Effects of Rhythmic Stimulation of Different Sensors on Rhythm Stability and Cognitive Load

Li Yu*
whes11102@gmail.com
National Taiwan University of Science and Technology
Taipei, Taiwan

Chien-Hsiung Chen
cchen@mail.ntust.edu.tw
National Taiwan University of Science and Technology
Taipei, Taiwan

Abstract

Both auditory and tactile metronomes have been found to increase cognitive load in instrument learners, which can negatively affect their musical expression and rhythm stability. Although multisensory integration has the potential to enhance user performance and subsequently reduce cognitive load, previous research has often overlooked the complex cognitive processes involved in playing an instrument. This pilot study tested how auditory, tactile, and combined metronomes affect users' cognitive load and rhythm stability. The results are as follows: (1) the combined metronome significantly improved rhythm stability during instrument playing, and (2) it is still unknown which metronome requires the least cognitive load because the task itself did not engage sufficient cognitive resources. This study suggests that the multisensory metronome can improve rhythm stability, enhancing the efficiency of practice and the musical performance of amateur musicians.

Keywords

rhythm stability, cognitive load, sensorimotor synchronization, music learning, multisensory Integration

1 Introduction

Metronomes are essential practice tools for both beginners and advanced players, helping them to maintain a steady tempo while practicing. Arthur et al. stated: "…, as the level of a musician's expertise increases, so too does the use of the metronome in their personal practice" [2]. Advanced players continue to use metronomes while practicing difficult passages, and their usage increases with skill level [8, 25, 30].

For the past 200 years, metronomes have indicated the correct tempo through auditory cues, but only in the past ten years have different ways emerged. Tactile metronomes have been invented, allowing performers to avoid auditory interference [26, 27]. However, both types of metronomes can increase cognitive load during instrument playing. Music performance is a complex task that involves controlling an instrument, reading music, listening to what is being performed, and conveying musical tension through expressive gestures [12]. Nevertheless, auditory metronomes may interfere with musicians' perception of their music [23], while tactile metronomes can disrupt their perception of the instrument's vibratory feedback [13, 18]. Moreover, the kinesthetic sensations caused by musical gestures may obscure the cues from the tactile metronome [1], further increasing cognitive load.

Additional cognitive load can impair musical expression and lead to rushing. Research by Çorlu et al. shows that under dual-task conditions, participants not only perform with less musicality but also are more prone to rushing during phrase breaks, their predictive ability also becomes less accurate [21].

Current research has not demonstrated which type of metronome leads to significantly better task performance and reduced cognitive load during music playing. Compared to auditory metronomes, task performance with tactile metronomes is poorer, but the difference is not statistically significant [5, 18]. Multisensory integration (including auditory and tactile sensing) may help individuals synchronize more precisely with the metronome; however, existing research has not fully considered the complex multitasking nature of instrument playing [28].

For musicians playing high-volume instruments or with hearing impairment, vibrotactile metronomes are not a convenience but a necessity. Wind instruments and drum kits can easily obscure the auditory metronomes, making it difficult to perceive the cues and reducing practice efficiency. Therefore, research on vibrotactile and multisensory metronomes is invaluable to them.

This study aims to help music learners reduce the cognitive load during instrumental practice and enhance rhythm stability. To achieve this goal, the study focuses on the following questions: (1) Among auditory, tactile, and multisensory metronomes, which requires the least cognitive load, and why? (2) Can multisensory integration improve the rhythm stability of music learners? A single-factor experimental design was adopted within the subject to examine differences in rhythm stability and cognitive load when using different types of metronomes during instrument playing. Each participant underwent three conditions: auditory, tactile, and both. In each condition, participants played a one-octave scale on a MIDI keyboard. After each condition, participants completed the NASA-TLX (NASA Task Load Index) scale to measure cognitive load. During the experiment, deviations from the target tempo (in milliseconds) were recorded in real-time. Post-experiment interviews were conducted to understand participants' preferences for different types of metronomes and the nuance between them.

2 Background and related works

To minimize cognitive load, having a deep understanding of cognitive load, as well as human's physiological limitations and capabilities is critically important.

2.1 Ways to reduce cognitive load

"Cognitive load refers to the total amount of cognitive resources during information processing" [35]. Its increase is related to excessive extraneous load and the number of information-processing channels involved, so modifying how information and tasks are

*Both authors contributed equally to this research.

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Table 1: A comparison of asynchrony and deviation from target IOI under different task types and conditions

Task type	Measures	Performance Ranking*
Finger tapping [22, 33]	Asynchrony	Auditory and tactile, (Auditory, Tactile), Visual
Drum playing [18]	Asynchrony	(Auditory and tactile, Auditory), Tactile
Guitar playing [5]	Asynchrony	Auditory, Tactile
Guitar playing [5]	Deviation from target IOI	(Auditory, Tactile)

* Ranked from best to worst. There are no significant differences between the senses listed in parentheses.

presented and leveraging multiple sensory modalities in task execution can reduce cognitive load [15]. According to Wickens, humans possess multiple information-processing channels (e.g., auditory and visual systems), and simultaneous processing through these channels does not impair individual efficiency [32]. Research shows that using multiple channels to perform multitasking yields better performance than relying on a single channel. Thus, providing information across multiple channels can reduce cognitive load and improve task performance.

2.2 Human physiological limitations & abilities

Following a metronome requires sensorimotor synchronization (SMS)—a temporal coordination of an action with events in a predictable external rhythm, such as music or someone else's walking pace [29]. According to Lederman and Klatzky, one's ability to resolve temporal information may constrain auditory and tactile perception [17]. Therefore, understanding the human temporal information resolving power can ensure that the cognitive load of the task does not exceed the user's ability.

The level of SMS can be assessed through measures such as asynchrony and deviation from target Inter-Onset Intervals (IOI), which is the time that elapses between the onsets of two consecutive notes. Asynchrony refers to the difference in time between motor output and stimulation; larger values indicate greater instability [22]. Deviation from target IOI refers to whether participants' IOI match or deviate from the target IOI; again, larger values suggest greater instability [19]. Both of them can reflect whether one's SMS ability is stable, and the latter also indicates whether the user can accurately follow the target tempo.

As shown in Table 1, the asynchrony of the auditory sense is generally superior to that of the other sensory modalities, and multisensory integration may yield even better results. The visual sense is less stable than the auditory sense [22], while the tactile and auditory senses are comparable. Combined sense (auditory and tactile) performs best [33], suggesting that multisensory cues help performers synchronize more accurately with a metronome. This is consistent with the prediction made by optimal multisensory integration models. However, such studies generally instruct participants to tap a surface with their index finger in sync with the metronome, and this task requires less cognitive load than playing an instrument, where musicians must pay attention to musical elements such as rhythms, notes, and dynamics [34]. Additionally, finger-tapping research typically applies tactile stimuli to the fingertips, which are the most sensitive tactile areas, but this is impractical while playing an instrument due to the fine motor control required from both hands. To more closely approximate real-world scenarios, Mead et al. and Giordano and Wanderley measured asynchrony in drummers and guitarists while playing instruments [5, 18]. Unlike finger-tapping experiments, these showed higher asynchrony for tactile than for auditory cues. Tactile suppression is a possible explanation: musical gestures are more complex than finger taps and may reduce tactile sensitivity [1].

According to Table 1, the deviations from target IOI under tactile and auditory senses are similar. Giordano and Wanderley analysed deviation from target IOI when guitarists used auditory versus tactile metronomes. At 60 BPM, the median value for both types was about 40 milliseconds, with similar variability [5].

In summary, current studies have not yet demonstrated that multisensory metronomes improve rhythm stability in the actual musical scenario. Therefore, this study aims to investigate the cognitive load required to use different types of metronomes and determine whether multisensory integration can improve performance while playing an instrument.

3 Research Methods

This study evaluated cognitive load using both subjective and objective methods. The subjective method is the NASA-TLX scale, the most commonly used scale for assessing cognitive load in human-computer interaction research [15]. Table 2 shows that NASA-TLX consists of six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration level. The average score of these six dimensions was used to estimate the overall workload score. The objective measure is deviation from target IOI, as it not only reflects whether participants' sensorimotor synchronization (SMS) is stable but also checks the accuracy of their rhythm. Aside from that, deviation from the target IOI was measured in the related literature [5], so the results of this study can be compared with previous research.

3.1 Task Design and A quick Tutorial

This study adopted a within-subjects single-factor experimental design, in which each participant experienced three types of metronomes: auditory, tactile, and both. Participants were recruited through convenience sampling and must have prior music learning experience, which is defined as having studied music outside of school music classes, such as through school clubs, bands, or private tutoring. The study did not limit participants to keyboard learners (the instrument used in this experiment), as any music learning experience can enhance SMS abilities. For instance, percussionists tend to have better rhythm stability than those without musical training [16], so such participants were not excluded. Complete counterbalancing was used to eliminate order and sequence effects, and each order was randomly assigned to participants.

Table 2: NASA-TLX rating scale definitions [10]

Title	Endpoints	Descriptions
Mental Demand (MD)	Low/High	How much mental activity was required (e.g., thinking, deciding, perceiving and reasoning, etc.)?
Physical Demand (PD)	Low/High	How much physical activity was required?
Temporal Demand (TD)	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred?
Performance (OP)	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter?
Effort (EF)	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level (FR)	Low/High	How discouraged, irritated, stressed and annoyed did you feel during the task?

Participants were instructed to follow the beat of metronomes, playing one octave of a musical scale on a MIDI keyboard at 60 BPM, which means the target IOI is 1000 milliseconds. The scale was chosen mainly because advanced learners and novices are inclined to practice scales when they want to improve technical skills [6]. Therefore, using a scale as a task is closer to the real scenario. Choosing a rather low speed is because practicing slowly can help music learners practice the difficult fast passages more effectively and improve their techniques [24]. Furthermore, although Wing et al. have shown that at a speed of 600 ms, the multisensory metronome has better performance than both auditory-only and tactile-only metronomes, lower speeds have not yet been verified [33]. Therefore, it is necessary to experiment with a slower tempo.

As not all participants had learned to play keyboard instruments, instructions on posture and fingering were provided before the task to avoid incorrect posture, hand positioning, or inconsistent fingerings, which might affect the experiment's effectiveness. For posture, the teaching method from the book *Piano Technique: Tone, Touch, Phrasing and Dynamics* is followed [20]. Participants were asked to adjust the chair to the keyboard so that their bodies were neither too close nor too far, which could put strain on their hands. The fingering was based on *The Virtuoso Pianist in Sixty Exercises for the Piano* and illustrated in the task instruction diagram, as shown in Fig. 1 [9].

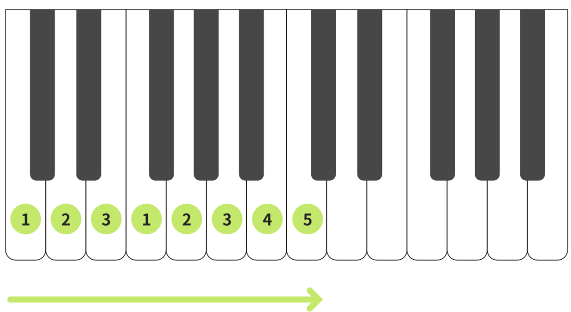

Figure 1: The task instruction diagram, which was shown to the participants

3.2 Experimental System Design

Max/MSP was used as the central system, which generated metronome signals as output and received MIDI keyboard signals as input. Max/MSP is a visual programming language that can create interactive installations, music, or multimedia performances, and has been widely used in related research [5, 14, 23].

3.2.1 Output Devices. Two types of outputs were used: auditory and tactile. The auditory output is delivered through Beyerdynamic DT900 PRO X headphones. It had a timbre similar to the preset timbre of Soundcorset Tuner, the most-downloaded and highest-rated metronome app on Google Play (as of February 7, 2026), to simulate the actual scenarios the users face. The waveforms of them are shown in Fig. 2. For the tactile output, an Eccentric Rotating Mass (ERM) vibration motor was connected to an Arduino Uno R3 board and fixed on the forearm of the participant's dominant hand through an elastic strap. The overall experimental equipment and setup are shown in Fig. 3. Common types of vibration motors include ERM, LRA, and piezoelectric motors. LRA and piezo motors require higher voltages, are expensive, and less accessible. In contrast, ERM motors are more powerful at the same voltage, cheaper, easier to obtain, and are used in most tactile metronomes on the market, making them the final choice for this experiment [11]. Since piano playing typically involves both hands, applying the stimuli to the performing hand better represents the real scenario.

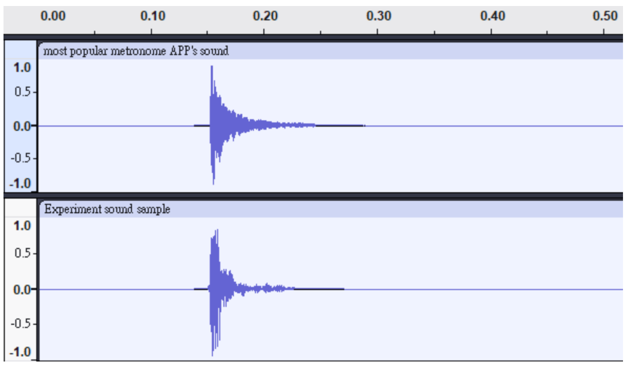

Figure 2: The waveform of the sound samples used by the metronome app (top) and this experiment (bottom)

3.2.2 Input Device. The experiment focused on the keyboard instrument because the piano and keyboard are the least gendered instruments [7]. Since MIDI keyboards are compatible with Max/MSP and convenient for data analysis, a Nektar Impact LX61+ was used in the experiment.

Table 3: Interview outline

Part	ID	Questions
1	Q1	Which metronome is the easiest or hardest to use when playing? Why?
1	Q2	Which metronome could help you focus on playing and require the least effort to perceive the metronome beat?
1	Q3	How would you rank these three metronomes?
2	Q4	Which tempo cues are clearer and easier to perceive, the tactile or the sound metronome?
2	Q5	Which sensory stimuli do you rely on more when using the multisensory metronome?

3.3 Experimental Procedure

The experiment followed these steps:

(1) **Participants' background investigation:** Participants' field of expertise, years of music learning, types of instruments learned, and frequency of playing instruments were investigated. Participants' dominant hands were also recorded to determine the performing hand and appropriate fingering.
(2) **Quick tutorial and stimuli adjustment:** The experimenter introduced the experiment's purpose, tasks, and procedure. Then, a quick piano tutorial and task explanation were provided. Once the participants fully understood the task, they wore the headphones and attached the tactile metronome. To prevent experimental bias caused by unequal perceived intensity of the sound and vibration stimuli, an equalization phase was performed for each participant. Both stimuli were played simultaneously at 30 BPM, and participants assessed whether the sound was stronger or weaker than the vibration stimuli. The sound volume was then adjusted accordingly.
(3) **Practice:** In the practice stage, each participant practiced the task 10 times before the formal experiment. This helped them become familiar with the keyboard layout and fingering and reduced order effects in the collected data.
(4) **Formal experiment:** After the metronome was played, the participants could decide when to start playing. During the task, the system recorded deviation from target IOI in real time. After each condition, the participants completed the NASA-TLX scale and explained their ratings for reference in subsequent analysis.
(5) **Interview:** After the experiment, the participants were interviewed. As shown in Table 3, the interview consisted of two parts: general impressions and detailed comparison. The first part collected participants' preferences and rankings, while the second part used pairwise comparisons to explore nuanced differences between metronomes.

Figure 3: The experimental equipment and setup

4 Data analysis

This experiment recruited 18 participants aged 20 to 29. As shown in Fig. 4, all participants had varying music learning experiences during their upbringing. Among them, 66.7% had less than three years of musical training, 22.2% had over five years, and 11.1% had three to five years of training. Additionally, the majority (94.4%) had not practiced or played any musical instruments in the last six months. All participants were right-handed.

More than half of the participants (12 individuals) had learned keyboard instruments (e.g., piano, MIDI keyboard), and half (10 individuals) had learned string instruments (e.g., violin, guitar, ukulele, etc.). A smaller number had experience with other instrument types, such as percussion (e.g., drums) and wind instruments (e.g., woodwinds or brass).

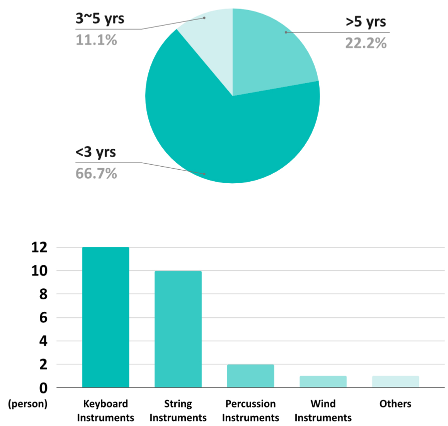

Figure 4: Participants' musical background

4.1 Analysis of Deviation from Target IOI

Deviation from target IOI was defined as the difference between the participant's inter-onset interval (IOI) and the target IOI (1000 milliseconds). Larger values indicate greater deviation from the intended tempo. Each participant played eight notes (Do, Re, Mi, Fa, So, La, Si, Do) per metronome condition, producing seven IOI values and, consequently, seven deviation values. Lower deviation indicated higher rhythm stability. The mean of the seven deviation values was used to represent the participant's performance under each metronome condition. Data were analyzed using one-way repeated measures ANOVA in IBM SPSS Statistics, a software platform that provides statistical analysis

Table 4: Descriptive and ANOVA test of deviation from target IOI (milliseconds)

	Auditory Mean(SD) *	**Tactile** Mean(SD)	**Both** Mean(SD)	**F**	**P**
Deviation from taget IOI	57.18 (29.78)	49.75 (21.40)	37.78 (13.93)	4.42	0.020**

* SD = Standard Deviation
** P<0.05 indicates statistical significance

[3]. The analytical method can be found at https://www.spss-tutorials.com/spss-repeated-measures-anova/.

The descriptive statistics and ANOVA results for the three metronome types are shown in Table 4. There is a statistically significant effect of the metronome type on deviation from target IOI (F=4.42, P=0.020<0.05). As shown in Table 5, Post-hoc LSD tests revealed significant differences between the "both" condition (Mean=37.78, Standard Deviation=13.93) and both auditory-only (M=57.18, SD=29.78) and tactile-only (M=49.75, SD=21.40) conditions. However, there was no significant difference between the auditory-only and tactile-only conditions. This indicates that the "both" condition improved rhythm stability. This result suggests that the "both" metronome may require lower cognitive load than either modality alone, given that higher cognitive load tends to impair task performance [15].

Table 5: Post-hoc LSD test of deviation from target IOI

	Auditory	Tactile	Both
Auditory	-	0.289	0.020*
Tactile	-	-	0.033*
Both	-	-	-

* P<0.05 indicates statistical significance

The findings are consistent with a model of optimal multisensory integration [4], which predicts that bimodal stimuli (auditory and tactile) lead to better task performance compared to unimodal stimuli (auditory-only or tactile-only). This study filled a gap in the literature, as no prior study has demonstrated that multisensory integration can enhance rhythm stability while playing an instrument. This outcome also supports the multiple resource theory, suggesting that utilizing both auditory and tactile channels can reduce errors and enhance performance [32]. As shown in Fig. 5, the medians of deviation from target IOI, from highest to lowest, were tactile (40.00) > auditory (39.00) > both (30.00), with all medians below the mean, indicating right-skewed distributions. The medians for both auditory and tactile were around 40 ms, consistent with the previous study, while the "both" condition showed the lowest median. The IQRs from largest to smallest were auditory (53.00), tactile (42.00), and both (39.00). The "both" condition had the lowest median and variability, indicating that multisensory integration substantially enhanced performance and rhythm stability.

According to the interview data, the multisensory metronome was more robust than the auditory and tactile metronomes. Most participants had limited musical experience, so perceiving auditory cues alone could be challenging. Adding tactile stimuli enhanced the perceived intensity of correct tempo and allowed better focus. As Participant 15 said, "*Having two sensory channels acts as a kind of backup mechanism—if I forget to rely on one sense, I can still perceive the rhythm through the other.*"

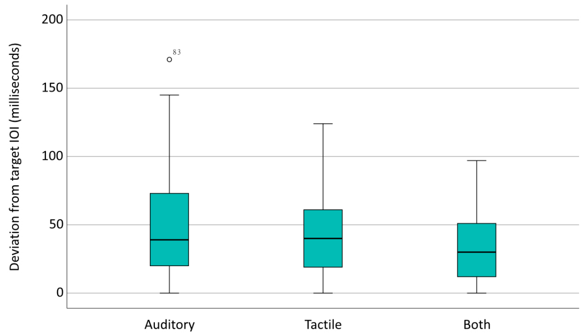

Figure 5: The boxplot of deviation from target IOI

In addition, the multisensory metronome can fully utilize the advantages of each sense. Most of the participants (83.33%) relied primarily on auditory stimuli to adapt and anticipate beat timing because the human hearing system is more accurate in perceiving temporal information. This supports the modality precision hypothesis [31]: if there are differences between multisensory stimuli, people will rely on a more precise or a more appropriate sense. At the same time, tactile stimulation played a supporting role, helping to guide the timing of pressing the keys and reducing judgment delays. As participant 9 stated, "*Adding tactile feedback gives a sense of guidance—it reminds my hand to press at specific points in time.*"

The absence of a significant difference between the auditory-only and tactile-only conditions suggests that neither modality was superior, as each had limitations. The auditory metronome could cause discomfort or stress, leading to poorer performance. The tactile metronome also has its drawbacks: the kinesthetic feedback produced by gestures caused tactile suppression, resulting in reduced tactile sensitivity and requiring greater effort to perceive the stimuli. However, combining the two stimuli can eliminate the drawbacks of each alone, resulting in the lowest deviation. As Participant 1 stated, "*When relying on sound alone, … the time pressure feels greater. But when both cues are present, it feels more balanced.*"

4.2 Analysis of NASA-TLX Workload

Participants rated six dimensions of the NASA-TLX workload scale: mental demand, physical demand, temporal demand, performance, effort, and frustration. Each dimension was rated on a scale of 1 to 7. Aside from the fourth dimension (performance), high scores mean the dimensions are high. The overall workload was estimated using Raw-TLX scores.

The descriptive and ANOVA results are shown in Table 6, which indicates that the six dimensions and the Raw-TLX scores for all three conditions were below 4, and no significant differences were observed between the three types of metronomes.

Table 6: Descriptive and ANOVA test of NASA-TLX per metronome type

	Auditory M(SD)	**Tactile** M(SD)	**Both** M(SD)	**F**	**P**
MD	3.37(1.51)	3.80(1.49)	3.15(1.43)	1.27	0.293
PD	2.07(0.79)	2.28(1.05)	2.13(1.08)	0.86	0.431
TD	2.67(1.15)	2.55(1.35)	2.63(1.43)	0.07	0.931
OP	2.55(0.97)	2.83(1.31)	2.38(1.15)	0.76	0.477
EF	3.00(1.44)	3.12(1.43)	2.60(1.35)	1.36	0.270
FR	1.98(0.94)	2.23(1.26)	1.90(1.14)	0.50	0.614
RTLX	2.61(0.87)	2.81(1.09)	2.48(1.00)	0.88	0.424

This suggests that the workload required was similar across conditions and was relatively low. Since the task did not involve sufficient cognitive resources, the differences in cognitive load required by each metronome are difficult to distinguish.

5 Discussions and Conclusion

This study investigated the effects of different sensory stimuli on cognitive load and rhythm stability in music learners using both subjective and objective measures. Compared to auditory-only and tactile-only metronomes, the multisensory metronome yielded better rhythm stability when playing an instrument, indicating that non-professional musicians can benefit from this approach to improve their tempo accuracy. No significant differences were found between the auditory-only and tactile-only conditions; however, the variability in deviation from target IOI was greater in the former condition. This may suggest that auditory metronomes make user's performance more unstable.

This study is not only helpful for amateur musicians, but also opens up more possibilities for those who play high-volume instruments or have hearing impairments. In the near future, they may perceive the cues more clearly using tactile or multisensory metronomes while having the same or even higher rhythm stability.

The increase in cognitive load is similar across all three types of metronomes, because the task did not consume adequate cognitive resources to demonstrate the differences between them. In this pilot study, participants were instructed to play an ascending scale with a single hand. Future research could modify the tempo, rhythm, and melody of the task. For instance, the melody could be made longer and more complex (e.g., descending scale, rolled chords), the rhythm could be changed (e.g., binary, triple, syncopated rhythm), and both hands could be used. In this way, more cognitive resources could be engaged to differentiate the cognitive load associated with different metronomes.

6 Ethical Standards

There are no sources of funding or potential conflicts of interest (financial or non-financial) associated with this research project. Before the experiment, all participants were clearly informed about the purpose, procedure, and potential risks, given sufficient time to ask questions and consider whether to participate, and then signed informed consent forms. Participants could withdraw at any time during the experiment. After the experiment, the personal data of the participants were anonymized, securely stored, and used only for research purposes.

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