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Active Inference in Music Perception: Motor Engagement to Syncopation Modulates Rhythmic Prediction Error

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ABSTRACT

In active inference, the sensory surprisal (a log-probability of sensory data) of the prediction error between prediction and sensory input is modulated by action. The urge to move (groove) induced by syncopation, which provides metric uncertainty, can be considered a case of active inference in music perception. The present study investigated whether rhythmic prediction error is modulated by improving the precision of rhythm perception through tapping in sync with the rhythm. Thirty-five participants listened to a rhythmic sequence while tapping the half-note beat (tapping condition) or holding a pillow (no-tapping condition), and electroencephalography (EEG) was recorded. In both conditions, the onset of the syncopated tone was rarely earlier (timing deviant: 20%) than the standard (80%). The timing deviant elicited mismatch negativity (MMN) in both the tapping and no-tapping conditions, reflecting a prediction error in timing. Moreover, the MMN was larger in the tapping condition than in the no-tapping condition, which may indicate increased precision due to tapping, even when motor-related potentials were controlled for. Neural entrainment was measured by calculating intertrial phase coherence (ITPC), which reflects oscillatory activity synchronized to stimulus frequency, and ITPC differed between the two conditions at beat-related frequencies. These results suggest that tapping enhanced meter and beat information and reduced the sensory surprisal of syncopation, resulting in a larger precision-weighted prediction error. These effects were not due to physiological arousal differences between conditions, as assessed by EEG power and heart rate variability. These results are discussed as evidence that bodily engagement modulates sensory prediction error within the active inference framework.

1 | Introduction

Humans enjoy moving and dancing to music. How does the human brain give rise to this complex engagement with music? One possible framework for explaining this musical phenomenon is active inference via the free energy principle (Vuust et al. 2018; Vuust and Witek 2014). The free energy principle explains perception, learning, and action in terms of free energy minimization (Friston 2005, 2010, 2012). The characteristics of agents (biological systems) are the maintenance of their states and forms in a constantly changing environment. Thus, the repertoire of agents' physiological and sensory states is limited. This means that the probability of sensory states of interoception and exteroception must have low entropy, where only a limited number of states occur with high probability (Friston 2010). Here, entropy is the expected value of the information-theoretic surprise (i.e., Shannon surprise) of the sensory input. Surprise, a log-probability of sensory data, is provided by a prediction error between the sensory input and prediction (Buckley et al. 2017). To avoid confusing the term surprise with the everyday language of surprise, which has a psychological meaning, the present study uses "surprisal" as per Buckley et al. (2017). Because free energy is an upper bound on surprisal, minimizing free energy leads to the suppression of surprisal (Friston 2010). Therefore, agents

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perceive, learn, and act to minimize free energy in order to suppress surprisal. Free energy can be suppressed by changing sensory input through action or by updating the agent's internal model of the environment (Buckley et al. 2017). The former is known as active inference, which involves changing sensory input to suppress prediction errors that lead to sensory surprisal.

In music perception, action induced by music can be related to active inference. For example, when we listen to jazz and dance music, we feel the urge to move or dance. This sensation has been defined as groove and is accompanied by pleasure (Etani et al. 2024; Janata et al. 2012; Stupacher et al. 2022; Vuust et al. 2018). Groove is induced by medium levels of complexity, which are often indexed by the degree of syncopation (Sioros et al. 2014; Witek et al. 2014). Rhythm is the organized pattern of variable note durations. When we hear the rhythmic sequence, we feel a sense of beat—a regularly repeating pulse—and the meter patterns the beats into strong and weak beats. A syncopated rhythm creates a deviation by shifting the tone onset from the metrically strong beat to the weak beat (Temperley 1999). Therefore, syncopation generates a prediction error between the metric prediction and the actual tone onset, resulting in higher sensory surprisal and entropy during rhythmic perception. In this situation, the urge to move may stem from a desire to reduce the surprisal that leads to sensory uncertainty by changing the precision of the sensory input through actions that establish beat or meter.

Several studies have discussed the origin of the groove sensation in terms of the link between action and perception (Vuust et al. 2018, 2022; Witek 2017; Witek et al. 2017; Vuust and Witek 2014). Witek et al. (2017) proposed that the gap afforded by syncopation invites the body to fill in for a phenomenally perceived accent without actual sound input. This study argued that the body becomes the beat, manifesting the beat pulse through which the groove is understood and completed. Groove sensation has also been explained in terms of predictive processing under active inference (Vuust et al. 2018, 2022). Vuust et al. (2018) proposed that the prediction error induced by rhythmic incongruence (i.e., syncopation) is weighted by the precision of the sensory input, which is the inverse of variance. They also considered that the repeated syncopation pattern induces a feeling of urge to move (groove) to strengthen the metric model, which leads to a reduction of surprisal (entropy) in rhythmic prediction. Previous studies have also demonstrated that tapping improves timing perception in the detection of timing deviation (Manning and Schutz 2013, 2016) and in the extraction of subjective pulse or temporal structures (Su and Pöppel 2012). Therefore, bodily engagement that enhances meter or beat information seems to improve precision in rhythmic perception by reducing sensory surprisal. The present study investigated empirical evidence for active inference during rhythmic prediction.

Rhythmic prediction can be examined using event-related potentials (ERPs) in electroencephalography (EEG). Mismatch negativity (MMN), which reflects neural prediction error, has been regarded as an indicator of predictive processing in the auditory modality (Friston 2005; Garrido et al. 2009; Winkler and Czigler 2012). MMN is recorded using an oddball paradigm in which tones with different characteristics are presented in a sequence with high (standard) and low (deviant) probability. The latter tone, which deviates from a regularity formed from standard tone characteristics, elicits an MMN, typically in the front-central scalp region, for about 100–250 ms (Fishman 2014; May and Tiitinen 2010; Näätänen et al. 2005, 2007; Picton et al. 2000). The MMN is a neural prediction error, reflecting surprisal in the sensory input (Friston 2005). Vuust et al. (2009) showed that syncopated rhythms elicit MMN, reflecting the violated expectations provided by the temporal grid or meter. Moreover, Lumaca et al. (2019) examined the relationship between the size of MMN amplitude and Shannon entropy, which relates to sensory uncertainty in the rhythmic context. In their study, the MMN response elicited by a small deviant that occurred 100 ms earlier than the standard tone was larger when the rhythmic context was simple (low entropy) than when the rhythmic context was complex (high entropy). Therefore, the MMN reflects a precision-weighted prediction error, and its magnitude is influenced by precision, which varies with the entropy or uncertainty of the sensory input (Koelsch et al. 2019; Quiroga-Martinez et al. 2019, 2020; Tsogli et al. 2022).

The present study investigated whether prediction error in syncopated rhythm is modulated by a tapping action that enhances meter information using syncopation. To examine this, participants performed tapping and no-tapping conditions while listening to a rhythmic sequence. In the tapping condition, participants tapped with their index finger on the half note beat, corresponding to a strong beat in the meter, while in the no-tapping condition, they held a pillow while concentrating on the rhythmic sequence. The effect of the action on prediction error in rhythmic prediction was measured by recording MMN, as its amplitude is modulated by precision or sensory entropy (Lumaca et al. 2019). The rhythmic pattern was occasionally violated by one of the syncopated tones presented earlier (temporal deviant) than the original (standard). Because tapping involves motor-related potentials, the ERP during silent tapping was subtracted from the standard and deviant ERPs. This motor correction is based on methods used in research on omitted stimulus potentials. In this research, the ERP associated with a button press alone is subtracted from the ERP elicited when an expected stimulus is omitted after the button is pressed (Dercksen et al. 2020; Ishida and Nittono 2024b). Therefore, the difference in MMN amplitude between the tapping and no-tapping conditions cannot be attributed to differences in motor-related potentials. If action that enhances meter information modulates prediction error by changing sensory uncertainty, the MMN amplitude would be larger in the tapping condition than in the no-tapping condition, reflecting prediction error weighted by the precision of the sensory input.

In addition to MMN, neural entrainment during rhythmic listening was measured by intertrial phase coherence (ITPC) to examine the enhancement of meter, beat, and rhythm information in the brain. ITPC is a measure of the phase consistency of brain activity that is time-locked to stimulus presentation (Van Diepen and Mazaheri 2018; Varela et al. 2001). It has been used to investigate the entrainment of neural oscillations in response to frequent stimuli during rhythm listening (Cameron et al. 2019) and statistical learning (Batterink and Paller 2017, 2019). Stefanics et al. (2010) showed that the more predictable the rhythmic stimulus, the more accurately the phase of neural oscillations was locked to the expected timing

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of the tone onset. They also found that entrainment was significantly correlated with reaction time to the cued tone. Therefore, if tapping enhances meter information, the ITPC of the beat frequency ($ITPC_{two\text{-}beat}$) would be greater in the tapping condition than in the no-tapping condition. We further explored the difference in the ITPCs of rhythm ($ITPC_{rhythm}$) and four-beat ($ITPC_{four\text{-}beat}$) frequencies.

Groove sensation was measured using questionnaire items based on previous studies that examined the degree of syncopation and groove sensation (Matthews et al. 2019; Witek et al. 2014). Groove was defined as “the sensation of wanting to move some part of your body in relation to some aspect of the music,” as per Sioros et al. (2014). Three aspects of groove sensation were subjectively measured: the extent to which participants felt the want to move, the extent to which this want was satisfied, and the degree of pleasure experienced while listening to the rhythm. We hypothesized that pleasure would be higher in the tapping condition than in the no-tapping condition because the urge to move is satisfied by modulating sensory uncertainty in the rhythmic context through tapping.

2 | Methods

2.1 | Participants

Power analysis was conducted using G*power (Faul et al. 2007). Although we were primarily interested in the difference between tapping and no-tapping conditions, none of the other studies examined this. Therefore, assuming a medium effect size of $dz = 0.5$, a sample size of $N = 34$ was calculated with power $1 - \beta = 0.80$ and error rate $\alpha = 0.05$. Note that Vuust et al.'s (2012) data on the rhythmic-deviant MMN suggested an effect size of $dz = 1.75$ ($t(10) = 5.82$ in the nonmusician group), resulting in a sample size of $N = 5$ with power $1 - \beta = 0.80$ and error rate $\alpha = 0.05$. Considering the data exclusion, 40 participants were sampled and randomly assigned to two groups with different orders of tapping and no-tapping conditions to counterbalance the order of conditions: Group I was tapping to a no-tapping order and Group II was no-tapping to a tapping order. Finally, data from 35 participants (16 women and 19 men, 18–27 years old, $M = 21.3$ years, equal number of participants for each group) were used for hypothesis testing after the exclusion of five participants. These five participants were excluded because the number of deviant trials in either the tapping or no-tapping condition fell below the predetermined threshold of 70 due to excessive noise. Of these, 33 participants were right-handed, one was left-handed, and one was ambidextrous, as per the FLANDERS handedness questionnaire (Okubo et al. 2014). None of the participants had a hearing impairment or a history of neurological or cardiovascular disease. The participants' musical ability was assessed using the Japanese Gold-MSI questionnaire (Sadakata et al. 2023; the original is Müllensiefen et al. 2014): general sophistication ($M = 62.3$, $SD = 22.3$), as well as subscales of active engagement ($M = 30.3$, $SD = 10.9$), perceptual abilities ($M = 39.9$, $SD = 10.9$), musical training ($M = 20.3$, $SD = 10.5$), emotions ($M = 30.3$, $SD = 5.6$), and singing abilities ($M = 23.0$, $SD = 9.0$). Moreover, according to the Gold-MSI, participants had various experience with formal instruction of musical instruments (20 participants had 0 years, two had 0.5 years, two had 1 year, one had 2 years, seven had 3–5 years, two had 6–9 years, and six had 10 or more years of experience) and music theory (29 participants had 0 years, three had 0.5 years, two had 1 year, one had 2 years, two had 3 years, two had 4–6 years, and one had 7 or more years of experience). This study's protocol was approved by the Behavioral Research Ethics Committee of Osaka University School of Human Sciences, Japan (HB024-015), and written informed consent was obtained from all participants. Participants received a cash voucher of 4000 Japanese yen as an honorarium.

2.2 | Stimuli and Procedure

Figure 1 shows an example of the rhythmic sequence. Because the complex syncopated rhythm reduced the ability to tap synchronously (Fitch and Rosenfeld 2007), a simple syncopated rhythm was created. The tones of the rhythmic sequence were generated by the cowbell timbre of MuseScore 3 (Version 3.6.2.548021803, Werner Schweer) and edited using Audacity 3.4.2 (Audacity Team 2014). The rhythm was played at 200 BPM, and a sequence consisted of eight bars. In the first bar, two half notes were presented as a two-beat introduction. In the second bar, no notes were presented. The syncopated rhythm was then presented in the third through eighth bars. The second note of the rhythm was rarely presented 50 ms earlier than the standard (shown in blue in Figure 1) as a timing deviant (shown in red in Figure 1). This corresponds to an 8.33% deviation of the interbeat interval (per 600 ms). Since the cowbell tone included a decay phase, the deviant shifted 50 ms earlier could also be interpreted as a duration deviant relative to the preceding tone. However, because this deviant appeared in both the tapping and no-tapping conditions, it could not explain the difference in MMN amplitudes between the two. A 9.6-s sequence was presented 100 times with no interstimulus interval (0 ms) in both the tapping and no-tapping conditions. The total number of trials for the standard and deviant conditions was 600 bars (trials), counting the third to eighth bars of a sequence. Of these, 480 trials (i.e., 80% of the bars) were standard, and 120 trials (20% of the bars) were deviant. The deviant could occur at any position from the third to the eighth bar. Therefore, the timing deviant was expected to elicit the MMN reflecting a violation of the syncopated rhythmic pattern.

Participants were administered both the tapping and no-tapping conditions. Each condition consisted of four blocks, with 25 sequences presented per block (approximately 4 min each). In the tapping condition, they were asked to tap on the half note beat with the index finger of their dominant hand and to not move any other part of their body. No notes were presented in the second bar of a sequence to facilitate beat prediction by tapping because trying to maintain tapping generates predictions. Prior to the experiment, practice was conducted by presenting four sequences consisting only of the standard rhythms (i.e., 32 bars for approximately 1 min) while visually presenting scores of two-beat notes. Importantly, participants wore soundproof earmuffs over their earphones as an additional measure to prevent the tapping sound from overlapping with the rhythm sounds while tapping on pads that absorbed

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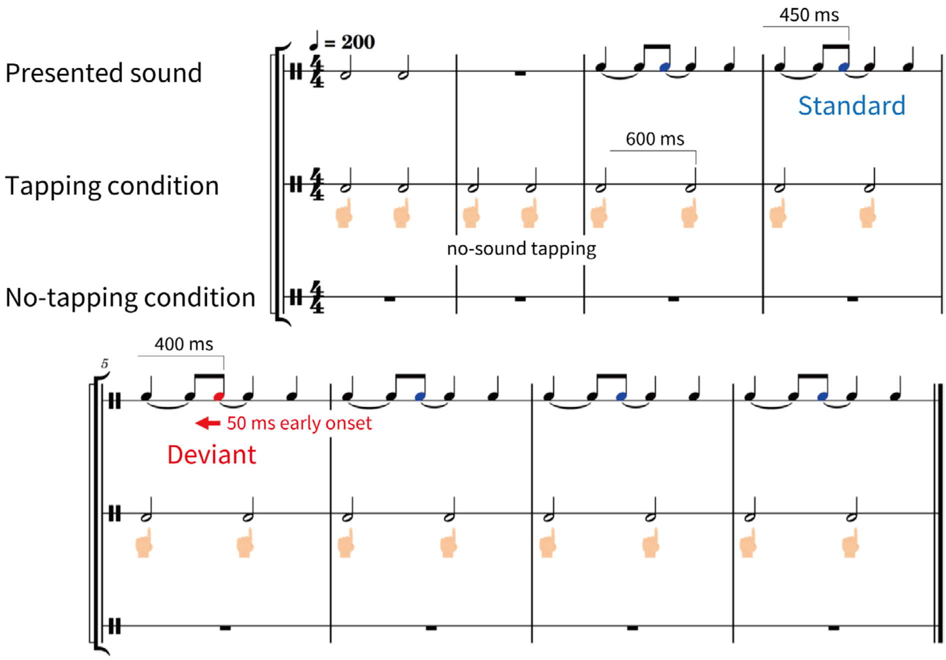

FIGURE 1 | Rhythmic sequence and tapping and no-tapping conditions. The target was the syncopated eighth note. The blue note indicates the standard with the correct timing, and the red note indicates the deviant, which had a 50 ms earlier onset than the standard. In the tapping condition, participants tapped to the beat of the half note in time with the presented sound. In the no-tapping condition, participants just concentrated on the presented sound while holding a pillow.

the sound. Thus, the tapping sound did not overlap with the rhythmic sequence. In the no-tapping condition, participants were asked to concentrate only on the rhythm and to hold a pillow with both hands and to not move any part of their body to prevent unconscious tapping while listening to the rhythmic sequence. In both conditions, participants were asked to fixate on a point on the screen.

For the rhythm and trigger output, a stereo audio file was created with the rhythm sequence in the first channel and the trigger sound indicating the onset of the tones in the second channel. These channels were output separately via a stereo-to-monoaural splitter cable. The rhythm channel was connected to left and right headphones (MDR-EX650AP; SONY, Tokyo, Japan) at 60 dB SPL. The trigger channel was connected to an auditory signal detector (StimTrak; Brain Products, Gilching, Germany), which immediately (< 1 ms) sent a trigger to an electroencephalography (EEG) amplifier.

Groove sensation was quantified using three questionnaire items—using 5-point scales—answered after the fourth block of EEG recordings for both the tapping and no-tapping conditions:

- Q1. To what extent does the rhythm make you want to move?
- Q2. To what extent was the feeling of wanting to move resolved?
- Q3. How much pleasure do you experience listening to the rhythm?

Q1 and Q3 followed previous studies examining groove (Matthews et al. 2019; Witek et al. 2014). However, unlike previous studies where participants only listened passively, this study involved active tapping that allowed participants to move. Therefore, the extent to which their desire to move was satisfied was assessed in Q2. Participants were asked to recall how they felt while they were tapping. After completing the groove-related questions, participants answered the Emotion and Arousal Checklist (EACL; Oda et al. 2015), consisting of five emotion factors (fear, anger, sadness, disgust, and joy) and four arousal factors (energy positive, energy negative, tension positive, and tension negative). Participants rated how well the adjective for each emotion and arousal factor matched their feelings while listening to the rhythm on a 4-point scale ranging from 0, *Not at all*, to 3, *Very much*. Including electrode preparation, EEG recording, the questionnaire session, and short breaks between blocks, the entire experiment took approximately 2 h.

2.3 | Data Recording

Physiological data were recorded using QuickAmp (Brain Products, Germany) with Ag/AgCl electrodes. For EEG recording, 34 scalp electrodes were placed according to the 10–20 system (Fp1/2, F3/4, F7/8, Fz, FC1/2, FC5/6, FT9/10, C3/4, T7/8, Cz, CP1/2, CP5/6, TP9/10, P3/4, P7/8, Pz, O1/2, Oz, PO9/10). Additional electrodes were placed on the left and right mastoids, the left and right outer canthi of the eyes, and above and below the right eye. Data were referenced offline to the nose electrode. The sampling rate was 1000 Hz, and the online filter was DC–200 Hz. Electrode impedances were kept below 10 kΩ. The electrocardiography (ECG) was recorded bipolarly with two active electrodes at the left lower rib and the right clavicle site. The tapping response was recorded using a clip from the CLIPHIT drum module (Korg, Tokyo, Japan), which detects a vibration of tapping and sends a signal to StimTrack with a delay of < 1 ms.

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2.4 | Data Reduction

2.4.1 | ERP Data Reduction

EEG data were analyzed using EEGLAB (Delorme and Makeig 2004; version 2024.1). First, a finite-impulse-response filter of 0.5–30 Hz was applied to the data, following the recommendation of Zhang et al. (2024). Bad electrodes were removed for 12 participants before applying independent component analysis (ICA), and these electrodes were corrected by spherical interpolation after ICA. ICA with the InfoMax algorithm was applied to the filtered data to remove ocular, heartbeat, and muscle artifacts. The ADJUST algorithm (Mognon et al. 2011) was used to automatically detect artifact ICs, which were manually rejected after visual inspection.

For MMN without motor correction, data were segmented into a 400 ms period: 100 ms before and 300 ms after the standard and deviant onsets (for a maximum of 120 trials each). This epoch was predefined to ensure that successive tones did not overlap with it, and a baseline correction was performed by subtracting the mean amplitude of the 100 ms pre-stimulus period from each point of the waveform. Finally, epochs with voltages exceeding ±80 μV in any channel were removed. Valid trials were then averaged for the standard and deviant in the tapping and no-tapping conditions, respectively. The mean number of averaged deviant epochs was 117 (Min–Max = 101–120) for the tapping condition and 119 (114–120) for the no-tapping condition.

For MMN with motor correction, data were segmented into a 1800 ms period: 1000 ms before and 800 ms after the onset of standard, deviant, and no-sound tapping (see Figure 1). To extract the motor-related potentials associated with tapping at 0 and 600 ms (relative to the start of the bar) and subtract them from the ERP waveforms of the standard and deviant conditions, it was necessary to obtain ERP waveforms spanning from the end of the standard to the beginning of the bar. The duration from the beginning of the bar to the end of the standard ERP epoch was 750 ms, and to the end of the deviant ERP epoch was 700 ms. Therefore, aligning the onset of the standard, deviant, and no-sound tapping conditions at 0 ms, setting the baseline to −1000 to 0 ms, and extending the end of the epoch generously to 800 ms ensures that the no-sound tapping epoch includes the −100 to 300 ms window of the standard and deviant ERPs. In this way, ERP epochs of sufficient length were extracted, and the ERP waveforms during silent tapping were subtracted from those of the standard and deviant trials. Therefore, in the initial stage of motor correction, longer epochs were extracted compared to those used for the MMN without motor correction. After motor correction, the length of the epochs was adjusted to match that of the MMN without motor correction. In the segmentation, epochs with voltages exceeding ±80 μV in any channel were removed. The mean number of averaged deviant epochs was 114 (Min–Max = 95–120) for the tapping condition and 116 (109–120) for the no-tapping condition. The epochs were then averaged. Subsequently, the average ERP of the no-sound tapping (motor-related ERP) was subtracted from the average ERP of the standard and deviant after aligning their positions with the bar lines. Then, the onset of the standard and deviant was aligned to 0 ms, and the data were edited into a 400 ms epoch ranging from −100 to 300 ms. A baseline correction was performed using the −100 to 0 ms pre-stimulus interval. In addition to the subtraction method, another motor correction was performed to confirm that the MMN amplitude was still enhanced in the tapping condition compared to the no-tapping condition, with nearly identical peak latencies. This check was reported in Supporting Analysis S2.

The calculation method of the MMN was the same for ERPs with and without motor correction. The deviance-related difference waveforms were calculated by subtracting the standard ERP waveforms from the deviant ERP waveforms (i.e., deviant—standard) in two conditions. Five frontal electrodes (F7, F3, Fz, F4, and F8) were then clustered for statistical evaluation, as in previous studies (Ishida and Nittono 2022, 2024a, 2024b). The difference grand-averaged ERP waveforms—averaged in participants' difference waveforms—of the tapping and no-tapping conditions were further averaged. The most negative peak was detected in the 100–250 ms time window on the final difference grand-averaged waveform, and the 40 ms period centered around the negative peak was defined as the MMN interval. Therefore, 174–214 ms (peak was 194 ms) and 176–216 ms (peak was 196 ms) were used to calculate the mean MMN amplitudes without and with motor correction for the two conditions.

2.4.2 | Intertrial Phase Coherence

Neural entrainment to the rhythmic sequences was quantified by calculating the ITPC, whose value ranges from 0 (non–phase-locked) to 1 (fully phase-locked). To calculate ITPC values in the two conditions, six of the eight bars were used from the second to the eighth bar, in which the syncopated rhythm was presented. The maximum epoch of the six bars was 100 (sequences) in each tapping condition, and this epoch was extracted after ICA-based artifact correction in EEG preprocessing. To capture the phase synchronization of the EEG at the frequencies of the rhythm (0.833 Hz) and the four-beat (3.33 Hz), an epoch long enough to encompass more than one cycle of the rhythm was needed. This corresponds to one bar. Therefore, ITPC was calculated using epochs from a single sequence. Since all 100 sequences included deviant trials, ITPC was calculated including deviant trials. Because ITPC was calculated with deviant trials in both the tapping and no-tapping conditions, the inclusion of deviant trials cannot explain the difference in ITPC between the two conditions. ITPC was computed using a Morlet wavelet transform from 0.5556 to 5 Hz in steps of 0.1389 Hz to extract rhythm- and beat-related frequencies. The calculation was performed using the *newtimef* function of EEGLAB (Delorme and Makeig 2004). Finally, the ITPC calculated at each of the 34 scalp electrodes was averaged. Because averaging ITPCs across the whole scalp may include motor- or tactile-related potentials during tapping, differences in ITPCs were exploratorily examined across regions of interest (ROIs) and are reported in Supporting Analysis S3. The ITPC of 0.8333, 1.6667, and 3.333 Hz was extracted for the evaluation of neural entrainment to rhythm ($\mathrm{ITPC}_{\mathrm{rhythm}}$), beat ($\mathrm{ITPC}_{\mathrm{two\text{-}beat}}$), and triplet ($\mathrm{ITPC}_{\mathrm{four\text{-}beat}}$), respectively.

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2.4.3 | Power Spectral Density

The power spectral density (PSD) of theta and alpha power in EEG was calculated to rule out the possibility that differences in MMN and ITPC between conditions were due to differences in neurophysiological arousal. EEG data were filtered at 1–60 Hz (finite-impulse-response filter) and used to calculate the PSD. The full range of each tapping and no-tapping condition block was used for calculation, and blocks were segmented in 2.048 s, with an overlap of 1.024 s. The PSD was calculated using the fast Fourier transform with a Hanning window with the *spectopo* function of EEGLAB. Electrode clusters were formed for theta (4.0–8.0 Hz), alpha (8.0–13.0 Hz), and beta (13.0–30.0 Hz) bands (theta band: Fz, Cz, FC1, FC2; alpha and beta bands: P3, Pz, P4, O1, O2), and the total power of EEG was calculated and square root transformed. These channel clusters did not include interpolated channels. One participant with values greater than three times the third quartile of the data in the theta and beta bands was removed from the analysis as an outlier, resulting in $N = 34$ for the analysis of PSD.

2.4.4 | ECG Data

ECG was preprocessed using a Python library, Neurokit2 (Makowski et al. 2021), which can process biological data, including ECG data. First, the ECG data were segmented into four blocks for each condition. The length of each block of data was approximately 4 min. Second, the data from each block were cleaned using the *ecg_clean* function with the 'neurokit' method, which applies a 0.1–50 Hz Butterworth filter to the data. Third, the cleaned data were submitted to the *ecg_peak* function, which automatically detects R-peaks with artifact correction based on Lipponen and Tarvainen (2019). Fourth, the preprocessed data were submitted to the *hrv* function, which can calculate various heart rate variability (HRV) indices, including root mean square of successive differences of RR intervals (RMSSD), and heart rate (HR) and RMSSD were averaged over four blocks for each condition. Due to excessive noise and poor peak detection quality, one block from one participant and two blocks from another participant were excluded from averaging. To examine the difference in physiological arousal between the tapping and no-tapping conditions, HR and RMSSD were compared between the two conditions as indices of autonomic nervous system activity.

2.4.5 | Tapping Performance

Tapping performance was evaluated using two types of measures. First, the inert-tapping interval (ITI), defined as the interval (ms) between the previous and current taps, was calculated according to the method described by Patel et al. (2005). The mean and standard deviation (SD) of the ITI were computed as indices of tapping timing and variability, respectively. Second, tapping error was assessed by calculating the absolute difference (in milliseconds) between the correct and actual tapping times, averaged across all taps, following Tomyta et al. (2023). ITIs of ≤ 100 ms or ≥ 1200 ms were excluded before computing the mean and SD of the ITI for each participant, as these values were considered to reflect double taps or missed taps. As a result, the average proportion of excluded taps was 20.56% (SD = 28.26%). For the tapping error calculation, taps with an absolute error exceeding 300 ms were excluded from the average, resulting in a mean exclusion rate of 18.33% (SD = 26.68%). Due to technical issues such as malfunctioning recording equipment, participants for whom data were not completely recorded throughout an entire block were excluded from the analysis. Consequently, tapping performance was analyzed for the remaining 31 participants. Although tapping accuracy was relatively low compared to previous studies (e.g., Patel et al. 2005), participants with poor tapping accuracy were not excluded from the EEG analysis. This decision was based on the current study's aim to investigate how movement modulates rhythmic prediction, regardless of tapping accuracy. The analysis comparing the MMN and ITPC between groups divided by high and low tapping performance is reported in Supporting Analysis S4.

2.5 | Statistical Analysis

Both classical (frequentist) and Bayesian analyses were performed using JASP 0.19.1 (JASP Team 2024). Bayes Factors (BF_{10} for two-tailed) were calculated to assess the absence (null hypothesis) or presence (alternative hypothesis) of the difference. The Cauchy distribution (scale parameter r of 0.707) was used as the prior distribution for the effect δ. For statistical evaluation, the type I error rate (α) was set at 0.05. A $BF_{10} > 3$ and a BF_{10} smaller than 0.33 (1/3) were considered moderate evidence for the alternative and null hypotheses, respectively, as per Schönbrodt and Wagenmakers (2018).

First, tapping performance (i.e., ITI and tapping error) was compared between the no-sound tapping position and the rhythm position using classical and Bayesian paired *t*-tests. This comparison evaluated the validity of the motor-subtraction approach, which assumes that motor and tactile related potentials occur at the same timing due to consistent tapping performance. Moreover, a one-way repeated-measures ANOVA was conducted with the factor block (1–4) to examine how tapping performance changed throughout the experimental session.

Second, PSD (theta and alpha power), HRV indices, EACL scores, MMN amplitudes, and ITPCs were compared between conditions using traditional and Bayesian paired *t*-tests. An effect size of paired *t*-tests was calculated as $dz = t / \sqrt{n}$. For multiple comparisons of ITPCs, p values were corrected using the Bonferroni method. For MMN and ITPC analyses, the group effect with different order of conditions was examined using a two-way mixed analysis of variance (ANOVA) with condition (tapping and no-tapping) and group (Group I and Group II). As no group effects were significant, the results of this analysis are not reported in the main text but in Supporting Analysis S1.

Third, EACL scores were calculated as the total score of question items for each factor and compared between the two conditions. Ratings of the groove-related questions were compared between conditions using traditional and Bayesian Wilcoxon signed-rank sum tests because a 5-point scale was used. The rank-biserial correlation r_B was reported as an effect size in the Wilcoxon

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signed-rank sum test. In the Bayesian Wilcoxon signed-rank sum test, the sample size of the simulation was set to 1000.

Finally, correlations between MMN, ITPC, and groove-related question ratings were analyzed exploratorily. Because the groove-related question ratings were included in the correlation analysis, Spearman's rank correlation coefficient was calculated. A false discovery rate (FDR) correction was applied for multiple comparisons in the correlation analysis ($q = 0.05$). Additionally, the relationship between tapping performance and neural responses (MMN and ITPC) was examined exploratorily (see Supporting Analysis S5). The stimulus materials and data necessary to replicate the results are available at https://osf.io/nej9k/.

3 | Results

3.1 | Tapping Performance

Table 1 shows the ITI and tapping error of each position. The grand means of the mean ITIs of all positions were around 616–636 ms, close to the beat interval of 600 ms. The grand means of the SD of ITI were around 78–89 ms. Given the relatively high exclusion rate of tapping data (see Section 2.4) and the large SD of ITI, it is evident that tapping was difficult for some participants. The means of tapping error were around 72–86 ms. As with the ITI, the relatively large exclusion rate of tapping data (see Section 2.4) and the large standard deviation of tapping error indicate that not all participants were able to tap accurately.

Tapping performance was compared between the no-sound and rhythm positions. A paired t-test of the mean ITI revealed no significant difference between the two positions, $t(30) = 1.12$, $p = 0.271$, $dz = 0.20$, $BF_{01} = 2.94$, suggesting the absence of a difference in tapping performance. However, the SD of ITI, $t(30) = -3.06$, $p = 0.005$, $dz = -0.55$, $BF_{01} = 0.12$, and the tapping error were significantly different between the positions, $t(30) = -4.91$, $p < 0.001$, $dz = -0.88$, $BF_{01} = 0.001$, suggesting a difference in tapping timing relative to the beat onset between the no-sound tapping and rhythm positions. This difference in tapping performance is discussed as a limitation in the Discussion section.

The progression of tapping performance over the experimental session was examined by comparing the ITI and tapping error between blocks. A one-way ANOVA revealed no significant effect for the mean ITI, $F(3, 87) = 0.65$, $p = 0.511$, $\eta_p^2 = 0.022$, Greenhouse–Geisser $\varepsilon = 0.598$, $BF_{incl} = 0.09$, SD of ITI, $F(3, 87) = 0.58$, $p = 0.627$, $\eta_p^2 = 0.020$, $BF_{incl} = 0.09$, and tapping error, $F(3, 87) = 0.40$, $p = 0.687$, $\eta_p^2 = 0.014$, Greenhouse–Geisser $\varepsilon = 0.721$, $BF_{incl} = 0.07$. These results suggest that tapping performance remained constant throughout the experimental session.

3.2 | Physiological and Psychological Arousal

Possible differences in physiological and psychological arousal were tested by examining the PSD of EEG, HRV, and EACL checklist scores. Summary and test statistics of these measures are shown in Table 2. The PSDs of the theta, alpha, and beta bands were compared between the two conditions. The PSDs were not significantly different, and the absence of the effect was supported by the Bayes factor in either band. These results suggest that neurophysiological arousal was not different between the tapping and no-tapping conditions.

HR and RMSSD were compared between the tapping and no-tapping conditions using a paired t-test. None of the differences were statistically significant, and Bayes factors supported the null effects, suggesting that autonomic activity and physiological arousal did not differ between conditions.

Psychological valence and arousal were compared between the two conditions using a paired t-test. For valence, joy was significantly higher in the tapping condition than in the no-tapping condition. For arousal, energy positive, energy negative, and tension negative were significantly different between the two conditions, indicating that psychological arousal was higher in the tapping condition than in the no-tapping condition.

3.3 | Comparison of the Tapping and No-Tapping Conditions

Figure 2 shows the grand average waveforms and scalp topographies of MMN and ITPC. When analyzing ERP without motor correction, MMN responses were observed in the tapping condition as −0.98 μV (SD = 0.81 μV), $t(34) = -7.09$, $p < 0.001$, $d_z = -1.20$, $BF_{10} = 399418.24$, and in the no-tapping condition as −0.48 μV, (SD = 0.72 μV), $t(34) = -3.94$, $p < 0.001$, $d_z = -0.67$, $BF_{10} = 73.76$. MMN amplitudes were significantly larger in the tapping condition than in the no-tapping condition, $t(34) = -3.57$, $p = 0.001$, $d_z = -0.60$, $BF_{10} = 29.35$. The MMN response, as an index of precision-weighted prediction error, was enhanced by tapping.

Because the MMN results reported above are contaminated by motor-related ERP responses, the MMN response was further examined after subtracting the motor-related ERP response obtained during the no-sound tapping in the second bar of the eight-bar sequence (see Figure 1). Again, MMN responses were statistically significant in both the tapping ($M = -0.84$ μV,

TABLE 1 | Mean (SD) of ITI and tapping error at each position.

(ms)	Leading sound position	Silent position	Rhythm position	All positions
Mean ITI	616 (44)	636 (42)	626 (80)	625 (69)
SD of ITI	87 (50)	78 (56)	89 (53)	89 (54)
Tapping error	83 (34)	72 (39)	86 (41)	84 (39)

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TABLE 2 | Indices of physiological and psychological arousal.

		Tapping	No-tapping	t	
		M **(SD)**	***M*** **(SD)**	**(*p*)**	$\mathbf{BF_{10}}$
PSD (μV)	Theta (4.0–8.0 Hz)	22.6 (5.4)	22.9 (6.0)	−0.45 (0.655)	0.20
(N = 34)	Alpha (8.0–13.0 Hz)	1.4 (0.4)	1.4 (0.4)	0.46 (0.648)	0.20
	Beta (13.0–30.0 Hz)	0.9 (0.4)	0.9 (0.4)	−0.43 (0.672)	0.20
HRV	HR (bpm)	69.9 (8.6)	69.5 (7.9)	0.86 (0.395)	0.26
(N = 35)	RMSSD (ms)	48.3 (33.2)	45.4 (21.4)	0.75 (0.459)	0.24
EACL	Fear	0.6 (1.0)	0.7 (1.2)	−0.12 (0.909)	0.18
(N = 35)	Angry	1.2 (1.6)	1.8 (2.8)	−1.10 (0.280)	0.32
	Sad	1.1 (1.7)	1.3 (1.8)	−0.72 (0.475)	0.23
	Disgust	1.7 (2.2)	2.3 (2.9)	−1.20 (0.237)	0.35
	Joy	5.0 (3.1)	3.7 (3.1)	2.08 (0.045)*	1.22
	Energy positive	5.5 (3.4)	3.7 (3.3)	3.23 (0.003)*	13.05
	Energy negative	1.4 (1.8)	2.2 (1.9)	−2.13 (0.041)*	1.33
	Tension positive	2.4 (1.7)	2.3 (2.6)	0.12 (0.903)	0.18
	Tension negative	2.8 (2.4)	3.7 (2.8)	−2.11 (0.043)*	1.28

Note: Asterisks indicate statistical significance in a paired t-test ($p < 0.05$).
Abbreviations: EACL, emotion and arousal checklist; HRV, heart rate variability; PSD, power spectral density.

SD = 1.07 μV), $t(34) = -4.64$, $p < 0.001$, $d_z = -0.78$, $BF_{10} = 466.88$, and no-tapping ($M = -0.44$ μV, SD = 0.72 μV) conditions, $t(34) = -3.61$, $p < 0.001$, $d_z = -0.61$, $BF_{10} = 32.45$. MMN was significantly larger in the tapping condition than in the no-tapping condition, even after motor correction, $t(34) = -2.13$, $p = 0.041$, $d_z = -0.36$, $BF_{10} = 1.34$.

The values of $ITPC_{rhythm}$, $ITPC_{two\text{-}beat}$, and $ITPC_{four\text{-}beat}$ were, respectively, 0.12, 0.24, and 0.14 in the tapping condition and 0.11, 0.15, and 0.11 in the no-tapping condition. $ITPC_{two\text{-}beat}$ and $ITPC_{four\text{-}beat}$ were significantly greater in the tapping condition than in the no-tapping condition, $t(34) = 5.21$, corrected $p < 0.001$, $d_z = 0.88$, $BF_{10} = 2217.26$, $t(34) = 4.17$, corrected $p = 0.001$, $d_z = 0.70$, $BF_{10} = 134.01$. However, $ITPC_{rhythm}$ was not significantly different between the two conditions, $t(34) = 0.84$, corrected $p = 1.000$, $d_z = 0.14$, $BF_{10} = 0.25$. These results suggest that neural entrainment to beat-related frequencies was stronger in the tapping condition, but neural entrainment to rhythm did not differ between the two conditions.

The ratings of the three questionnaire items were compared between the two conditions. The degree of wanting to move (Q1) was $M = 3.0$ (SD = 1.2) in the tapping condition and $M = 2.6$ (SD = 1.2) in the no-tapping condition and was not significantly different between conditions, $W_s = 157$, $p = 0.143$, $r_B = 0.36$, $BF_{10} = 0.56$. Satisfaction with the wanting to move (Q2) was $M = 2.5$ (SD = 1.3) in the tapping condition and $M = 2.0$ (SD = 1.0) in the no-tapping condition and was not significantly different between conditions, $W_s = 205$, $p = 0.112$, $r_B = 0.37$, $BF_{10} = 0.49$. The degree of pleasure (Q3) was $M = 2.9$ (SD = 1.1) in the tapping condition and $M = 3.0$ (SD = 1.0) in the no-tapping condition and was not significantly different between conditions, $W_s = 145$, $p = 0.889$, $r_B = -0.03$, $BF_{10} = 0.18$. Finally, groove sensation and pleasure were not significantly different between the tapping and no-tapping conditions.

3.4 | Correlation Analysis

Correlations between MMN, ITPCs, and groove-related question ratings were explored. Table 3 shows the Spearman's rank coefficient ρ in the tapping and no-tapping conditions. The correlations between the groove-related questions were observed only in the tapping condition, but not in the no-tapping condition. The degree of wanting to move (Q1) and satisfaction with wanting to move (Q2) were significantly correlated only in the tapping condition, $\rho(33) = 0.50$, corrected $p = 0.020$. Moreover, the sense of groove was significantly correlated with pleasure (Q3) only in the tapping condition, $\rho(33) = 0.54$, corrected $p = 0.010$.

4 | Discussion

The present study examined whether rhythmic prediction error is modulated by tapping. MMN responses were observed in both tapping and no-tapping conditions. Before and after subtracting motor-related ERPs, the MMN response was larger in the tapping condition than in the no-tapping condition, suggesting greater precision due to the suppression of sensory surprisal and uncertainty in syncopation. Moreover, ITPC, as an indicator of neural entrainment, showed greater power at the two- and four-beat frequencies in the tapping condition than in the no-tapping condition, reflecting the enhancement of meter and beat

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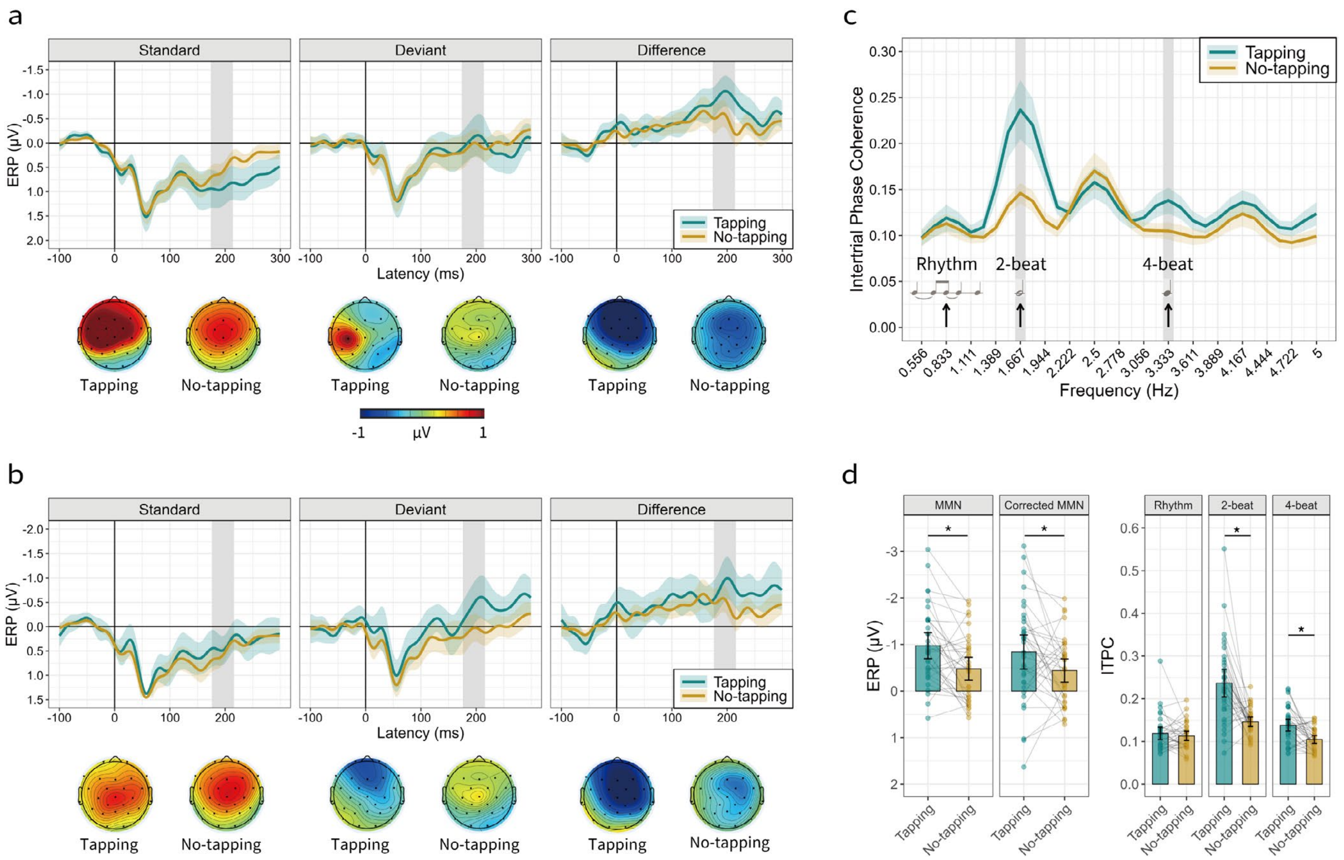

FIGURE 2 | ERP responses and ITPCs in the tapping and no-tapping conditions. (a) Grand ERP waveforms of the standard, deviant, and deviant-related difference without motor subtraction. ERP waveforms were calculated by averaging the five frontal electrodes (F3, F4, F7, F8, and Fz). The gray area indicates the MMN interval (174–214 ms) defined as the peak ±20 ms. The topographic distribution shows the mean ERP amplitude of the MMN interval. (b) The motor-related ERP response was subtracted from the standard and deviant ERPs of the tapping condition. The topographic distribution shows the mean ERP amplitude at 176–216 ms. (c) The ITPC of each frequency is shown with arrows indicating the rhythm, two-beat, and four-beat frequencies. (d) Mean MMN amplitudes with and without motor correction and ITPC values of each frequency are shown as bar graphs. Each point represents individual data, and asterisks indicate statistically significant differences. The light-colored bands on the ERP and ITPC waveforms and the error bars in the bar graph indicate a 95% confidence interval.

TABLE 3 | Spearman's rank correlation coefficient of tapping and no-tapping conditions.

	Wanting to move	Satisfaction of wanting to move	How pleasure	MMN	Corrected MMN	$ITPC_{rhythm}$	$ITPC_{two\text{-}beat}$	$ITPC_{four\text{-}beat}$
Wanting to move		0.16	0.15	−0.22	−0.18	−0.09	0.04	−0.14
Satisfaction of wanting to move	0.50*		−0.003	0.15	0.14	−0.07	0.14	−0.19
How pleasure	0.54*	0.39		0.09	0.06	−0.18	−0.14	−0.19
MMN	0.01	−0.06	−0.20		0.98*	0.08	−0.07	−0.09
Corrected MMN	0.05	0.07	−0.08	0.77*		0.15	−0.08	−0.03
$ITPC_{rhythm}$	−0.26	0.002	−0.23	−0.07	−0.15		0.23	0.28
$ITPC_{two\text{-}beat}$	0.09	0.16	0.24	−0.13	0.04	−0.03		−0.13
$ITPC_{four\text{-}beat}$	0.01	0.08	0.06	−0.28	−0.14	0.02	0.26	

Note: The left of the diagonal shows Spearman's rank correlation coefficient (ρ) in the tapping condition, while the right shows that in the no-tapping condition. Asterisks indicate statistical significance after FDR correction.

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information by tapping. ITPC at the rhythm frequency was not significantly different between the two conditions. Although physiological arousal was not statistically different between the two conditions, subjective arousal was higher in the tapping condition than in the no-tapping condition. Additionally, participants felt more joyful in the tapping condition than in the no-tapping condition. However, ratings of groove-related questions were not statistically different between the two conditions. These results are discussed within the framework of active inference or the relationship between groove sensation and body movement.

The MMN response was larger in the tapping condition than in the no-tapping condition, even after motor correction. The present results verified behavioral studies that reported facilitation of timing deviance detection by tapping (Manning and Schutz 2013, 2016), using the neural MMN response, which has been regarded as a neural deviance detection response (Fishman 2014; Picton et al. 2000). In the active inference framework, MMN is considered a precision-weighted prediction error (Friston 2005, 2012; Garrido et al. 2009; Winkler and Czigler 2012). The lower the entropy of the sensory data, the larger the MMN amplitude (Lumaca et al. 2019; Quiroga-Martinez et al. 2019, 2020; SanMiguel et al. 2021). Consistent with this property, the MMN amplitude was larger in the tapping condition than in the no-tapping condition. Importantly, the difference in MMN response cannot be attributed to the difference in physiological arousal because differences in EEG powers, which relate to arousal (Barry et al. 2007, 2020), and HRV indices were not supported. Instead, the sensory uncertainty of rhythm was regulated by reducing sensory surprisal through tapping, which enhanced precision and resulted in a greater prediction error (i.e., surprisal) for timing violations of rhythm. Therefore, the precision-weighted prediction error is a possible explanation for the current MMN results. This result resembles the suggestion made by Vuust et al. (2018), who discussed groove sensation in terms of predictive processing under the active inference framework, in which the brain minimizes surprisal by prediction error through actions that enhance meter and beat information.

The mismatch response elicited by the deviant may have partially overlapped with the N2b component, which reflects attentional allocation and the response to novel stimuli (Folstein and van Petten 2008; Krokhine et al. 2020). In the present study, participants attended to rhythmic stimuli that included the deviant. Under such task conditions, it is plausible that the deviant elicited an N2b. Therefore, another interpretation of the difference in negativity is that the negativity observed around the 174–214 ms and 176–216 ms intervals reflects differences in N2b amplitude due to attentional allocation. Even if the current mismatch response is an N2b, a larger N2b in the tapping condition would also align with predictive coding theory within the active inference framework. This is because enhancing precision corresponds to increasing the gain of sensory input by attention (Feldman and Friston 2010). In the present study, tapping may have increased precision, thereby enhancing attentional processing of the unexpected deviant. However, this interpretation is post hoc and assumes an attentional mechanism underlying the N2b component. Importantly, the falsifiability of predictive coding is under debate (Bowman et al. 2023). If all phenomena are explained retroactively within the predictive coding framework, the theory risks becoming unfalsifiable. Therefore, future research should formalize hypotheses about the N2b component within the predictive coding model and test whether its predictions correspond to measurable improvements in attentional gain.

The enhancement of meter and beat information was supported by the ITPC of two types of beat-related frequencies. $\text{ITPC}_{\text{two-beat}}$ and $\text{ITPC}_{\text{four-beat}}$ were greater in the tapping condition than in the no-tapping condition. This difference was observed not only in the whole-head average but also in the occipital and frontal regions, where motor-related potentials are minimal (see Supporting Analysis S3). The increased neural entrainment to the beat frequency may have facilitated rhythmic prediction, and this could be a way to modulate sensory uncertainty. Using the steady state evoked potential (SSEP), a periodic evoked brain response whose frequency remains constant in amplitude and phase, Nozaradan et al. (2011, 2012) observed the peak of the SSEP at the meter frequency, which is based on the interpretation of the beat. Neural entrainment to the meter and beat was also observed in the current ITPC, and it was greater in the metrically strong beat position (two-beat frequency) than in the four-beat frequency. ITPC increases with the frequency of relevant stimuli. For example, previous studies (Batterink and Paller 2017; Moser et al. 2021) reported that ITPC was selectively enhanced in the frequency of tone chunks (i.e., word or tone triplet) when learned in structured sequences, whereas ITPC in tone frequency did not change between structured and random sequences. Therefore, it was speculated that enhanced neural entrainment to the beat was due to movement, which enhanced meter and beat information, thereby regulating sensory surprisal in rhythmic prediction. However, this speculation was not supported by the data and was inconclusive, as MMN amplitude and ITPC were not significantly correlated. One possible reason is that the rhythmic stimulus used in the present study was relatively simple, allowing for strong and consistent phase-locking across participants and reducing individual variability in ITPC. This is indicated by the small standard deviations ($\text{ITPC}_{\text{two-beat}}$ is 0.09 and 0.03 for tapping and no-tapping conditions, respectively). This reduced variance may have limited the statistical power to detect significant associations with MMN. Future research should examine the relationship between MMN and ITPC using rhythms with varying degrees of syncopation.

$\text{ITPC}_{\text{rhythm}}$ was not significantly different between the two conditions. When perceiving complex rhythms, such as syncopation, processing the entire rhythmic structure is not the optimal way to reduce sensory uncertainty (entropy). Instead, enhancing meter and beat information is an effective way to reduce the entropy of the rhythmic context because it fills the gap of syncopation. This may be the reason why $\text{ITPC}_{\text{rhythm}}$ was not different between the two conditions, but beat-related ITPC showed stronger power in the tapping condition than in the no-tapping condition. Large et al. (2015) demonstrated that SSEP synchronizes with pulse (meter) frequency in the motor network, even though the rhythm itself does not contain an input at the pulse frequency, with a simulation using a neural model of dynamic attention theory. In the present study, the enhancement of beat-related ITPC with and without tapping compared to rhythm-related ITPC may reflect a strategy to fill in gaps in the rhythmic

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structure while listening to syncopated music, as suggested by Witek et al. (2017).

ITPC has a local peak at 2.5 Hz, which corresponds to three of the two-against-three rhythms. This frequency corresponds to a sound presentation interval of 400 ms within a single bar (1200 ms). According to the ITI results, participants tapped within around 500–700 ms intervals. Thus, the enhancement of the ITPC at 2.5 Hz cannot be attributed to the tapping movement. Rather, it may be due to inaccurate rhythm grouping, as the syncopated rhythm in the present study had three notes per bar. When listening to a rhythmic sequence, listeners perceive tones with grouping and chunking (Hestermann et al. 2023; Iversen et al. 2014). Therefore, it could be chunked as a two-against-three rhythm due to an inaccurate perception of syncopation. It seems that the ITPC of 2.5 Hz is slightly smaller in the tapping condition than in the no-tapping condition, although this difference is not statistically significant. This reduction may also be due to the enhancement of meter information, and rhythmic perception becomes more accurate with tapping.

The neural responses in the present study were not due to the sound produced by finger-tapping because of earmuffs. Instead, the interoceptive and proprioceptive sensations produced by tapping may have increased the precision of rhythmic prediction. Aschersleben et al. (2001) showed that under the tapping task, the degree of tapping asynchrony increased when the tactile sense was completely blocked by local anesthesia compared to when it was not blocked. Goebl and Palmer (2008) suggested that temporal accuracy in piano playing was positively related to finger-key surface impact. The action-induced interoceptive or proprioceptive sensation synchronized with the external rhythm signal would be used as meter and beat information that elaborates rhythmic prediction in such a way that the body becomes a beat that fills a gap (Witek 2017). Therefore, the urge to move, the groove sensation, may stem from a bodily desire to reduce the surprisal and sensory uncertainty of syncopation. Previous studies have suggested a relationship between the accuracy of interoceptive sensation (e.g., cardiac response) and rhythm perception (Tanaka et al. 2021; Tomyta et al. 2023). Future research could examine whether the modulation of sensory surprisal in rhythmic prediction differs by individual interoceptive accuracy.

The difference in groove sensation was not statistically significant between the tapping and no-tapping conditions. One possibility is that the level of syncopation was lower and simpler compared to stimuli used in previous studies featuring drum breaks (Céspedes-Guevara and Witek 2023; Witek et al. 2014). Another possibility is that tapping in sync with the rhythm was difficult and diminished the positive groove sensation associated with movement. Céspedes-Guevara and Witek (2023) also reported no difference in groove sensation when foot tapping to rhythms versus remaining still. This suggests that the positive effect of movement on groove may have been outweighed by the difficulty of the synchronization task. Moreover, in the present study, the lack of difference in the sense of wanting to move and pleasure between conditions may be because the amount of syncopation was not manipulated and only one rhythm was used. This could have caused the lack of difference in the groove between conditions and limited the generalizability of the modulation of rhythmic prediction error to other types of rhythms. Previous studies have suggested that the degree of wanting to move and pleasure is related to the amount of syncopation (Matthews et al. 2019; Witek et al. 2014). An inverted U-shaped relationship between the degree of syncopation and groove sensation or pleasure has been proposed theoretically (Koelsch et al. 2019; Stupacher et al. 2022; Vuust et al. 2018, 2022; Vuust and Witek 2014) and empirically (Sioros et al. 2014; Witek et al. 2014). In this relationship, the urge to move and pleasure are stronger at the medium degree of syncopation, and groove sensation and pleasure are a function of syncopation degree (Matthews et al. 2019; Witek et al. 2014). Thus, it is not surprising that there were no differences between the conditions in the ratings of wanting to move and pleasure, as the syncopation pattern was the same across conditions.

Overt movement in sync with the rhythm (e.g., finger-tapping and dancing) is not necessarily required to feel groove or pleasure, as previous studies have been able to examine groove sensation without overt movement (Madison et al. 2011; Senn et al. 2018; Sioros et al. 2014; Witek et al. 2014). As Witek et al. (2017) pointed out, groove-related pleasure may not be the result of satisfying the desire to move but the "process pleasure" that arises from the process of experiencing the groove itself. This may explain the lack of difference in satisfaction with the urge to move (Q2) between the tapping conditions. This is because if the movement itself induces pleasure, the urge to move is likely to persist and therefore may never be fully satisfied. Another explanation for the null difference in satisfaction is that the urge to move may not be fully satisfied by tapping because the movement is small. Regarding this, Witek et al. (2017) showed that torso synchronization was significantly correlated with the degree of syncopation, whereas hand synchronization was not.

Despite the lack of difference in groove sensation between the tapping and no-tapping conditions, qualitative differences in groove ratings were observed in the correlation analysis between conditions. In the tapping condition, participants who felt a stronger sense of groove also experienced a greater sense of pleasure, similar to Witek et al. (2014). Using functional magnetic resonance imaging, Matthews et al. (2020) reported associations between ratings of pleasure and wanting to move, and motor and reward-related regions, such as the nucleus accumbens. They concluded that groove sensation is driven by a combination of motor and reward-related regions in the brain. Moreover, Cheung et al. (2019) demonstrated that a high-surprisal chord was more pleasurable than a low-surprisal chord in a low uncertainty musical chord context. Syncopation involves prediction errors in meter prediction. If beat tapping reduces the entropy of meter prediction and syncopation provides an optimal level of surprisal (i.e., prediction error), groove sensation may be modulated. Then, the right level of syncopation offers groove sensation and pleasure (Vuust et al. 2022).

This study has several limitations. First, the attentional state was qualitatively different between the tapping and no-tapping conditions, although participants attended to the rhythmic sequence in both conditions, and physiological arousal did not differ between conditions. MMN amplitude is sensitive to the content of an attentional task (Sussman 2007; Sussman

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et al. 2014). Using a phonemic sequence in which phonemes and intensity were changed infrequently, Szymanski et al. (1999) reported that the MMN elicited by an intensity change (deviant) was larger when participants detected the intensity changes (task relevant) than when they detected phoneme changes (task irrelevant). Similarly, tapping may have facilitated the interpretation of the rhythmic context compared to the no-tapping condition because of its task relevance. Future research should clarify this by controlling for the qualitative difference in attentional state between the tapping and no-tapping conditions. Regarding the task demands, the MMN is often reduced due to task demands associated with concurrent tasks during auditory deviant detection (see the meta-analysis by Wiens et al. 2016). Therefore, the difference in MMN amplitude between the tapping and no-tapping conditions cannot be explained by higher task demands in the tapping condition.

Second, the tapping performance differed between the silent position (used for motor correction) and the rhythm position (used for standard and deviant trials). Therefore, the subtraction may contain some bias because the tapping positions were jittered due to the performance differences between the silent and rhythm positions. However, another correction method revealed that the MMN was still enhanced in the tapping condition compared to the no-tapping condition (see Supporting Analysis S2), with the same peak latency of the MMN with and without motor correction. Therefore, the difference in MMN amplitude cannot be solely attributed to bias from motor subtraction.

In summary, the present study investigated active inference in music perception by examining whether prediction error in rhythmic prediction is modulated by reducing the sensory surprisal and uncertainty of syncopation through tapping, which enhances meter information. The MMN response was larger in the tapping condition than in the no-tapping condition, suggesting an improvement in precision by reducing uncertainty in the rhythmic context. The enhancement of meter information was supported by a larger ITPC of the beat-related frequency in the tapping condition than in the no-tapping condition. Regarding groove sensation, the degree of wanting to move correlated with pleasure only in the tapping condition. The present results can be interpreted as evidence for active inference in music perception accompanied by bodily engagement with syncopation. Future research should examine the relationship between groove and active inference more precisely by using various types of rhythms with differing degrees of syncopation.

Author Contributions

Kai Ishida: conceptualization, methodology, software, data curation, investigation, validation, formal analysis, funding acquisition, visualization, project administration, writing – original draft. **Hiroshi Nittono:** conceptualization, methodology, software, formal analysis, validation, supervision, resources, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The sound materials used and datasets analyzed for the present paper are available at https://osf.io/nej9k/.

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