The Haptic Metronome: A Study on Steady Tempo

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***Abstract*— One of the most prevalent issues that plagues aspiring (and professional) musicians is maintaining a steady tempo. The remedy is often hours of practice under the guidance of a steady auditory metronome. With experience, a feedback loop between the sound of the metronome and that of the instrument is optimized to minimize error. However, there are instances where an auditory metronome is not feasible and other modalities may provide an alternate approach to deliver the rhythmic cues, e.g., tactile metronomes. The effectiveness of tactile cues in drumming was tested and compared against auditory and combined (tactile and auditory) modalities between subject groups with disparate rhythm abilities. Although the haptic metronome was not able to reduce each subject's asynchrony as effectively as the auditory metronome, it was statistically proven to be effective at maintaining tempo. These outcomes may be utilized in live performances where a standard metronome is impractical, for musicians with disabilities who are unable to respond to auditory stimuli, and in motor rehabilitation that utilizes rhythmic cues.**

Keywords*— *tempo, metronome, rhythmic cueing, auditory, tactile, asynchrony, sensorimotor synchronization

I. Introduction

The metronome is a clock-like device that maintains a steady time period between each cycle. Metronomes are common when teaching musicians how to sustain a steady rate while practicing or performing [3]. Defined in beats per minute (bpm), the musician can program an intended tempo into the device. Most metronomes use audible feedback, or the user can watch the display screen to see the beat timing visually. In 2016, Soundbrenner introduced a wearable vibratory metronome called the Soundbrenner Pulse which offered a new (sensory) modality for the expression of steady tempo.

For musicians, using a metronome is a way to practice an exercise or song and ensure the speed stays constant. The metronome typically beeps every quarter note, which is once per beat. As the musician plays, they can hear the lack of synchrony between their note and the metronome. With experience, the user can quickly correct their performance based on the time error (i.e., "asynchrony") they perceive [4]. It is unknown if the perception of this asynchrony is most effective for an audible metronome compared to other modalities. For amateurs, a tactile metronome can give easy-to-understand feedback on rhythm, which has been found to have a reaction time in finger tapping that was 28% shorter than the corresponding auditory modality [14]. This study aims to compare the effectiveness between an audible metronome and a haptic metronome. The effect(s) of different sensory modalities may benefit applications of rhythmic cueing in a variety of fields such as music training, evaluation of rhythm and motor abilities.

II. Prior Work

A. Haptic Tutor

Tom et al. explored the use of haptic devices to improve multi-limb coordination [1]. The devices, called Vibropixels, have a modular design, where individual devices can be mounted on each limb. The devices indicate which limb should hit to perform the exercise with a pulse vibration on the beat, or with a short ramp vibration. The authors found that a short pre-ramp helps with anticipation. In two experiments, the haptic device improved the user's ability to perform patterns in a way that was statistically significant [1].

B. Tactile Metronome

Giordano et al. performed one of the first pilot studies in the field of tactile metronomes in 2015 [2]. Their experiment was done on proficient level guitar players (3+ years of experience). The test was performed at 60bpm and 120bpm, with an auditory or tactile metronome. The preliminary results showed that the tactile metronome was effective in helping the guitarists play at a steady tempo. The average asynchrony and standard deviation with the tactile metronome were higher, which the researchers attributed to increased processing time required for tactile stimuli [2]. Tactile metronomes may enhance initial learning and reaction time for beginners [14], but the benefits appear to diminish in complex musical tasks for more experienced individuals. There is limited research in this area to understand the specific reasons behind this.

C. Rhythmic Cueing in Motor Rehabilitation

Finger tapping, a form of sensorimotor synchronization (SMS) task, is often tied to rhythm reproduction [15, 16]. Individuals with prior musical training typically exhibit better rhythm production abilities compared to their non-musical counterparts [17]. In addition, the disparity in rhythm production abilities was shown to limit the effectiveness of gait rehabilitation interventions such as rhythmic auditory cueing (RAC) [18]. It was found that rhythm production (rather than rhythm perception) was a significant factor in the variability of gait responses to RAC [18].

Rhythm production, quantified by the subject's asynchrony (difference in time between motor output and stimulation), is reflective of the subjects' SMS ability. Additionally, tapping serves as a rhythmic motor-cognitive activity commonly utilized to forecast rhythm disorders, motor-cognitive skills such as attention and memory, sensorimotor capabilities, model individual motor timing aptitudes, assess fall risk, and potentially anticipate gait patterns, and is also used in other fields as well, such as reading and spelling tasks in first-grade children [19-23]. However, most tapping studies use auditory metronome(s), thereby limiting our understanding of SMS between different sensory modalities.

III. PROJECT METHODOLOGY

This project investigated asynchrony of percussion performance. The exercise chosen was simple to allow beginners to perform without requiring excessive skill or drum technique.

A. System Design

The system input was generated by a piezoelectric sensor mounted to a drum pad. The drum pad was an Evans HQ RealFeel Practice Pad, which has a rubber head that gives a realistic stick rebound (similar to that of a drum). When the pad was struck with a drumstick, the sensor sent a signal that was interpreted by an Arduino Uno microcontroller (Fig. 1).

The Arduino's built-in clock calculated timing, effectively acting as a metronome. It generated the timing, in milliseconds (ms), of each beat and the timing of each drum hit. Offline analysis was then performed to calculate the time error (i.e., "asynchrony") of each hit using Microsoft Excel 2021.

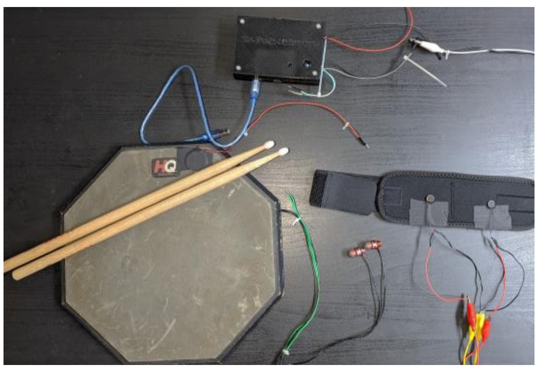

Fig. 1. System setup: drum pad with mounted sensor, Arduino system and breadboard (inside black box), tactile metronome, and earbuds.

The system has two different outputs which portray the steady timing to the user. An audible metronome was delivered via generic earbuds. The sound generated was a sine wave with a duration of 5ms. The tactile metronome was created with two coin-cell vibration motors, mounted approximately 180 degrees apart on an adjustable arm strap. The strap was mounted on the user's forearm. The vibration was 150ms in duration at 200Hz. The vibration was time-shifted forward to account for its ramp in intensity, to synchronize the two stimulation modalities.

B. Drum Exercise

The drum exercise consisted of quarter notes, performed with the test subject's dominant hand (Fig. 2). Each drum hit corresponds to one pulse or sound from the metronome. Only one hand was used in this experiment, which was the same arm the haptic metronome was mounted on.

The exercise was performed at three tempos: 60 bpm, 90 bpm, and 120 bpm. The time duration between subsequent cues, i.e., inter-onset intervals, for these tempos were 1 second, 0.67 seconds, and 0.5 seconds, respectively.

Fig. 2. Sheet music transcription of exercise.

C. Metronome Methodology

The participants were tested for four different metronome configurations corresponding to each tempo.

1) *No metronome*
2) *Auditory metronome*
3) *Tactile metronome*
4) *Auditory + Tactile metronome*

Each participant performed 12 tests. The testing order of metronome type and tempo was randomized for each user. The "no metronome" configuration is referred to as "none," while the combined auditory and tactile metronome configuration is referred to as "both."

D. Procedure

All users read and signed a consent form approved by the USF Institutional Review Board.

Each participant was allowed as much time as requested to acclimate themselves to the drumsticks, drum pad, and metronome systems. For each new user, a test program was run that generated the tactile metronome and the auditory metronome. This test program was run at a different tempo than any of the real trials. The test program read the piezoelectric drum input, and the practice trial was used to make sure each user hit the pad in a way that was recognized by the system.

The users were instructed that each test begins with four measures (16 beats) of both the tactile and auditory metronomes, to acclimate them to the tempo before the trial. This is similar to the "counting in" process before a song, where one member of the band signals the tempo for the other members. For the last eight beats before the test begins (beats 9-16), the test administrator verbally counted down from eight, ending with the verbal cue "begin."

The users were instructed that once the 16 beats conclude, either the auditory metronome, the haptic metronome, both, or neither will continue. They were instructed to maintain steady rhythm to the best of their ability, using the metronome feedback if applicable. The subject intentionally did not know which metronome configuration would be used for each test.

The test consisted of 64 consecutive beats, which is 16 measures, chosen because it is a standard length of a passage of music [5, 6]. However, the participants were asked to continue playing until they were instructed otherwise, to reduce distractions. The test administrator watched the output, which showed a real-time display of hit number. The test concluded once 64 drum hits had been registered, accounting for missed or "unrecognizable" strokes.

E. Data Analysis

The asynchrony between each metronome beat's time and the corresponding drum hit was calculated in milliseconds. For a hit before the beat, a negative value was reported, while a hit after the beat was recorded as a positive value. Negative asynchrony corresponded to a "predictive" response (response initiated before stimulus), and positive asynchrony indicated an "adaptive" response [7, 8]. Both types of error contribute to an overall lack of adherence to the metronome. The absolute value of asynchrony was used in calculating the average since the scope of the study did not constitute differences between anticipatory and "adaptive" responses. When average asynchrony is discussed in this paper, it refers to the absolute value.

Asynchrony variability was calculated using the standard deviation of the asynchrony. The standard deviation demonstrates the spread of asynchrony values in each test (i.e., "error variability"). A specific case of interest is that of the unimodal tactile metronome, as each vibration was 150ms long. Due to the extended pulse, a high average asynchrony and a low standard deviation could indicate that the subject was precise in their timing but interpreted a different part of the vibration signal as the zero point. All statistical analyses were performed using IBM SPSS 27.

IV. Results

Testing was performed on eight subjects with varying musical backgrounds. Four subjects had significant recent musical experience (20+ years including present), one individual had 13 years of experience, and three had less than 5 years of experience.

A. *Asynchrony and Standard Deviation*

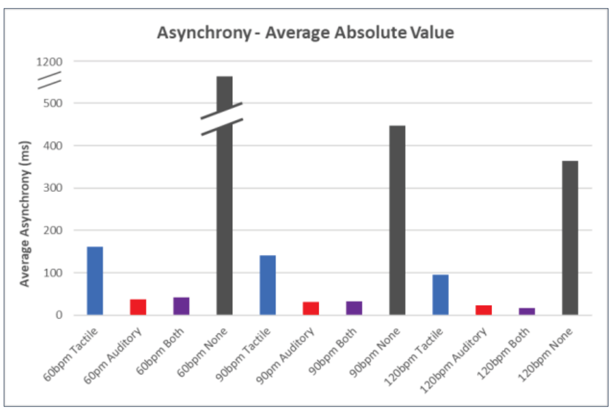

Fig. 3. Average absolute value of asynchrony vs tempo and metronome configuration

The average absolute asynchrony and the average standard deviation trends appear nearly identical (Fig. 3 & Fig. 4). Test subjects had the greatest asynchrony and standard deviation in the "none" condition. Without any cues over the test, the error compounded: a small percentage of error added up for every hit, and in many instances the subjects were a full beat off by the end of the test. Even professional musicians in the study ended more than a full beat off by the end of the test. The "none" conditions were randomized and therefore unexpected, possibly leading to such a high asynchrony and standard deviation.

The other three metronome configurations that gave some feedback to the test subject resulted in a much smaller average asynchrony and standard deviation. Of the three, the tactile metronome resulted in the highest asynchrony and standard deviation for all three tempos. Both are highest for 60bpm and lowest for 120bpm. The auditory-only metronome and the "both" conditions performed the best, demonstrating similar outcomes. At 60bpm, the auditory-only condition performed

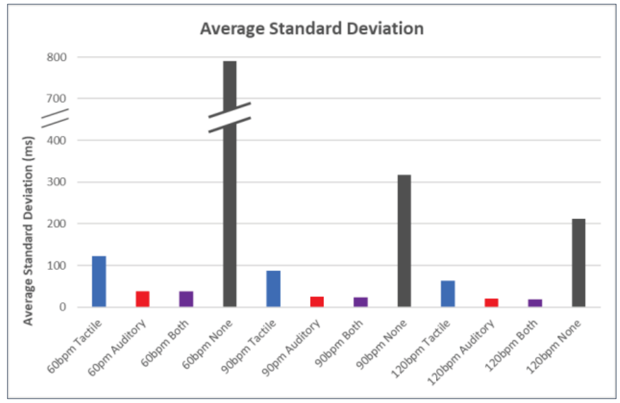

Fig. 4. Average standard deviation vs tempo and metronome

better by an average of 6ms, while at 120bpm, the "both" condition exhibited performance improvement by the same amount. At 90bpm, the averages were nearly identical.

The average asynchronies for each configuration were compared as percentages of their tempo's inter-onset interval in Table 1. The percentage difference between each tempo's average asynchrony is very similar, with 60bpm "none" as a notable exception.

TABLE I. Average Asynchrony as a Percentage of the Inter-Onset Interval.

	60 bpm	90 bpm	120 bpm
Tactile	16.1%	21.1%	19.0%
Auditory	3.7 %	4.7%	4.5%
Both	4.3%	4.9%	3.2%
None	116.3%	67.1%	72.7%

B. *Asynchrony Distribution*

Each test subject's average absolute value of asynchrony for each tempo and metronome condition was compiled. A Shapiro-Wilk test of normality was completed. 11 of the 12 conditions showed evidence of normality ($p > 0.05$). The only condition that was not normal was the tactile metronome at 120bpm ($p = 0.005$).

A Shapiro-Wilk test of normality was also conducted on the standard deviation for each subject's tests. 8 of the 12 tempo and metronome combinations reported as normal. The non-normal conditions were: 60bpm "both" condition ($p = 0.040$), 90bpm auditory ($p = 0.020$), 90bpm "both" ($p = 0.037$), and 120bpm auditory ($p = 0.018$).

With both asynchrony and standard deviation showing mostly normal data, a two-way ANOVA test was performed. Also, the normality of the average absolute value of asynchrony data supports the decision to use standard deviation as a metric.

C. *Two-Way ANOVA: Asynchrony*

A two-way analysis of variance (ANOVA) performed for the asynchrony showed that the following factors were statistically significant: (i) metronome modality: $F(3,84) = 16.2$, $p < 0.001$, and (ii) tempo: $F(2,84) = 3.5$, $p < 0.001$.

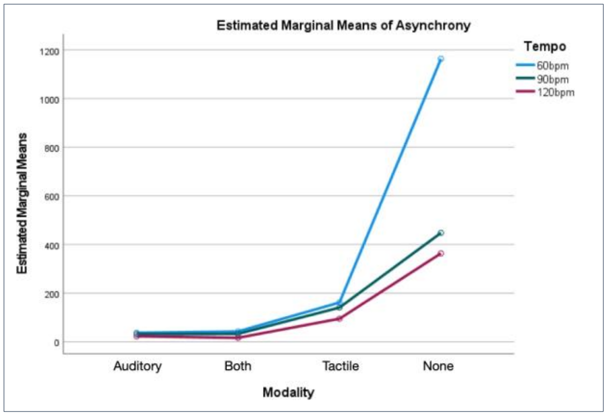

Fig. 5. Average asynchrony (ms) comparison for each modality, across all three tempos.

The pairwise comparison for different metronome modalities returned significance between "none" and the other three metronome configurations ($p < 0.001$). No significance was seen when comparing the tactile, auditory, or both metronomes (Fig. 5). In the pairwise comparison of tempos, 60bpm revealed significantly greater asynchrony than 120bpm ($p = 0.045$).

D. Two-Way ANOVA: Asynchrony variability

Two-way ANOVA for the standard deviation of the asynchronies revealed statistical significance for both modality and tempo. For metronome modality, $F(3,84) = 14.3$, $p < 0.001$. For tempo, $F(2,84) = 3.9$, $p = 0.025$.

The pairwise comparison for different metronome modalities returned significance between "none" and the other three metronome configurations ($p < 0.001$). In the pairwise comparison of asynchronies between tempos, 60bpm exhibited significantly greater asynchrony variability compared to 120bpm ($p = 0.030$).

E. User Feedback

Between each test, subjects were asked to provide feedback on the system regarding the (perceived) effectiveness of each metronome modality. All the users agreed that having the tactile metronome on the same arm that they used to hold the drumstick led to some confusion between the metronome's pulse and the vibration from hitting the drum pad. When the drum hit and the metronome pulse occurred at the exact same time, the subjects reported that the metronome signal seemed to disappear. However, as the subject strayed from the correct tempo, leading to a discrepancy between the two vibrations, they could feel the metronome more and try to adapt to eliminate the error.

Users also commented that the tactile metronome pulse felt longer than the audible pulse. They expressed confusion regarding the temporal "stage" of the tactile sensation that was supposed to be "the zero point" (i.e., perfect synchrony) to trigger a response. The vibratory pulse was tuned to 150ms long to allow a ramp up to an appropriate level of intensity, as opposed to the 5ms steady audible signal.

The users wore earbuds for all metronome configurations. One subject noted that because of these, and the quiet response of the drum pad, they could not hear their drum hits very well. The biofeedback from each hit is critical to calculate the error versus the metronome.

Most users agreed that the tactile metronome was the hardest to follow, while auditory feedback was the most intuitive. Many test subjects were musicians, who have significant experience with audible metronomes. For the metronome conditions with both tactile and auditory, all users commented that they focused mostly on the audible tone.

F. Experts vs. Beginners

Tactile metronome performance between musicians with significant experience, called "experts" (> 20 years of recent experience), and "beginners" (< 5 years of past experience) was apparently disparate (Fig. 6). However, the difference in average asynchrony between the two populations was not statistically significant.

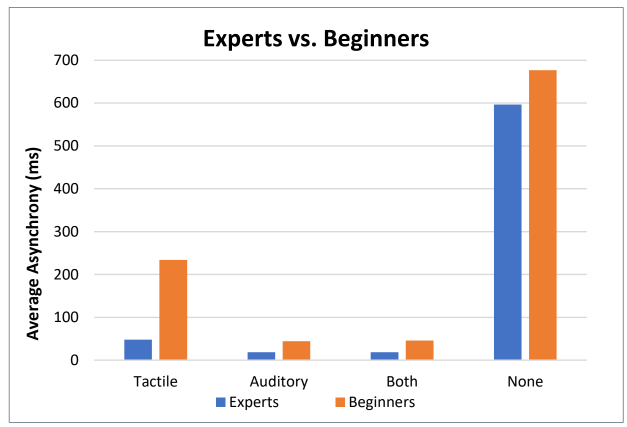

Fig. 6. Average asynchrony comparison between experts and beginners across all tempos.

Better time-keeping performance was expected for experts due to years of experience of playing with an auditory metronome. The data supports this, with an average asynchrony for experts of 18.7ms for an audible metronome, versus 44.5ms for beginners. For "both" (combined tactile and auditory), the average is also 18.7ms for experts, and 45.9ms for beginners. However, performance with the tactile metronome shows an even bigger gap of 48.1ms for experts and 234.1ms for beginners. Considering the size of this discrepancy between subject groups, an understanding of temporal perception via tactile cues may help us understand the significance of modality with respect to rhythm abilities. The outcomes may help optimize human-machine interfaces using temporal perception in unimodal and multi-modal contexts and their corresponding motor/music performance at a range of different tempos and vibration characteristics.

V. CONCLUSION / DISCUSSION

A. Effect of modality

The magnitude of temporal discrimination (6ms), i.e., "minimum detectable gap," is consistent with previous studies that studied rhythm perception in the auditory (6-9ms for 200-2000Hz) and tactile modalities (8-12ms for 20dB and 35dB) [9]. Despite being the first time using a haptic metronome for all test subjects, it was statistically proven to help users maintain a steady rhythm when compared to the no-metronome condition. Although the average asynchrony was better using an auditory metronome than its tactile counterpart, it is worth considering that all the musicians tested have extensive experience following the audible sound. Beginners exhibited a smaller error with the auditory modality than the tactile modality. This is consistent with a previous study that found auditory cues to result in fewer rhythm production errors than tactile cues [10].

Since the tactile metronome proved successful with unaccustomed users, it supports the idea of incorporating haptic interactions into music. During performance and musical training, the auditory cortex may be more occupied with external music (which also provides feedback), making this modality ineffective to transmit instructions. Previous studies have found that there are common neural mechanisms for rhythm perception in the auditory and tactile modalities [13]. This may be attributed to "co-embedded" temporal processing units in the auditory cortex that also modulate tactile sensitivity, i.e., modality-specific or modality-invariant regions [11, 12]. Consequently, haptic communications could be a new way to silently deliver instructions or tempo to aspiring musicians.

B. Interpreting the Tactile Metronome

The location of the tactile stimulation on the subjects and the type of haptic pulse to apply were major considerations. Because their drum stroke seemed to cancel out the tactile vibration when both occurred at the same time, some test subjects would instead alternate between their hit and the tactile signal. After testing a range of subjects, some individuals would hit at the exact time as the pulse's peak (considered correct by the system), some hit just before or after the pulse to feel the feedback better, and some alternated with the vibration. Since the goal of this system is to maintain a steady tempo, all the strategies listed may potentially be successful. Since error (or asynchrony) magnitude was the purpose of the study, possible alternate strategies were not investigated in depth.

C. Applications

The most frequent application for metronomes is to practice music alongside to facilitate learning how to maintain a steady tempo during performance. The tactile metronome would be a direct addition (or replacement) to an auditory metronome in such contexts.

Many musicians or bands practice with a metronome, a tool that is sometimes not feasible during a performance. When a full band is playing on stage, the environment may approach 100dB (especially if the drummer is using a drum set), which is a difficult environment to decipher cues from fellow musicians. Each person typically has a speaker (a "stage monitor") pointed at them, in addition to the speakers aimed at the crowd. It is possible to generate a metronome tone through the monitors; however, this would also be heard by the audience, a consequence that is undesirable for a music performance.

Professional-level musicians solve this problem by replacing stage monitors with in-ear monitors. It functions in a similar manner, but the sound is sent directly to molded earbuds that seal out outside noise. This allows for an auditory metronome without the audience hearing. However, there are times when the band may still speed up or slow down, intentionally or not. When there is a piercing metronome, but it is no longer on the same beat as the band, it is very distracting and troubling. The only solution is for the band to try to get back onto the beat the best they can. A silent tactile metronome is a good solution to this problem because it can be interpreted effectively in different ways. While it showed as error in this test, it is feasible to have the tactile pulse in between the beat or offset some amount. The tactile metronome is an interesting solution for on-stage performance when knowing a set tempo is important, but there is flexibility in how the band follows it. Notably, the tactile metronome can help musicians with disabilities. Whether the musician is not able to hear a standard auditory metronome, or the loud piercing tone overstimulates them, a tactile metronome may be a feasible and more accessible method for learning and maintaining steady tempo.

In addition, the utility of tapping as an assessment for motor-cognitive abilities, and, consequently fall-risk in elderly cohorts may be explored via tactile or multimodal methods [20, 23]. These outcomes would indicate whether age-related decline in rhythm abilities may be mitigated by leveraging different (or a combination of) sensory modalities.

D. Sources of error

As the testing rig was designed by a musician, the piezoelectric sensor level was set to a threshold appropriate for a light drum stroke. Non-musicians unaccustomed to using a drumstick often held it with a unique chopstick-like grip, and tapped very quietly. Most subjects were able to increase their input when instructed, however some had a small percentage of hits that were not registered by the system. If a hit was missed, that metronome beat was skipped in calculation, and the asynchrony for the next hit was done to the next metronome pulse. These misses were not used in analysis to minimize the likelihood of Type I errors in the results.

Some users reported confusion in following the haptic metronome. During the test when users found themselves in an alternating pattern between their hits and the metronome vibrations, they sometimes attempted to correct their asynchrony by drifting to the next beat. When the user made a clear and obvious effort to change their target beat, their asynchrony was calculated versus the new target from the time they passed the halfway point of the interval. If the user tried to return to their original beat, their data was left as is. The intention of this adjustment was to calculate asynchrony to the beat the user was trying to match.

VI. Future Work

In consideration of the reported variability in individual rhythm abilities, the sample size in this study was somewhat limited. Collecting more data from both beginners and experts could allow statistical analysis between the two groups.

While the tactile metronome was proven statistically successful, additional tuning and development could be done to improve it. Duration of stimuli, intensity (amplitude), and frequencies are all factors that could be considered. In addition, the feasibility and utility of the tactile metronome in a practical setting (i.e., live performance) could be investigated to assess external factors such as environmental distractions.

Future studies may also incorporate additional electrophysiological information such as electroencephalogram (EEG), magnetoencephalogram (MEG), and electromyogram (EMG) to further our understanding of the underlying motor-cognitive attributes of sensorimotor integration as they correspond to individual or combined sensory modalities in maintaining a steady pace during rhythmic tasks [8, 24, 25].

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