms of rhythm, tempo, and dynamics, that it gives an indication of their motivation or intention, and helps with "being together" or "finding synchronization". P4 noted that Professor Plucky does not currently convey a sense of intention through its plucking mechanisms:

P4: "Gesturally it is helpful, you get a sense of attack and dynamic from watching other people. You get a sense of intention, what they are hoping to do when you look at the musicians. Maybe that is the difficult thing here, is that you struggle to find that expressive intention."

5 DISCUSSION AND FUTURE WORK

There is likely a considerable disconnect between how the participants consciously and subconsciously interact through movement. During the interviews, the participants all discussed ensemble movement in terms of deliberate and obvious cuing gestures. The kinetic pluckers, by contrast, move continuously but without gesture, and the participants did not find this helpful, particularly given the predictable music that did not require cues. The data however suggest that it may be more subtle than that. This is highlighted by one of the two participants who did not notice that different plucking mechanisms were employed in the two main tasks. This participant was clearly staring directly at the respective mechanisms for a substantial period of time during the tasks, yet was shocked to see the difference later when we demonstrated it again after the experiment had ended. This same participant did also move their hands significantly more in response to the kinetic pluckers, suggesting that they did notice and respond to the difference, although completely subconsciously. Presumably this type of subconscious interaction routinely happens during normal ensemble playing. So one obvious followup study would be to check whether the participants actually played better in any of the tasks without having noticed it (they all reported no difference in their playing). Another obvious followup study would be to have the robot play more unpredictably, e.g. with variable-length pauses, so that the participants would need to consciously look for movement cues.

Moreover, the participants who found the kinetic pluckers to be distracting also appeared to be the least comfortable improvising. Ironically, these participants might subconsciously benefit the most from the distraction despite consciously disliking it. This is because certain motor-learning tasks have been shown to be more effective when the performer focuses their attention on the outcome of the task (external focus of attention) rather than on their own body (internal focus of attention) [18]. The ostensible distraction provided by the plucker movement may in fact provide exactly the shift of attention away from the participant's own playing that would enhance learning. This theory is at least partially supported by the increased time the participants spent looking at the robot when the kinetic pluckers were used. So another potential followup study would be to employ the participants in learning tasks with the robot, and check whether they learn faster with the kinetic mechanisms than the control ones.

Finally, in future iterations, the motors need to be moved off of the soundboard of the guitar. It is not surprising that the participants all had opinions about the motor noise, as the researchers consciously accepted the noise as a reasonable trade-off given the aims of the study. Nonetheless the noise does present some unnecessary obstacles in the studies, and should therefore be remedied.

6 CONCLUSION

In summary, we built a prototype robot that can pluck guitar strings with mechanisms that either do or do not employ visually appealing movement. In a preliminary pilot study we found that guitarists do look at the robot more and move their hands more when the visually appealing mechanisms are employed. However, the guitarists do not prefer this movement. As a pilot study with a small number of participants, these findings may not generalize. Nevertheless, some very clear themes emerged which have suggested some straightforward paths for additional research in this direction.

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REFERENCES

[1] Cecilio Angulo, Joan Comas, and Diego Pardo. 2011. Aibo jukeBox–A robot dance interactive experience. In *International Work-Conference on Artificial Neural Networks*. Springer, 605–612.

[2] Laura Bishop, Carlos Cancino-Chacón, and Werner Goebl. 2019. Eye gaze as a means of giving and seeking information during musical interaction. *Consciousness and Cognition* 68 (2019), 73–96. https://doi.org/10.1016/j.concog.2019.01.002

[3] Laura Bishop, Carlos Cancino-Chacón, and Werner Goebl. 2019. Moving to communicate, moving to interact: Patterns of body motion in musical duo performance. *Music Perception* 37, 1 (2019), 1–25.

[4] Laura Bishop and Werner Goebl. 2018. Beating time: How ensemble musicians' cueing gestures communicate beat position and tempo. *Psychology of Music* 46, 1 (2018), 84–106.

[5] Laura Bishop and Werner Goebl. 2018. Communication for coordination: Gesture kinematics and conventionality affect synchronization success in piano duos. *Psychological Research* 82, 6 (2018), 1177–1194.

[6] Davina Bristow, Geraint Rees, and Christopher D Frith. 2007. Social interaction modifies neural response to gaze shifts. *Social cognitive and affective neuroscience* 2, 1 (2007), 52–61.

[7] Andrew Chang, Steven R Livingstone, Dan J Bosnyak, and Laurel J Trainor. 2017. Body sway reflects leadership in joint music performance. *Proceedings of the National Academy of Sciences* 114, 21 (2017), E4134–E4141.

[8] Stelian Coros, Bernhard Thomaszewski, Gioacchino Noris, Shinjiro Sueda, Moira Forberg, Robert W Sumner, Wojciech Matusik, and Bernd Bickel. 2013. Computational design of mechanical characters. *ACM Transactions on Graphics (TOG)* 32, 4 (2013), 1–12.

[9] Donald Glowinski, Maurizio Mancini, Roddy Cowie, Antonio Camurri, Carlo Chiorri, and Cian Doherty. 2013. The movements made by performers in a skilled quartet: a distinctive pattern, and the function that it serves. *Frontiers in psychology* 4 (2013), 841.

[10] Rolf Inge Godøy and Marc Leman. 2010. *Musical gestures: Sound, movement, and meaning*. Routledge.

[11] Werner Goebl and Caroline Palmer. 2009. Synchronization of timing and motion among performing musicians. *Music Perception* 26, 5 (2009), 427–438.

[12] Guy Hoffman and Gil Weinberg. 2011. Interactive improvisation with a robotic marimba player. *Autonomous Robots* 31, 2 (2011), 133–153.

[13] Ollie Johnston and Frank Thomas. 1981. *The illusion of life: Disney animation*. Disney Editions New York.

[14] Ajay Kapur, Eric Trimpin, Afzal Singer, George Suleman, and George Tzanetakis. 2007. A comparison of solenoid-based strategies for robotic drumming. In *ICMC*. Citeseer.

[15] Moritz Kassner, William Patera, and Andreas Bulling. 2014. Pupil: An Open Source Platform for Pervasive Eye Tracking and Mobile Gaze-based Interaction. In *Adjunct Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (Seattle, Washington) *(UbiComp '14 Adjunct)*. ACM, New York, NY, USA, 1151–1160. https://doi.org/10.1145/2638728.2641695

[16] Michael Krzyżaniak. 2021. Musical robot swarms, timing, and equilibria. *Journal of New Music Research* (2021), 1–19.

[17] Laura Maes, Godfried-Willem Raes, and Troy Rogers. 2011. The man and machine robot orchestra at logos. *Computer Music Journal* 35, 4 (2011), 28–48.

[18] Nancy H McNevin, Charles H Shea, and Gabriele Wulf. 2003. Increasing the distance of an external focus of attention enhances learning. *Psychological research* 67, 1 (2003), 22–29.

[19] Marek P Michalowski, Selma Sabanovic, and Hideki Kozima. 2007. A dancing robot for rhythmic social interaction. In *Proceedings of the ACM/IEEE international conference on Human-robot interaction*. 89–96.

[20] Jim W Murphy, James McVay, Ajay Kapur, and Dale A Carnegie. 2013. Designing and Building Expressive Robotic Guitars.. In *NIME*. 557–562.

[21] Ye Pan, Min-Gyu Kim, and Kenji Suzuki. 2010. A Robot Musician Interacting with a Human Partner through Initiative Exchange.. In *NIME*. 166–169.

[22] Curtis Roads. 1986. The Tsukuba musical robot. *Computer music journal* 10, 2 (1986), 39–43.

[23] Richard Savery, Lisa Zahray, and Gil Weinberg. 2020. Shimon the Rapper: A Real-Time System for Human-Robot Interactive Rap Battles. *arXiv preprint arXiv:2009.09234* (2020).

[24] Eric Singer, Jeff Feddersen, Chad Redmon, and Bil Bowen. 2004. LEMUR's musical robots. In *Proceedings of the 2004 conference on New interfaces for musical expression*. Citeseer, 181–184.

[25] Eric Singer, Kevin Larke, and David Bianciardi. 2003. LEMUR GuitarBot: MIDI Robotic String Instrument.. In *Nime*, Vol. 3. 188–191.

[26] Jorge Solis, Keisuke Chida, Kei Suefuji, and Atsuo Takanishi. 2006. The development of the anthropomorphic flutist robot at Waseda University. *International Journal of Humanoid Robotics* 3, 02 (2006), 127–151.

[27] Antoine Stevens and Leornardo Ramirez-Lopez. 2022. *An introduction to the prospectr package*. R package version 0.2.4.

[28] Fumihide Tanaka, Javier R Movellan, Bret Fortenberry, and Kazuki Aisaka. 2006. Daily HRI evaluation at a classroom environment: reports from dance interaction experiments. In *Proceedings of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction*. 3–9.

[29] Clemens Wöllner, Frederik JA Deconinck, Jim Parkinson, Michael J Hove, and Peter E Keller. 2012. The perception of prototypical motion: Synchronization is enhanced with quantitatively morphed gestures of musical conductors. *Journal of Experimental Psychology: Human Perception and Performance* 38, 6 (2012), 1390.