Hear You Later Alligator

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Hear You Later Alligator: How delayed auditory feedback affects non-musically trained people's strumming

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ABSTRACT
Many musical instruments exhibit an inherent latency or *delayed auditory feedback* (DAF) between actuator activation and the occurrence of sound. We investigated how DAF (73ms and 250ms) affects *musically trained* (MT) and *non-musically trained* (NMT) people's ability to synchronize the audible strum of an actuated guitar to a metronome at 60bpm and 120bpm. The long DAF matched a subdivision of the overall tempo. We compared their performance using two different input devices with feedback before or on activation. While 250ms DAF hardly affected musically trained participants, non-musically trained participants' performance declined substantially both in mean synchronization error and its spread. Neither tempo nor input devices affected performance.

Author Keywords
Latency, compensation, music, guitar, assistive technology

ACM Classification
H.5.5 [Information Interfaces and Presentation] Sound and Music Computing H.5.2 [Information Interfaces and Presentation] User Interfaces — Prototyping

1. INTRODUCTION
Delayed auditory feedback (DAF) between activation of controls and production of sound can be disruptive, and reduce expressiveness and synchronization performance. DAF increases synchronization errors but musicians can use subdivisions of the overall tempo to reduce synchronization errors. Regardless of musical training, slow tempos reduce synchronization performance with an increased bias to tap before the beat. Studies conducted until now have focused mostly on how DAF affects musically trained people. The synchronization performance of people with no musical training under DAF and at different tempos is unknown. It is also unclear whether actuator feedback can help to cope with DAF. This is particularly important for assistive interfaces for musical expression (aIMEs), which often incur additional latencies, e.g. from filtering or verifying gestures to improve accessibility, and are used by people with less musical training, e.g. in musical therapy.

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2. BACKGROUND
Many instruments exhibit an inherent latency or *delayed auditory feedback* (DAF) between actuator activation and the occurrence of sound. For example, by moderating velocity a pianist can manipulate the latency by pressing (activating) a piano key to the audible onset of a soft note by as as much as 100ms [2]. While some musicians can detect latencies as low as 7-10ms [5], people tapping along to a beat on average have a tendency to tap before the actual beat. This *anticipation bias* amounts to around 50ms for non-musically trained people and about 14ms for musically trained people [1]. This bias, however, does not affect the ability to keep a continuous and steady beat. Highly skilled musicians can deviate from inter-tap intervals as little as 4ms [11]. Increased DAF can lead to note errors (sequencing of notes), prolonged play time, erratic changes in key stroke velocity, and errors in inter-hand coordination. This disruption increases with delay and its effect peaks at 200ms, after which it decreases again [5, 9]. DAF can degrade the perceived quality of an instrument [6]. Pfordresher and Palmer showed that DAF disruption in a rhythmical sequence using professional pianists could be lowered if the DAF was close to a subdivision of the overall tempo [9].

The average flutter, i.e. the differences between adjacent *Inter-Onset-Intervals* (IOI), of the hits by a professional percussionist playing along to a metronome ranged between 10 and 40ms or between 2-8% of the associated tempo in relative terms [4], suggesting that tempo moderated anticipation bias. Takano defined *synchronization error* (SE) as the difference between the point in time from a metronome beat and the activation of a note [12].

Asynchronies of 50ms or more between different orchestra members are common already from the spatial arrangements, e.g. a distance of 10 meters adds 30ms due to the speed of sound [10].

Interfaces for musical expression (IMEs) can provide primary feedback such as visual, auditive (instrument noise), tactile, and kinesthetic or secondary feedback (the generated sound). Bongers described *passive feedback* as the feedback produced by the physical characteristics of the system (clicking noise of a button etc.) or as active feedback produced in response to a certain gesture [3].

3. STUDY
The test investigated how precisely *musically trained* (MT) (regardless of instrument) and *non-musically trained* (NMT) people could synchronize the audible strum of the actuated

guitar [7] to a metronome given either a small (73ms) *inherent system delay* (from triggering the input device to sound) or a large *delay* of 250ms. We compared two foot pedals providing different haptic feedback to investigate if earlier haptic pre-activation feedback could help the participants to better synchronize the strum to the metronome beat.

3.1 The Strumming Device

The aIME used was the Actuated Guitar [7], which is an off-the-shelf electrical guitar (Epiphone SG) fitted with a strumming device operated by a foot pedal for improved accessibility. The strumming device was made from a motorised mixing desk fader positioned above the bridge pickup (see Figure 1) to drive a glued-on pick across the strings. Foam stoppers at each end of the fader shortened the distance the pick had to travel, lowering latency and reducing noise when the pick hit the end of the fader. An Arduino controlled motor managed the speed and direction of the pick. Two different foot pedals activated a strum of all strings. The first consisted of a momentary button mounted in a plastic housing, which raised the button 5.5cm above the ground. The button provided haptic feedback (resistance) from the time it was first touched to when it was fully depressed taking typically around 30ms. The second input device, made from a *force sensitive resistor* (FSR) taped flush to a surface board, only provided haptic feedback when the foot hit the wooden backboard, see Figure 2.

3.2 Data Logging

The momentary button, FSR and metronome were all connected to their own separate Arduino to avoid increasing the computations on the Arduino in the guitar and thereby increasing the latency of the guitar strum. An Adafruit Data Logging Shield with a built in clock and SD-card reader logged timestamps, metronome, sensor, and button data with millisecond precision. These components were built into the casing that held the momentary button.

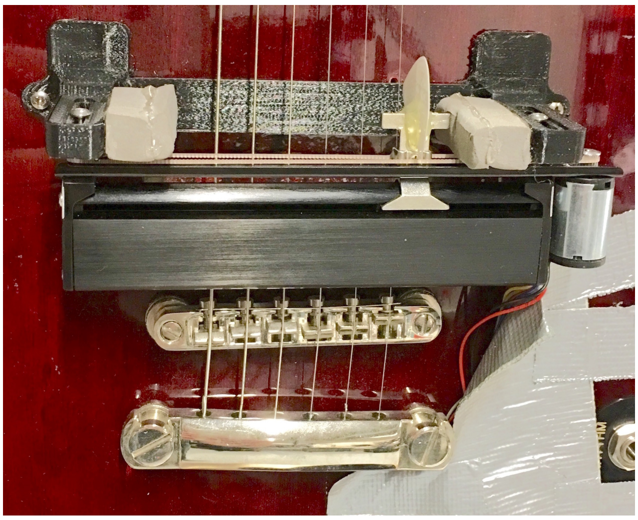

Figure 1: The motorised fader mounted above the bridge pickup. Gray foam stoppers on each side reduced noise and the pick's travel distance.

A custom-built Arduino-based metronome generated primary beats at 2.1kHz and the supporting beats at 1.7kHz with a buzzer at either 60bpm or 120bpm. It provided no visual indication of the beat. Each high beat was sent to the data logger that allowed for the computation of synchronization errors between the generated beats and the push

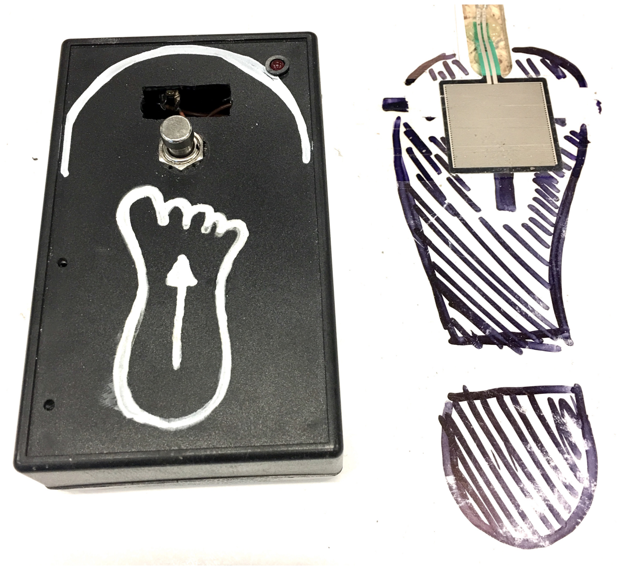

Figure 2: A momentary button in a plastic casing containing the data logger (left) and a force sensitive resistor button mounted flush on a board (right) to trigger strums

data from the two input devices.

Using a 240 frames per second GoPro camera we determined a 45ms system latency between activation of the momentary button and the plectrum picking the first string and 73ms for the pick to reach the last string. For more precise alignment and verification of activations a camera recorded an LED that lit up when the button closed the circuit. The participants had no access to this visual feedback.

At both 60bpm and 120bpm, 250ms was the subdivision closest to Finney and Pfordresher's most disruptive delay (200ms). To yield a 250ms delay between activation and strum the Arduino controlling the motor added 177ms to the system's inherent 73ms delay.

3.3 Participants

We recruited twelve participants (n=12, age= 39.9 years, from 16 to 65 years old, four women) - three from campus and nine without ties to higher education. Half of the participants had at least five years of musical training or experience from paid tuition or regular band practice - referred to as musically trained (MT) - the other half had no musical training or experience - referred to as as non-musically trained (NMT). All participants wore flat soled shoes. Guitar play experience was not required as the participants merely strummed through foot activations and did not 'play' the guitar, e.g. fretting chords.

3.4 Procedure

The test participants were divided into two groups, each of which consisted of three participants with musical training and three without musical training. The first group played at a *tempo* of 60bpm and the second at a *tempo* of 120bpm - the between subjects factor. Each participant played in four conditions of both *delays* (73ms, 250ms) combined with each *input device* (momentary button, FSR) as within subject factors. The orders of the *input device* and *delay* were counterbalanced. At 60bpm the participants played four minutes and at 120bpm two minutes at each condition to ensure that each participant got the same amount of training, i.e. the number of times they triggered the input device.

We observed, video recorded, timed, and helped change input devices and delays during each session. Before starting in each condition, the participants were allowed a few strums on the input device. The delay condition was not disclosed to the participants, who had to adapt their timing to synchronize to the metronome beat in each condition.

For each participant and condition we computed the median synchronization error (SE) - the time difference between the audible strum (derived from the activation times tamp plus the system latency) and the metronome beat. Negative values indicate strums before and positive values indicate strums after the metronome beat. We computed the SE spread as the difference between the third and the first quartile of the synchronization errors. The participants' median synchronization errors and synchronization error spreads - our dependent variables - were subjected to four-way ANOVA tests with *delay* and *input type* as within and *musical training* and *tempo* as between subject factors.

4. RESULTS

We found a significant main effect for *delay*, F(1, 36)=26.7, $p \ll 0.001$, and an interaction between *musical training* and *delay*, F(1, 36)=27.3, $p \ll 0.001$ on synchronization error.

While the mean synchronization error of musically trained participants was close to constant, irrespective of delay, the non-musically trained participants' mean synchronization error increased from −8.5ms for short (73ms) to 51ms for long (250ms) delay, see Figure 3.

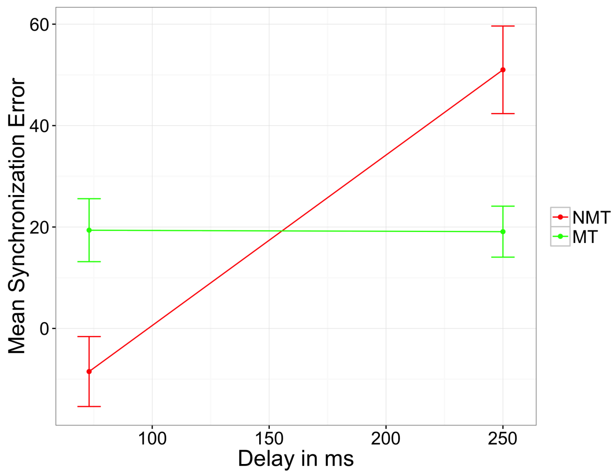

Figure 3: The mean synchronization error of musically trained (MT) and non-musically trained (NMT) participants (N=6+6) by delay including 0.95 confidence interval error bars.

Similarly, the ANOVA test of the spread of the participants' *synchronization error* found the same effects - for *delay*, F(1, 36)=21.7, $p \ll 0.001$, and the interaction (see Figure 4) between *musical training* and *delay*, F(1, 36)=10.6, p=0.002. While musically trained participants had an increased synchronization spread from 44ms to 55ms, this difference was not significant according to a t-test (t(5)=0.71, p=0.51). In comparison to the low delay, the high delay almost doubled the mean spread of the synchronization error (from 73ms to 137ms) of the non-musically trained participants. The density plots in Figure 5 for 60bpm, momentary button, 73ms and 250ms delay illustrate the bigger spread for the non-musically trained participants.

For *tempo* we found no effect on the mean synchronization error but the ANOVA on its spread bordered significance F(1, 36)=3.57, p=0.067. At 120bpm the spread of synchronization errors was larger (88ms) than at 60bpm (67ms). Neither on synchronization error nor on its spread did we find significant effects for *input type*. Regarding input devices all participants mentioned the lack of primary feedback (haptic, visual, auditive) [8] when using the FSR, which made correct positioning of the foot difficult. This lack of feedback prompted them to bend down and lift their foot to use the eyes for guidance. Three users lost the position during the test and struggled to quickly find the resting position again before continuing the test.

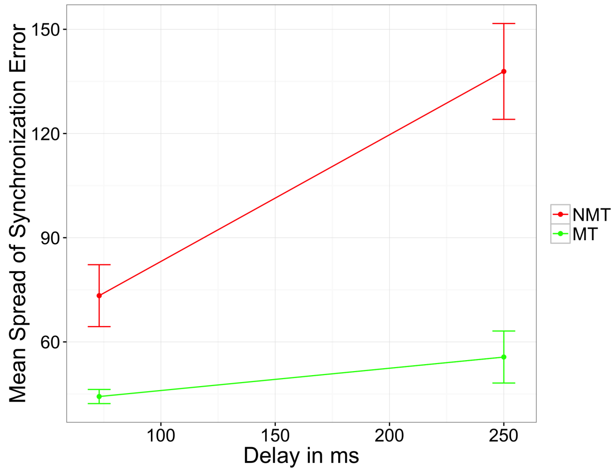

Figure 4: The mean spread of synchronization errors of musically trained (MT) and non-musically trained (NMT) participants (N=6+6) by delay including 0.95 confidence interval error bars.

Moreover, seven participants (all male) with bigger feet initially needed some time to find a comfortable foot position on the enclosure with the momentary button as the physical dimensions in height and length of the casing containing the momentary button made it difficult to quickly find a good pivot position. Four participants found that the passive feedback [3] (clicking sound) from the momentary button distracted them from focusing on the metronome. The height of the momentary button, combined with the short length of the housing, made it impossible to rest the heel on the floor while pushing the button, which forced the participants to position their foot on the edge of the housing to get a good pivot point. That caused some starting issues, but after a few minutes it was not an issue. Four participants (mixed) complained that it was difficult to focus on the metronome as some felt it was drifting, others locked on to an off-beat, and some felt the passive feedback from the momentary button was distracting.

5. DISCUSSION

Figure 3 shows that NMT participants performed better (with smaller synchronization errors) than MT participants with the short delay (73ms). At first glance this seems to contradict that musicians tend to have smaller synchronization errors (in the form of a small negative anticipation bias) compared to non-musically trained. However, remember that the synchronization error was computed as the distance from the strumming of the last string to the metronome beat. If we computed the synchronization error from the first string (45ms) the mean synchronization error would be -36ms for NMT and -10ms for MT. These values are a lot closer to what previous research has found [1, 4]. This shows that the participants were, in fact, trying to synchro-

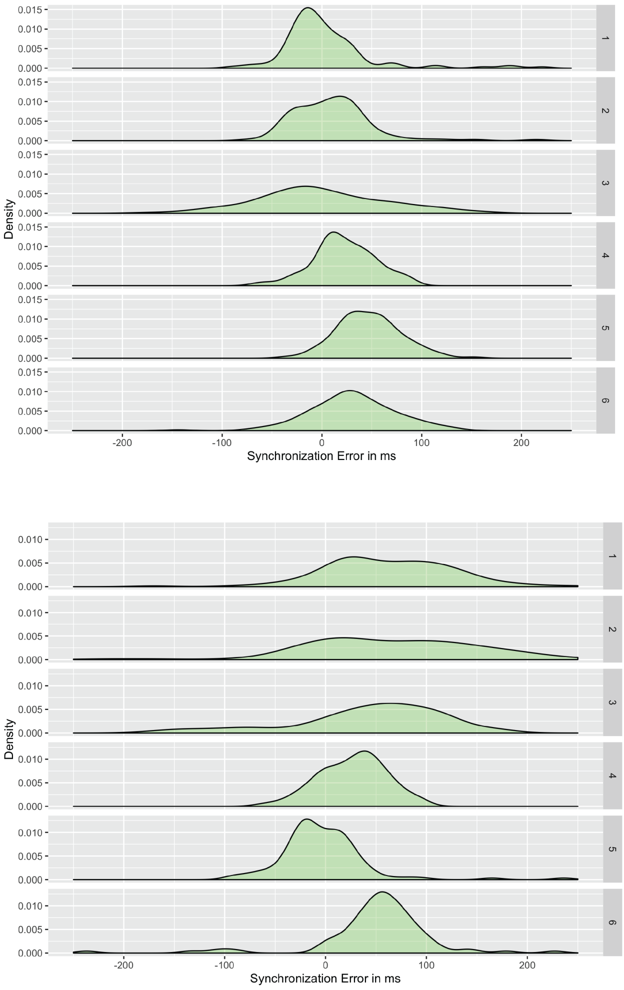

Figure 5: Density plots of six participants playing at 60bpm using the momentary button. Participant (1-3) non-musically trained and participant (4-6) musically trained with 73ms delay (top) and 250ms delay (bottom).

nize to the beginning of the strum and could factor in the system delay (45ms to first string). The results indicate MT participants were not affected by the large delay, but NMT participants' synchronization error was increased by 60ms. While the NMT's mean synchronization error of 50ms seems low, as these are common in musical performances [10], the actual spread of their synchronization errors at 250ms DAF was rather large (138ms) (see Figure 4 and 5), which shows that NMT participants were struggling to reliably synchronize to the beat. The MT participants performed equally well under both delays with a small increase in spread, suggesting that they could time their activations consistently, unaffected by the 250ms DAF. Asked about their strategy for coping with the long DAF, two MT participants explicitly mentioned recognising hitting the subdivision of the beat in this setting - in line with Pfordresher's findings. The two tempos used in our study did not affect synchronization error spread substantially (11ms difference), but the trend was in the opposite direction of previous findings by Dahl [4]. Her participants, however, did not play along to a metronome, played at faster tempo, and experienced no DAF. Future research needs to address this further.

While the input devices had some notable differences and participants struggled to a small degree with them, this did not affect the participants' performance. They performed equally well using the momentary button and the FSR to control the strumming. The qualitative feedback highlighted confusions stemming from the auditory pre–activation feedback that might have negated the tactile feedback benefits of the momentary button before activation.

6. CONCLUSION

Delayed auditory feedback has detrimental effects on synchronization performance of non-musically trained people. Unlike for musically trained people this cannot be overcome by increasing system delays to subdivisions of the overall tempo. When building assistive instruments for rehabilitation purposes designers should strive to minimize system latency. While our healthy participants' synchronization performance did not benefit from an input device with pre-activation feedback, this might not hold in musical therapy due to other benefits these controls provide. Musically trained people can be subjected to longer DAF if they are close to subdivisions of the overall tempo, which implies that aIMEs should allow for adjusting activation latency.

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