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Tapping in Synchrony With Beat Enhances Groove Sensation

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ABSTRACT

Music listening induces a pleasurable urge to move, termed *groove*, which the active inference framework explains as a motivation for bodily movement that emerges to refine beat and metrical predictions under rhythmic uncertainty. If this is the case, does bodily movement modulate the groove sensation? We asked 42 participants to rate *urge-to-move* and *pleasure* after withholding movement or tapping on the onbeat or offbeat within a four-beat meter while listening to melodies with three degrees of syncopation. At the low degree of syncopation, *urge-to-move* and *pleasure* ratings were higher in both the onbeat and offbeat tapping conditions compared with the no-tapping condition. Furthermore, relative to the offbeat and no-tapping conditions, onbeat tapping increased neural and behavioral entrainment to the beat, as reflected in the steady-state auditory evoked potentials in electroencephalography and intertap interval variability, respectively, and these measures of entrainment were positively associated with groove ratings. The results suggest that tapping enhances the sensation of groove, but the underlying mechanism may not be active inference.

1 | Introduction

Listening to music induces bodily movement, such as dancing or swaying one's body. The pleasurable urge to move in response to music is commonly referred to as *groove* [1–6]. The groove sensation is typically strongest at medium levels of syncopation and exhibits an inverted U-shaped relationship with the degree of syncopation [6–8]. Predictive coding accounts propose that groove sensation arises from higher precision-weighted prediction error in syncopation [9–12]. Specifically, syncopation creates prediction errors and metrical uncertainty by causing mismatches between tone onsets and metrically strong positions. In the context of syncopated rhythm, bodily movements expected to refine beat or metrical predictions may be motivated as a means of resolving metrical uncertainty, which forms the fundamental

basis of rhythm perception [13]. This view aligns with the active inference framework [10, 11, 14]. Minimizing prediction error by changing sensory input through action to increase the accuracy of an agent's internal predictions is referred to as *active inference* [16, 18]. Thus, groove sensation may be understood as a form of active inference; however, it remains unclear whether bodily movements that enhance beat or metrical information directly influence groove sensation.

Matthews et al. [17] demonstrated that the degree of reduction in metrical prediction error explains the urge to move. To quantify the extent to which precision-weighted prediction error is expected to be minimized by moving in synchrony with the beat of a given rhythm, the authors calculated the difference in Shannon surprise (Δ Shannon surprise) between two models:

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one with a meter and one without. Their results showed that medium levels of syncopation produced the highest Δ Shannon surprise, whereas low and high levels of syncopation produced lower Δ Shannon surprise values. These findings suggest that if bodily movement in synchrony with the beat is expected to reduce surprise, a stronger sensation of groove is elicited. This interpretation is consistent with the active inference framework, which posits that action minimizes the prediction error of sensory input [16]. Although these results support an active inference account for groove, the specific role that movement synchronized with a beat or meter plays in shaping groove sensation remains unclear.

Based on the active inference framework, Ishida and Nittono [18] showed that tapping at a two-beat frequency increased intertrial phase coherence (ITPC) in electroencephalography (EEG) at both two-beat and four-beat frequencies when compared with a no-tapping condition. This finding was interpreted as reflecting a reduction in metrical uncertainty and an enhancement of beat- or meter-related information. Importantly, the increase in ITPC at the four-beat frequency, which differed from the tapping frequency, was taken to reflect endogenous neural synchronization to the beat. However, groove sensation did not differ between the tapping and no-tapping conditions in that study. This null effect may have resulted from the use of only a single syncopated rhythm, which could have induced boredom and limited the elicitation of groove sensation. In a related investigation of the pleasurable aspect of groove, Céspedes-Guevara and Witek [19] also reported no differences in the pleasure or arousal experienced by participants who listened to rhythms with varying degrees of syncopation under foot-tapping and no-tapping conditions. The authors speculated that the difficulty of the movement may have outweighed its positive effects. Furthermore, since the study did not assess tapping performance or physiological measures, it remains unclear what internal neural or behavioral changes were involved in the movement. Although some studies [18, 19] have reported no effect of bodily movement on *urge-to-move* and *pleasure* ratings, another study reported that groove ratings were higher in the foot-tapping condition than in the no-tapping condition [20]. Thus, the effect of synchronized bodily movement on groove sensation remains unclear.

The present study investigated whether tapping in synchrony with beats, which is expected to reduce metrical uncertainty, while listening to melodies with varying degrees of syncopation, enhances groove sensation. To this end, the effects of the presence or absence of tapping were examined by comparing two conditions: onbeat tapping and no-tapping. Moreover, differences in effectiveness across tapping types were examined by comparing the onbeat tapping with the offbeat tapping, in which synchronizing with the beat is difficult. *Urge-to-move* and *pleasure* ratings were expected to exhibit an inverted U-shaped relationship with the degree of syncopation. Additionally, the onbeat tapping condition was expected to elicit greater *urge-to-move* and *pleasure* ratings at high degrees of syncopation compared with both the no-tapping condition and the offbeat tapping condition. In addition to assessing subjective groove-related ratings, we recorded steady-state auditory evoked potentials (SSAEPs) as an index of neural entrainment to meter and beat, following previous studies on neural entrainment to beat- and meter-related information [21–23]. SSAEP amplitudes at beat-related

frequencies (four-beat [meter] and eight-beat frequencies) were expected to be greater in the onbeat tapping condition at high degrees of syncopation compared with both the no-tapping and offbeat tapping conditions.

2 | Materials and Methods

This study was preregistered on the Open Science Framework (<https://osf.io/kc8x2/registrations>) before data were collected.

2.1 | Participants

A total of 55 participants were recruited for this study. This sample size was determined by a priori power analysis to ensure a sufficient power $1-\beta = 0.80$ to detect a significant difference in *urge-to-move* and *pleasure* ratings, as well as in the SSAEP amplitudes at beat-related frequencies, between tapping conditions. Details of this power analysis are reported in the Supplementary Analysis S1.

According to the preregistered criterion, participants were excluded if more than four trials [25% of 12] in any condition were excluded (following Manning and Schutz [24]) due to EEG noise ($n = 1$), irregular taps ($n = 8$), or both ($n = 3$) (see section 2.6 for details). As a result, 12 participants were removed. In addition, one participant was excluded based on a non-preregistered criterion because this participant provided a *pleasure* rating of zero for all trials. Finally, data from the remaining 42 participants (19 women and 23 men, $M = 23.06$ years old, $SD = 3.96$) were included in the analyses to test the preregistered hypotheses for ratings and SSAEP measures. All participants reported no hearing impairments, no history of neurological, respiratory, or cardiovascular disorders, no nasal obstruction, and right-handedness. Participants' musical abilities are summarized in Table S1. The study protocol was approved by the Behavioral Research Ethics Committee of the University of Osaka, School of Human Sciences, Japan (HB025-084: October 21, 2025). Written informed consent was obtained from all participants, and each participant received gift certificates worth 4000 Japanese yen as an honorarium.

2.2 | Stimuli

The original stimuli were adopted from Zalta et al. [8], and the arranged stimulus set is illustrated in Figure 1. In Zalta et al. [8], the degree of syncopation (low, medium, and high) was quantified using Longuet-Higgins and Lee's [25] method, and 12 bass-guitar melodies were created for each degree of syncopation, accompanied by a four-beat hi-hat rhythm. Each melody had a duration of 4 s. Because the present study includes nine experimental conditions (three tapping conditions $\times$ three syncopation degrees), 24 additional melodies were generated for each syncopation degree by transporting the original 12 melodies up and down by a half step while preserving their rhythmic structure. This procedure increased the total number of melodies from 12 to 36 for each degree of syncopation. For each of the nine conditions, 12 unique melodies (corresponding to 12 trials) were presented to prevent boredom from repeated listening. All melodies were rendered with a bass-guitar timbre at a tempo

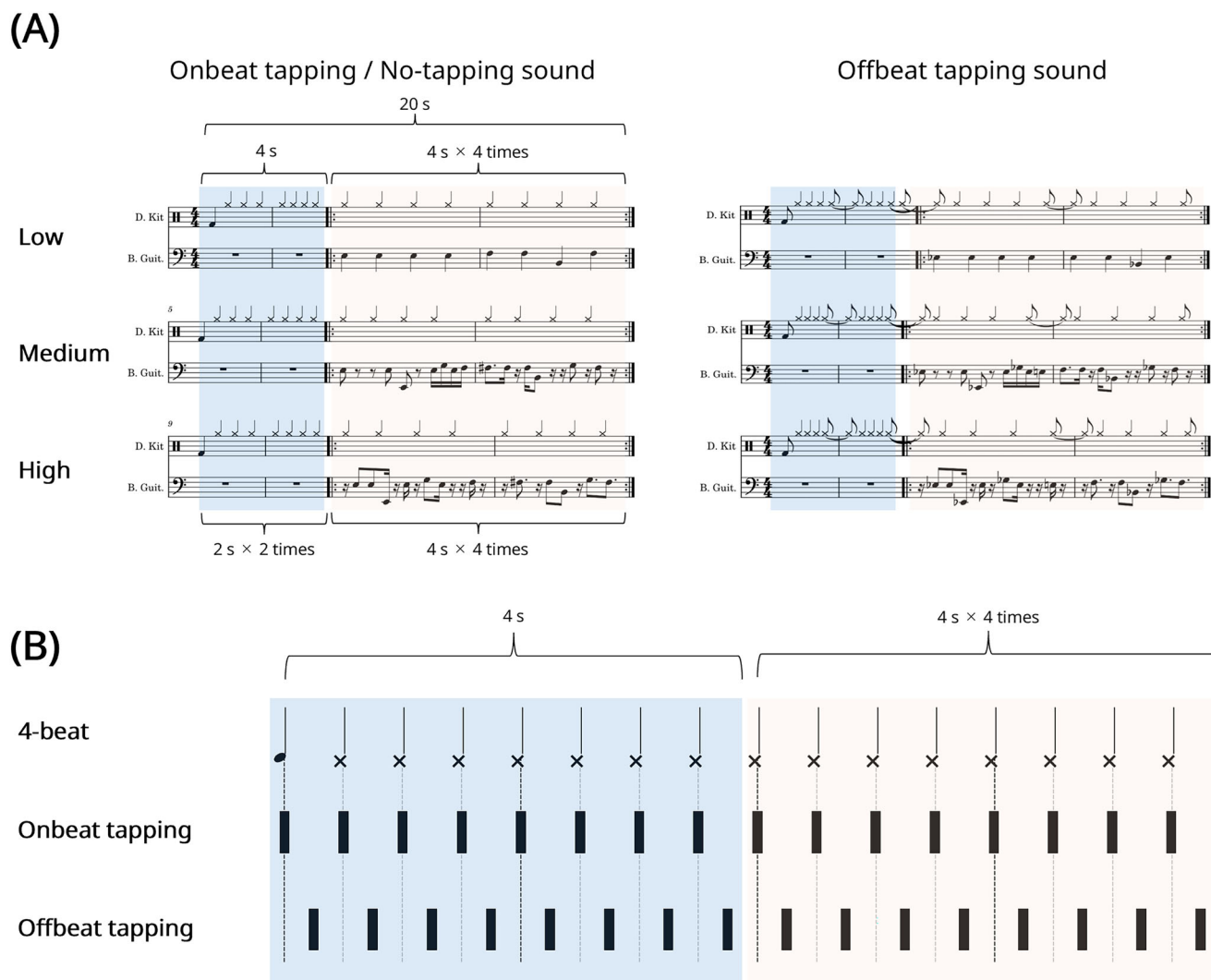


FIGURE 1 | (A) Examples of the melodies. The left panel shows the melodies with low, medium, and high degrees of syncopation presented in the onbeat tapping and no-tapping conditions. The right panel shows the melodies with the same rhythm pattern at different pitches presented in the offbeat tapping condition. The first bar consisted of one four-beat bass drum sound and three four-beat hi-hat sounds. The second bar consisted of four four-beat hi-hat sounds. The melody began in the third bar, and this two-bar melody was repeated four times. (B) Tapping pattern that participants were instructed to perform in the onbeat and offbeat tapping conditions. The black rectangles indicate the time points at which tapping occurred relative to the four beats. In both panels A and B, the blue shaded region denotes the introductory bars, whereas the orange shaded region denotes the melody bars.

of 120 BPM in 4/4 time. To facilitate tapping, each trial began with two introductory bars. The first bar contained a four-beat bass drum sound and three four-beat hi-hat sounds, and the second bar consisted of four four-beat hi-hat patterns. The initial bass drum sound was presented in all conditions, including the offbeat tapping condition, to indicate the downbeat. Following the introductory bars, the two-bar melody was repeated four times (16 s) without an interstimulus interval, resulting in each sequence (trial) having a total duration of 20 s. In the onbeat tapping and no-tapping conditions, an onbeat four-beat hi-hat rhythm was presented both before and during the melody. In contrast, an offbeat four-beat hi-hat rhythm was presented before and during the melody in the offbeat tapping condition.

For auditory sequence presentation and trigger output, stereo audio files were created, with the melody assigned to the first channel and the trigger sound indicating the onset of the tones assigned to the second channel. These channels were played

separately via a stereo-to-monoaural splitter cable. The rhythm channel was connected to left and right earphones (MDR-EX650AP; SONY, Tokyo, Japan) and played at 60 dB Sound Pressure Level. The trigger channel was connected to an auditory signal detector (StimTrak; Brain Products, Gilching, Germany), which immediately (<1 ms) sent a trigger to an EEG amplifier.

2.3 | Procedure

The experiment was conducted using Inquisit (version 7.1.3; Millisecond Software, LLC). Prior to EEG recording, participants completed the Japanese version of the Goldsmiths Musical Sophistication Index (Gold-MSI) [26, 27], the Japanese version of the Barcelona Music Reward Questionnaire (BMRQ) [28, 29] to assess sensitivity to musical reward, and the Japanese version of the FLANDERS handedness questionnaire [30, 31] to assess handedness.

The EEG recordings were divided into nine blocks, each corresponding to one experimental condition. The order of the tapping conditions (onbeat tapping, no-tapping, and offbeat tapping conditions) was counterbalanced across the participants. The order of syncopation degrees was randomized within each tapping condition, with the sole constraint that the same melodies were not presented. Each trial was conducted at the participants' own pace, and a mandatory short break was provided after every 12 trials, which marked the end of a block. In total, the participants completed 108 trials across nine conditions. Before the experiment, the participants practiced tapping until they felt confident enough to proceed. In the onbeat tapping condition, participants tapped along at a four-beat (2 Hz) rate on the onbeat, corresponding to the quarter note. In the offbeat tapping condition, participants tapped along at the same four-beat (2 Hz) rate but on the offbeat. Because the tapping frequency was theoretically identical across the two tapping conditions, any differences in SSAEP amplitude at the four-beat frequency cannot be attributed to simple motor-related activity; instead, they can be interpreted as reflecting internal metrical synchronization. To prevent tapping sounds from overlapping with the melody stimuli, the participants wore sound-attenuating earmuffs over their earphones and tapped on a sound-absorbing pad, ensuring that the tapping sound did not contaminate the melodic sequences. In the no-tapping condition, participants were instructed to focus on the melody while holding a pillow with both hands and refrain from moving any part of their bodies to prevent unintentional tapping. The no-tapping condition served as a control for the presence versus absence of tapping, whereas the offbeat tapping condition served as a control to evaluate whether only tapping that reinforces the metrical downbeat reduces metrical uncertainty and, conversely, enhances metrical precision.

In all conditions, participants were instructed to focus on a point displayed on the screen. Groove sensation was assessed using two items from the Japanese version of the Experience of Groove Questionnaire on a 7-point scale (0 = strongly disagree to 6 = strongly agree) [32, 33]. The first item was an urge-to-move item assessing the extent to which the participants experienced a desire to move. The second item was a pleasure item assessing the extent to which participants experienced pleasure while listening to music. Participants were asked to recall how they felt during each melody-listening trial. Additionally, they rated the subjective effect of tapping using three original tapping questionnaire items developed for the present study on a 7-point scale (0 = strongly disagree to 6 = strongly agree). The first item was a resolve item assessing the extent to which urge-to-move was alleviated, the second was a timing item assessing the extent to which tapping refined the prediction of sound timing, and the third was a synchrony item assessing how successfully participants were able to synchronize their tapping with the music. These tapping-related ratings were collected after each trial in the six tapping blocks. The five questionnaire items used in the present experiment are summarized in Table S1. Including electrode preparation, EEG recording, the questionnaire session, and short breaks between blocks, the entire experiment lasted approximately 3 h.

2.4 | Data Recording

EEG data were recorded using QuickAmp (Brain Products, Germany) with Ag/AgCl electrodes. Thirty-four scalp electrodes were used 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, Iz, and 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. The data were re-referenced offline by subtracting the average of all scalp electrodes [22]. The sampling rate was 1000 Hz, and the online filter was DC–200 Hz. Electrode impedances were kept below 10 k Ω during the EEG recording.

Using a custom-built pressure sensor switch, a digital signal indicating the tapping onset and an analog signal reflecting the pressure intensity were recorded. The pressure signal was transmitted to QuickAmp in less than 1 ms and recorded.

2.5 | EEG Data Preprocessing

EEG data were preprocessed using EEGLAB (version 2025.1.0) [34] on MATLAB R2023b (The MathWorks Inc., Natick, MA). First, a digital high-pass filter was applied to the data at 0.1 Hz [23]. Epochs lasting 16 s were obtained by segmenting each trial from +4 s to +20 s relative to the onset of the sequence. Thus, EEG data recorded during the first two bars were excluded. Ocular artifact correction based on independent component analysis was then applied, as in the previous study [23]. For each participant and condition, EEG epochs were averaged across trials (up to 12 trials) to enhance the signal-to-noise ratio of EEG activity time-locked to the beat, meter, and rhythmic patterns.

The averaged waveforms were transformed into the frequency domain using a discrete Fourier transform, which yielded a frequency spectrum of signal amplitude (μ V) ranging from 0 to 500 Hz. Although the true frequency resolution was determined by the 16 s analysis window (1/16 s = 0.0625 Hz), zero padding was applied to the data to achieve finer spectral sampling (0.031 Hz/bin), which matched the frequency binning used in a previous study [23]. Because the resulting frequency spectra were expected to include both stimulus-induced SSAEPs and unrelated residual background noise, noise was removed by subtracting the average amplitude measured in two flanking frequency bands ranging from –0.15 to –0.09 Hz and from 0.09 to 0.15 Hz relative to the target frequency bin (corresponding to approximately two bins on each side) [23]. The magnitude of the SSAEPs was then estimated by taking the maximum noise-subtracted amplitude measured within a range of three frequency bins centered on the expected SSAEP frequency based on the spectrum of the sound envelope: 1.98, 2.01, and 2.04 Hz for 2-Hz SSAEP, and 3.97, 4.00, and 4.03 Hz for 4-Hz SSAEP. To avoid electrode selection bias, SSAEP magnitudes were averaged across all scalp electrodes for each condition. The SSAEPs at the four-beat (2-Hz SSAEP) and eight-beat (4-Hz SSAEP) frequencies for each condition were used for hypothesis testing.

2.6 | Tap/EEG Data Cleaning

Data were cleaned according to the preregistered criteria. First, taps were excluded if the signed asynchrony (tap onset–four-beat onset) was greater than +250 ms or less than –250 ms, because 250 ms corresponds to a delay of half a beat in the four-beat melody. Second, to exclude missed taps and double taps, taps were excluded if the ITI was greater than 750 ms or less than 250 ms. Trials were then excluded when the number of missing or excluded taps exceeded eight (25% of 32 taps during melody listening) within a trial.

2.7 | Statistical Analyses

2.7.1 | ANOVAs on Groove-Related Ratings Averaged Across Melodies

For hypothesis testing, we initially performed factorial ANOVAs for urge-to-move and pleasure ratings across the nine experimental conditions. These dependent variables were computed by averaging the trial-level (melody-level) values within each condition.

Both traditional and Bayesian repeated-measures ANOVAs were conducted on urge-to-move and pleasure ratings with tapping condition (onbeat tapping vs. no-tapping vs. offbeat tapping) and degree of syncopation (low vs. medium vs. high) as within-subject factors for the preregistered analyses. Subsequently, a trend analysis was performed on urge-to-move and pleasure ratings as a function of the degree of syncopation (low vs. medium vs. high), averaged across tapping conditions, to test nonlinearity. Traditional ANOVAs were performed using the *aov_ez* function from the *afex* package [35], and post hoc comparisons were conducted using the *emmeans* function from the *emmeans* package [36]. Greenhouse–Geisser ϵ corrections were applied to all ANOVAs. For multiple comparisons, *p* values were adjusted using the Bonferroni method. For the Bayesian version of the ANOVAs, the inclusion Bayes factors (BF_{incl}) of the main effects and their interactions were calculated using JASP (version 0.95.4) [37]. The prior coefficient was 0.5 for the *r* scale of fixed effects and 1 for the *r* scale of random effects. A uniform distribution was set for the model prior. BF_{incl} was calculated as the odds ratio representing the likelihood of models that included the effect versus models that did not have the effect when averaged across all candidate models. Tapping-related ratings (i.e., resolve, timing, and synchrony) were analyzed using the same ANOVA approach as that applied to the groove-related ratings, as these analyses were ancillary to the main hypothesis (see Supplementary Analysis S2).

2.7.2 | Linear Mixed-Effect Model-Based ANOVAs on Groove-Related Ratings Accounting for Melody Differences

Groove is known to be influenced by individual differences [38] and the characteristics of musical materials [7, 39]. In addition to the preregistered analyses that averaged across melodies and to more appropriately evaluate our hypotheses, we conducted trial-level analyses that accounted for melody-specific variability, collapsing stimuli with different rhythmic and pitch structures.

These analyses were conducted using a linear mixed-effect model (LMM). In the LMM-based ANOVAs, ratings for each individual melody were entered as the dependent variable. The model equation for urge-to-move and pleasure ratings was as follows:

$$\begin{aligned} \text{Ratings} = & \text{tapping condition} + \text{syncopation degree} \\ & + \text{tapping condition} \times \text{syncopation degree} \\ & + (1|\text{participants}) + (1|\text{melodies}) + \text{total score of BMRQ} \\ & + \text{score of general sophistication from Gold - MSI} \end{aligned}$$

All ratings were normalized to a mean of 0 and an *SD* of 1 for each participant. The LMMs were fitted using the *lmer* function from the *lme4* package [40]. Type III ANOVAs were conducted with denominator degrees of freedom estimated using Satterthwaite's method [41]. Post hoc pairwise comparisons were performed using estimated marginal means with *t*-tests using Satterthwaite-approximated degrees of freedom and Bonferroni corrections. In all models, although the random effect of participants resulted in a singular fit due to limited between-participant variability, it was retained to account appropriately for the repeated-measures structure of the data [42]; such singular models remain statistically valid. The same LMM-based ANOVAs were also applied to tapping-related ratings (i.e., resolve, timing, and synchrony) to assess the effectiveness of tapping (see Supplementary Analysis S2).

Furthermore, to examine the relationship between the degree of syncopation while explicitly accounting for an inverted U-shaped pattern, syncopation of melodies was quantified as a continuous variable, and LMMs were fitted to urge-to-move and pleasure ratings using polynomial terms to capture curvilinear effects. Statistical significance of the main effects and interactions was assessed using the *anova* function from the *lmerTest* package. Post hoc *t*-tests with Satterthwaite-approximated degrees of freedom were conducted for significant interactions using the *emtrends* function from the *emmeans* package with Bonferroni correction.

2.7.3 | ANOVAs for SSAEP Amplitudes

As a preregistered analysis, we conducted both traditional and Bayesian repeated-measures ANOVAs for SSAEP amplitudes at beat-related frequencies (2-Hz SSAEP and 4-Hz SSAEP), with tapping condition and degree of syncopation as within-subject factors. Corrections for violation of sphericity and adjustment of *p* values for multiple comparisons were performed in the same manner as in the ANOVA for the rating data.

2.7.4 | Mediation Analysis Examining Neural and Behavioral Entrainment to the Beat

We examined whether neural and behavioral entrainment to beat were associated with changes in subjective groove sensation using Bayesian mediation analysis. To account for the random effects of participants and melody types, mediation effects were estimated within a Bayesian linear modeling framework. Tapping condition was specified as the independent variable, urge-to-move and pleasure ratings as the dependent variables, and two

TABLE 1 | Results of ANOVAs for groove-related ratings.

ANOVAs Averaged Across Melodies															
<i>N</i> = 42	Tapping Condition					Degree of Syncopation					Interaction				
	<i>F</i> (<i>df</i>)	<i>p</i>	η_p^2	ϵ	BF _{incl}	<i>F</i> (<i>df</i>)	<i>p</i>	η_p^2	ϵ	BF _{incl}	<i>F</i> (<i>df</i>)	<i>p</i>	η_p^2	ϵ	BF _{incl}
Urge-to-Move	0.72 (2, 82)	0.483	0.017	0.95	0.12	74.43 (2, 82)	<.001*	0.645	0.85	∞	2.39 (4, 164)	0.072	0.055	0.76	0.24
Pleasure	0.53 (2, 82)	0.588	0.013	0.99	0.08	67.55 (2, 82)	<.001*	0.622	0.84	2.00 × 10 ¹⁴	1.73 (4, 164)	0.160	0.041	0.80	0.07

LMM-Based ANOVAs Accounting for Melody Differences										
<i>N</i> = 42	Tapping Condition		Degree of Syncopation		Interaction		General Sophistication		BMRQ	
	<i>F</i> (<i>df</i>)	<i>p</i>	<i>F</i> (<i>df</i>)	<i>p</i>	<i>F</i> (<i>df</i>)	<i>p</i>	<i>F</i> (<i>df</i>)	<i>p</i>	<i>F</i> (<i>df</i>)	<i>p</i>
Urge-to-Move	7.69 (2, 1069.28)	<0.001*	326.33 (2, 236.04)	<0.001*	7.52 (4, 1070.14)	<0.001*	0.004 (1, 4182.65)	0.951	0.02 (1, 4231.54)	0.901
Pleasure	6.46 (2, 1009.14)	0.002*	335.14 (2, 224.51)	<0.001*	4.03 (4, 1009.93)	0.003*	<0.001 (1, 4236.13)	0.989	<0.001 (1, 4282.59)	0.993

Note: Asterisks indicate the statistical significance of the factor.

mediators were included: the amplitude of the 2 Hz SSAEP as a neural index of beat-prediction precision, and the *SD* of the ITI as a behavioral index of beat-prediction precision. Model fitting was conducted using the *brm* function from the *brms* package [43]. Although differences in tapping were expected to differently influence the SSAEP and *SD* of ITI, the SSAEP and *SD* of ITI (i.e., tapping variability) were assumed to have similar effects on groove-related ratings. Thus, the *a*-path was estimated as different slopes for each tapping condition, whereas the *b*-path was estimated as a common slope across tapping conditions.

3 | Results

3.1 | Groove-Related Ratings

3.1.1 | ANOVAs on Ratings Averaged Across Melodies

The preregistered two-way ANOVA with factors of tapping condition and degree of syncopation revealed a significant main effect of the degree of syncopation on the ratings of both *urge-to-move* and *pleasure* items (see Table 1). However, neither the main effect of tapping nor the interaction reached statistical significance. Subsequent trend analyses revealed significant positive linear trends for both *urge-to-move* (estimate = 0.73, $t[41] = 7.15$, $p < 0.001$) and *pleasure* ratings (estimate = 0.73, $t[41] = 7.15$, $p < 0.001$), as well as significant negative quadratic trends for *urge-to-move* (estimate = −1.94, $t[41] = −9.62$, $p < 0.001$) and *pleasure* ratings (estimate = −1.85, $t[41] = −8.58$, $p < 0.001$) that indicated an inverted U-shaped relationship. Post hoc analyses revealed that, compared with the low and high degrees of syncopation, both *urge-to-move* and *pleasure* ratings were highest at a medium degree of syncopation ($ps < 0.001$). Moreover, ratings were significantly higher at the high degree of syncopation than at the low degree of syncopation ($ps < 0.001$). The results of ANOVAs on the tapping-related ratings are reported in Supplementary Analysis S2.

3.1.2 | LMM-Based ANOVAs That Account for Melody Differences

The LMM-based ANOVA on *urge-to-move* ratings revealed significant main effects of tapping condition and degree of syncopation, as well as a significant interaction between these factors (see Table 1, bottom panel). Post hoc *t*-tests examining the simple main effect of tapping condition revealed that, at the low degree of syncopation, *urge-to-move* ratings were significantly higher in both the onbeat ($p < 0.001$) and offbeat ($p = 0.003$) tapping conditions than in the no-tapping condition (see Figure 2A). The difference between the onbeat and offbeat tapping conditions at the low degree of syncopation was not statistically significant ($p = 0.244$). At the medium and high degrees of syncopation, no significant differences between tapping conditions were observed ($ps > 0.089$). Post hoc *t*-tests examining the simple main effect of degree of syncopation revealed that, across all tapping conditions, *urge-to-move* ratings were highest at the medium degree of syncopation, followed by high and low degrees ($ps < 0.001$), resulting in an inverted U shape.

For the *pleasure* ratings, the LMM-based ANOVA revealed significant main effects of the tapping condition and degree of syncopation, as well as a significant interaction (see Table 1, bottom panel). Post hoc *t*-tests examining the simple main effect of tapping condition showed that at the low degree of syncopation, *pleasure* ratings were significantly higher in both the onbeat ($p < 0.001$) and offbeat ($p = 0.039$) tapping conditions than in the no-tapping condition (see Figure 2A). However, the difference between the onbeat and offbeat tapping conditions at the low degree of syncopation was not statistically significant ($p = 0.431$). No significant differences between tapping conditions were observed at medium and high degrees of syncopation ($ps > 0.168$). Post hoc *t*-tests examining the simple main effect of the degree of syncopation revealed that, across all tapping conditions, *pleasure* ratings were highest at the medium degree of syncopation, followed by high and low degrees of syncopation

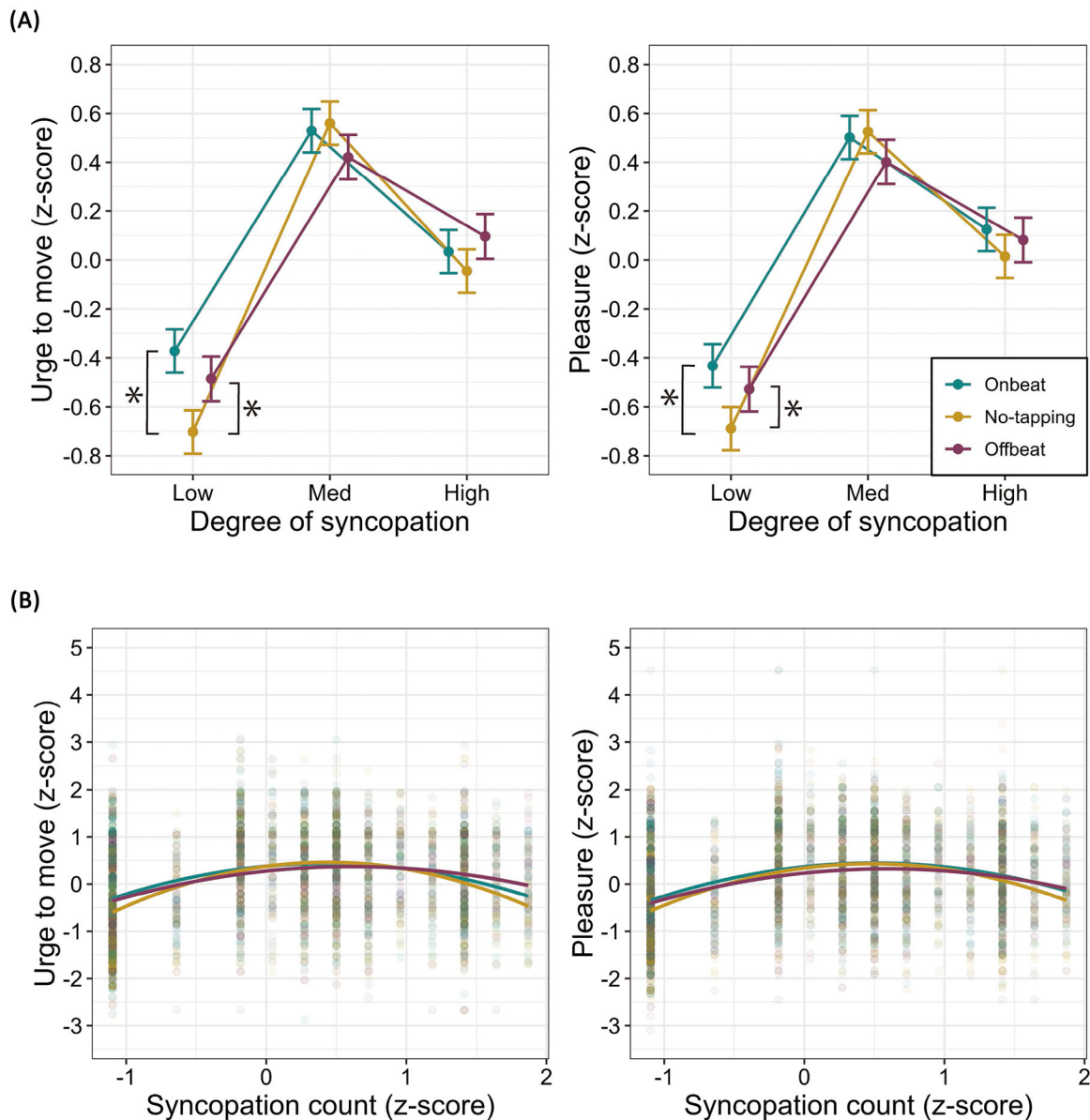


FIGURE 2 | (A) Groove-related ratings across melodies. Large dots represent the estimated marginal means derived from the linear mixed-effect model (LMM), and error bars indicate 95% confidence intervals. Asterisks indicate only those pairs that showed significant differences in the simple main effects of the tapping condition within the tapping condition $\times$ degree of syncopation interaction. Significant differences in the simple main effect of the degree of syncopation are not indicated. (B) Groove-related ratings predicted by LMMs incorporating numeric syncopation counts. Jittered dots represent observed trial-level ratings, and solid lines indicate quadratic fits predicted by LMMs as a function of z-scored syncopation counts across tapping conditions.

($ps < 0.001$), resulting in an inverted U shape. Relatedly, the results of the LMM-based ANOVAs on the tapping-related ratings (i.e., resolve, timing, and synchrony) are provided in Supplementary Analysis S2.

3.1.3 | Modeled Quadratically

The LMM analysis, which included numeric syncopation counts and their quadratic terms, revealed significant linear and quadratic effects of syncopation count and significant interactions between tapping condition and the quadratic term of syncopation count for both *urge-to-move* and *pleasure* ratings (see Figure 2B and Table 2). For *urge-to-move* ratings, the post hoc t -

tests for the significant interaction revealed that the coefficient of the quadratic trend was significantly more negative in the no-tapping condition ($\beta = -0.45$) than in the onbeat tapping condition ($\beta = -0.32$) ($p = 0.005$). There were no significant differences between the onbeat and offbeat tapping conditions or between the no-tapping and offbeat tapping conditions ($ps > 0.071$). Because the quadratic coefficient reflects the curvature of the function, the larger negative value in the no-tapping condition indicates a steeper inverted U-shaped curve, corresponding to a more pronounced reduction in ratings at low and high levels of syncopation. For *pleasure* ratings, there were no significant differences between tapping conditions ($ps > 0.079$), although the quadratic coefficient was numerically more negative in the

TABLE 2 | Results of ANOVAs based on the LMM including quadratic terms.

<i>N</i> = 42	Fixed-effect predictor	<i>F</i>	<i>df</i>	<i>p</i>
Urge-to-move	Syncopation count (linear)	78.30	1, 85.58	< 0.001*
	Syncopation count (quadratic)	61.01	1, 85.61	< 0.001*
	Tapping condition	0.43	2, 217.03	0.650
	Syncopation count (linear) × Tapping condition	7.23	2, 216.46	0.001*
	Syncopation count (linear) × Tapping condition	6.28	2, 216.80	0.002*
	BMRQ total score	0.13	1, 4370.52	0.714
Pleasure	General Sophistication Score of Gold-MSI	0.03	1, 4351.87	0.860
	Syncopation count (linear)	96.43	1, 97.46	< 0.001*
	Syncopation count (quadratic)	62.68	1, 97.50	< 0.001*
	Tapping condition	0.88	2, 258.87	0.418
	Syncopation count (linear) × Tapping condition	2.75	2, 258.08	0.066
	Syncopation count (linear) × Tapping condition	3.27	2, 258.56	0.040*
	BMRQ total score	0.0003	1, 4374.63	0.986
	General Sophistication Score of Gold-MSI	0.003	1, 4354.81	0.958

Note: Asterisks denote statistically significant fixed effects. BMRQ (Barcelona Music Reward Questionnaire; adapted from Mas-Herrero et al. [29] by Honda et al. [28]) and Gold-MSI (Goldsmiths Musical Sophistication Index; adapted from Müllensiefen et al. [26] by Sadakata et al. [27]) were used as control measures.

TABLE 3 | Results of ANOVAs for SSAEP amplitudes.

<i>N</i> = 42	Tapping condition					Degree of syncopation					Interaction				
	<i>F</i> (<i>df</i>)	<i>p</i>	η_p^2	ϵ	<i>BF</i> _{incl}	<i>F</i> (<i>df</i>)	<i>p</i>	η_p^2	ϵ	<i>BF</i> _{incl}	<i>F</i> (<i>df</i>)	<i>p</i>	η_p^2	ϵ	<i>BF</i> _{incl}
2-Hz SSAEP	88.67 (2, 82)	< 0.001*	0.684	0.99	1.88 × 10 ¹⁸	76.65 (2, 82)	< 0.001*	0.179	0.97	1.50 × 10 ⁸	12.48 (4, 164)	< 0.001*	0.233	0.63	1.36 × 10 ⁸
4-Hz SSAEP	56.89 (2, 82)	< 0.001*	0.581	0.88	6.67 × 10 ¹⁴	8.93 (2, 82)	< 0.001*	0.179	0.90	69.63	2.87 (4, 164)	0.034*	0.065	0.83	6.15

Note: Asterisks indicate statistical significance.

no-tapping condition ($\beta = -0.40$) than in the onbeat tapping condition ($\beta = -0.31$).

3.2 | ANOVAs on SSAEP Amplitudes

The SSAEP waveforms showed clear peaks at frequencies of 2 and 4 Hz, which reflect neural entrainment to the four-beat (meter) and eight-beat, respectively (see Figure 3 and Table 3). For the 2-Hz SSAEP, the two-way ANOVA revealed significant main effects of tapping condition and degree of syncopation, as well as the interaction of these factors. Post hoc *t* tests examining the simple main effect of the tapping condition revealed that, at the high degree of syncopation, the SSAEP amplitude was significantly larger for both the onbeat tapping and offbeat tapping conditions than for the no-tapping condition ($ps < 0.001$), whereas no significant difference was observed between the onbeat and offbeat tapping conditions ($p = 1.000$). At the low and medium

degrees of syncopation, the SSAEP amplitude was larger in the onbeat tapping condition than in the no-tapping and offbeat tapping conditions ($ps < 0.001$). Moreover, at the medium degree of syncopation, SSAEP amplitude was significantly larger in the offbeat tapping condition than in the no-tapping condition ($p < 0.001$), but not at the low degree of syncopation ($p = 0.146$). Post hoc *t* tests examining the simple main effect of degree of syncopation revealed that, in the no-tapping condition, SSAEP amplitudes were larger at the low degree of syncopation than at the medium and high degrees ($ps < 0.001$) with no significant difference observed between the medium and high degrees ($p = 1.000$). In the onbeat tapping condition, SSAEP amplitudes were larger at the low degree of syncopation than at the medium ($p = 0.007$) and high ($p < 0.001$) degrees, and amplitudes at the medium degree were larger than at the high degree ($p = 0.002$). In contrast, SSAEP amplitudes did not significantly differ across degrees of syncopation in the offbeat tapping condition ($ps > 0.065$).

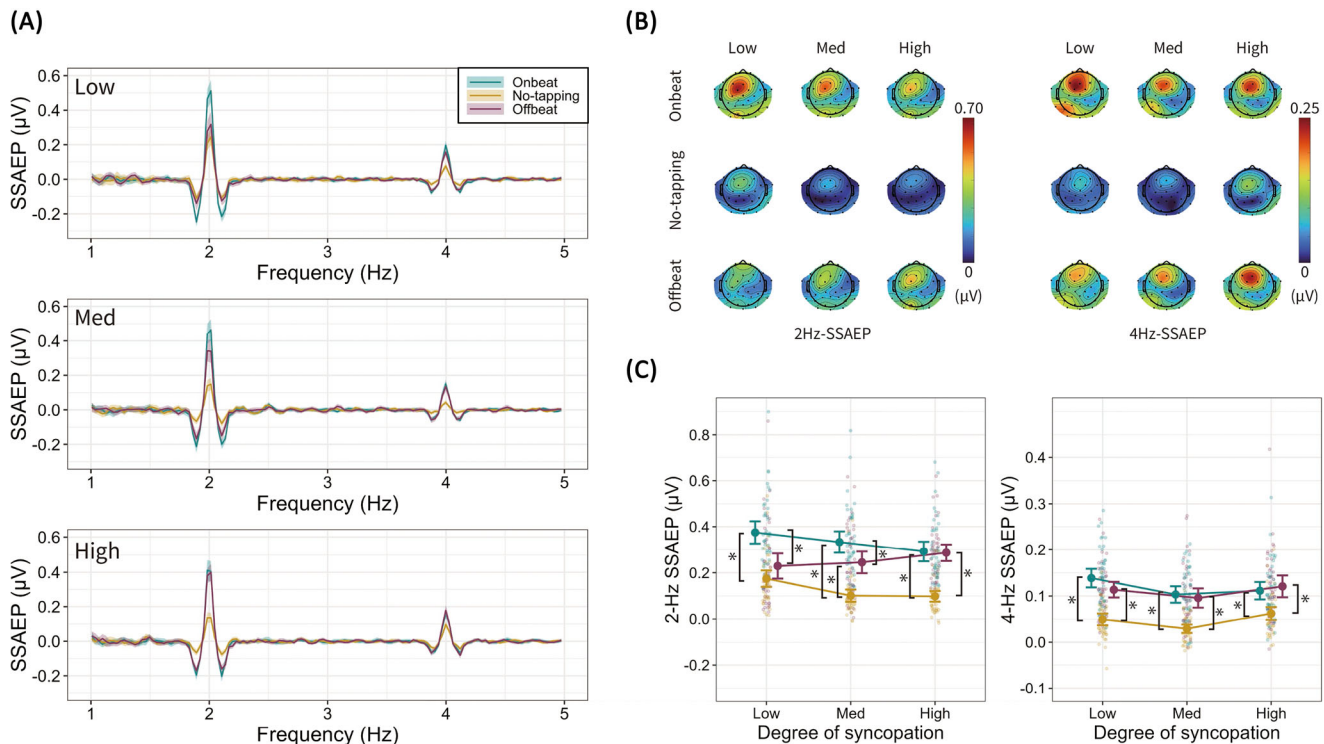


FIGURE 3 | (A) SSAEP waveforms for each degree of syncopation. (B) Topographic distribution of SSAEP amplitude at 2 and 4 Hz. (C) Mean SSAEP amplitudes at 2 and 4 Hz. In all panels, large dots represent the means of observed ratings, and error bars and ribbons indicate 95% confidence intervals. Asterisks indicate only those pairs that showed significant differences in the simple main effects of the tapping condition within the tapping condition $\times$ degree of syncopation interaction. Significant differences in the simple main effect of the degree of syncopation are not indicated.

For 4 Hz, the two-way ANOVA revealed significant main and interaction effects (see Table 3). Post hoc t tests examining the simple main effect of the tapping condition showed that SSAEP amplitudes were significantly larger in both the onbeat and offbeat tapping conditions than in the no-tapping condition at the low, medium, and high degrees of syncopation (p s < 0.001). However, no significant differences in SSAEP amplitudes were observed between the onbeat and offbeat tapping conditions at any degree of syncopation (p s > 0.074). Post hoc t tests examining the simple main effect of degree of syncopation revealed that, in the no-tapping condition, SSAEP amplitudes were significantly larger at the high (p < 0.001) and low (p = 0.009) degrees of syncopation than at the medium degree of syncopation. In the onbeat tapping condition, SSAEP amplitudes were significantly larger at the low degree of syncopation than at the medium degree of syncopation (p = 0.003), whereas the high–low and high–medium comparisons were not statistically significant (p s > 0.054). No significant differences in SSAEP amplitudes were observed across degrees of syncopation in the offbeat tapping condition (p s > 0.170).

3.3 | ANOVAs on SD of ITI

We analyzed the SD of ITI as an index of tapping accuracy. Analyses of the other tapping performance indices are reported in Supplementary Analysis S3. The two-way ANOVA on the SD of the ITI revealed significant main effects of tapping condition and degree of syncopation, as well as a significant interaction between these factors (F (2, 82) > 5.85, p s < 0.005, η_p^2 > 0.125, ϵ

> 0.95, BF_{incl} > 53.41). Post hoc analyses examining the simple main effect of the tapping condition revealed that the SD was significantly smaller in the onbeat tapping condition than in the offbeat tapping condition at the low (p < 0.001) and medium (p = 0.007) degrees of syncopation but not at the high degree of syncopation (p = 0.544). Post hoc analyses examining the simple main effect of degree of syncopation showed that, in the onbeat tapping condition, the SD was significantly smaller at the low degree of syncopation than at the medium (p = 0.002) and high (p < 0.001) degrees of syncopation, but did not differ between the medium and high degrees of syncopation (p = 0.279). In the offbeat tapping condition, no significant differences were observed between degrees of syncopation (p s > 0.599).

3.4 | Mediation Analysis

3.4.1 | 2-Hz SSAEP as a Neural Mediator

Bayesian mediation analysis revealed that the 2-Hz SSAEP amplitude was positively associated with *urge-to-move* ratings (posterior median = 0.05, 95% Bayesian credible interval [CI] = [0.02, 0.08]). After marginalizing over the three degrees of syncopation, the onbeat tapping condition showed a stronger indirect effect via SSAEP than both the no-tapping condition (posterior median = −0.02, 95% Bayesian CI = [−0.04, −0.01]) and the offbeat tapping condition (posterior median = −0.06, 95% Bayesian CI = [−0.11, −0.02]) (see Figure 4). The magnitude of the indirect effect progressively decreased with increasing

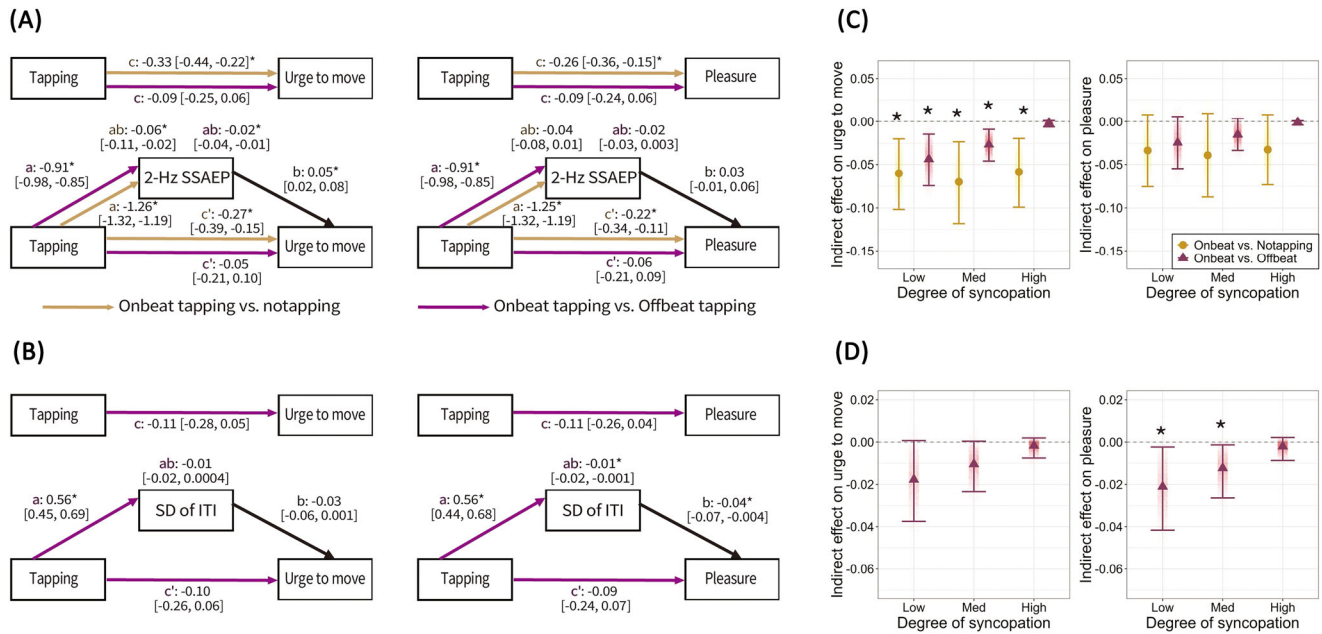


FIGURE 4 | (A) A mediation model tested with the 2-Hz SSAEP amplitude as the mediator. (B) A mediation model tested with the SD of the ITI as the mediator. In panels (A) and (B), the *a*-path reflects the effect of tapping condition on 2-Hz SSAEP amplitude and the SD of the ITI, with the onbeat tapping condition set as the reference level; a common *b*-path reflects the effect of 2-Hz SSAEP amplitude and the SD of the ITI on groove-related ratings across tapping conditions; the *c*-path reflects the direct effect of tapping condition on groove-related ratings; and the *c*-path reflects the total effect of tapping condition on groove-related ratings. The product of *ab* reflects the indirect effect. Colors indicate the effects when comparing the onbeat tapping condition with the no-tapping or offbeat tapping conditions. (C) Indirect effects on ratings via 2-Hz SSAEP amplitudes estimated across degrees of syncopation. (D) Indirect effects on ratings via the SD of the ITI estimated across degrees of syncopation. In panels (C) and (D), large dots and triangles indicate posterior medians, and error bars denote 95% credible intervals. In all panels, asterisks indicate that the 95% CI does not include zero.

syncopation when comparing the onbeat and offbeat tapping conditions.

In contrast, for *pleasure* ratings, the 2-Hz SSAEP amplitude did not show a positive association (posterior median = 0.03, 95% Bayesian CI = [−0.08, 0.06]). Consistently, no reliable indirect effects on *pleasure* ratings via the 2-Hz SSAEP were observed. The indirect effect of the onbeat tapping condition did not differ from either the no-tapping condition (posterior median = −0.04, 95% Bayesian CI = [−0.08, 0.01]) or the offbeat tapping condition (posterior median = −0.01, 95% Bayesian CI = [−0.03, 0.003]).

3.4.2 | ITI SD as a Behavioral Mediator

Bayesian mediation analysis of *urge-to-move* ratings revealed that the SD of the ITI did not have a reliable effect on the ratings (posterior median = −0.03, 95% Bayesian CI = [−0.06, 0.001]). Moreover, no reliable indirect effect was supported when comparing the onbeat and offbeat tapping conditions (posterior median = −0.01, 95% Bayesian CI = [−0.02, 0.0002]).

However, regarding *pleasure* ratings, the SD of the ITI showed a reliable negative association (posterior median = −0.04, 95% Bayesian CI = [−0.08, −0.005]), which indicates that more stable tapping was associated with higher pleasure (see Figure 4). When marginalizing over the three levels of syncopation, the indirect effect was larger in the onbeat tapping condition than in the offbeat tapping condition (posterior median = −0.01, 95%

Bayesian CI = [−0.02, −0.002]). This indirect effect gradually decreased as the degree of syncopation increased.

4 | Discussion

The present study examined whether bodily movement synchronized with rhythm modulates groove sensation by refining metrical predictions for syncopated melodies. Furthermore, we explored whether—if tapping did modulate groove sensation—neural entrainment and tapping performance mediated the effects of movement on groove. Using the stimuli from Zalta et al. [8], the present study successfully replicated the inverted U-shaped relationship between the degree of syncopation and both *urge-to-move* and *pleasure* ratings. Groove sensation is influenced by factors other than degree of syncopation, such as affective qualities [44], harmonic complexity [7], and tempo [39, 45] of the musical stimuli, as well as listeners' musical expertise and musical biography [38]. To appropriately address these factors, LMM analyses that incorporated stimulus characteristics and individual differences were used to complement the preregistered analyses. Although the preregistered ANOVAs failed to detect the effect of tapping, the LMM analyses revealed higher *urge-to-move* and *pleasure* ratings at the low degree of syncopation in the onbeat and offbeat tapping conditions than in the no-tapping condition, with no difference observed between the two tapping conditions. However, in contrast to the hypothesis, no effects related to tapping were observed at either the medium or high degrees of syncopation.

In the present study, tapping effectively enhanced *urge-to-move* and *pleasure* ratings at low degrees of syncopation. However, the absence of differences at medium or high degrees of syncopation contrasts with the findings of Spiech et al. [20], who reported significantly higher groove ratings in the foot-tapping condition than in the no-tapping condition across different degrees of pulse entropy. Unlike their study, the participants in the present study performed a smaller motor movement (finger tapping) while wearing sound-attenuating earmuffs. This setup may not have produced enough somatosensory and auditory feedback to reinforce the beat. Consequently, tapping may not have sufficiently enhanced beat perception to influence groove sensation across different degrees of syncopation. Under the active inference model, a mixture of action feedback, such as tapping sounds and motor-contingent somatosensory signals, may be crucial for enhancing the precision of beat prediction. Relatedly, Aschersleben et al. [46] found that eliminating tactile feedback disrupted temporal synchrony in tapping tasks. Therefore, blocking sound and motor-related signals may hinder active inference and reduce the effectiveness of tapping.

The enhancement of groove sensation via both onbeat and offbeat tapping at the low degree of syncopation, with no significant differences between the two, does not support the active inference account. There are several alternative explanations. First, motor engagement and attentional state during tapping may have prevented boredom by increasing task engagement and arousal relative to the no-tapping condition. Critically, the lack of a difference in groove ratings between the onbeat and offbeat tapping conditions suggests that the uncertainty reduction did not occur through the onbeat tapping. Second, synchronizing taps with simple rhythms may further motivate listeners to move more because these rhythms convey strong metric clarity and are easy to entrain to [47]. In contrast, synchronizing taps with complex rhythms may decrease the motivation to move because the tapping task is difficult. Third, in the offbeat tapping condition, tapping out of phase with the beat may have functioned as syncopated accents and generated metric prediction error. This could increase the rhythmic complexity of a low-syncopation rhythm, leading to greater information gain and enhanced groove sensation [9]. Finally, the null effect at medium and high degrees of syncopation may indicate that the difficulty of tapping itself outweighed its positive effects [19]. In sum, these possibilities differ from predictions derived from active inference, which proposes that the reduction of metrical uncertainty through bodily movement contributes to groove sensation.

Although the main results of the present study did not provide evidence supporting active inference, some findings were nonetheless consistent with its predictions. First, the quadratic LMM of *urge-to-move* ratings revealed that the inverted U curvature was flatter in the onbeat tapping condition than in the no-tapping condition, which indicates that bodily movement attenuated the reduction in groove ratings at both low and high degrees of syncopation (see Figure 2B). At high degrees of syncopation, pulse-based tapping may have reduced uncertainty. This is suggested by the finding that the curvature was significantly flatter in the onbeat (but not offbeat) tapping condition than in the no-tapping conditions. Second, the Bayesian mediation analyses indicated that higher groove ratings, mediated by enhancements

in neural and behavioral entrainment, may reflect a greater resolution of metrical uncertainty. This, in turn, may have increased the precision of the onbeat (but not offbeat) tapping, as proposed in the active inference framework [9, 18]. Therefore, further investigation of these aspects of groove elicitation is needed to determine whether the active inference framework can be truly ruled out as an explanation of groove modulation via tapping.

Clear peaks were observed at beat- and meter-related frequencies in the SSAEP, consistent with previous studies showing that SSAEPs at these frequencies are enhanced during rhythm listening [22, 23]. At low and medium degrees of syncopation, SSAEP amplitude at 2 Hz—the four-beat frequency in this study—was larger in the onbeat tapping condition than in the no-tapping and offbeat tapping conditions. The difference in SSAEP amplitude between the tapping and no-tapping conditions is partly attributable to motor-related potentials. However, SSAEP amplitude and behavioral tapping variability (*SD* of *ITI*) independently predicted *urge-to-move* and *pleasure* ratings, suggesting partially separate contributions of neural entrainment and motor performance. These findings indicate that, although SSAEPs contain motor-related activities, they cannot be interpreted as purely motor-driven responses. Rather, they may reflect differences in SSAEPs associated with the relative ease or difficulty of entraining to the beat. Thus, the present study further demonstrates that tapping also enhances neural entrainment at beat-related frequencies. Alternatively, the positive association between the 2-Hz SSAEP and *urge-to-move* ratings (i.e., the *b*-path of the mediation model of *urge-to-move* ratings) is consistent with previous findings showing that the strength of beat-frequency oscillations in a neural network model is positively associated with groove ratings [8]. Therefore, the neural resonance theory can also account for the present data in terms of the mode locking of neural oscillations to the beat as a mechanism underlying beat perception and groove sensation, as reflected in SSAEPs [8, 48, 49].

Tapping influenced both the *urge-to-move* and *pleasure* aspects of groove. In the mediation analysis, neural entrainment to the beat (2-Hz SSAEP) was significantly associated with *urge-to-move*, whereas behavioral entrainment (*SD* of the *ITI*) was significantly associated with *pleasure*. Consistently, Cameron et al. [50] reported that neural entrainment to the beat and meter was associated with *urge-to-move* ratings, but not with *pleasure* ratings. In their study, *pleasure* ratings were more strongly related to the accuracy of behavioral tapping. The dissociation between *urge-to-move* and *pleasure* may reflect different underlying mechanisms. The former may reflect a motivation to move that depends on the perceived precision—which is the inverse of uncertainty or entropy [20, 51] in the current rhythmic context, whereas the latter may reflect an affective response resulting from the extent to which uncertainty is resolved by synchronized tapping, consistent with prediction error reduction in the predictive coding framework [14, 52–54]. However, because the indirect effects of the 2-Hz SSAEP and *SD* of *ITI* on *urge-to-move* and *pleasure* ratings showed similar patterns, it remains unclear whether the observed contributions of neural and behavioral entrainment reflect distinct processing mechanisms or are due to limited statistical power, representing key topics for future research.

The lack of evidence supporting active inference may be attributable to limitations specific to the present study. First, whereas predictive coding of music models uses prediction error and uncertainty as key indices [10, 11], the present study operationalized complexity using the degree of syncopation, which represents only one aspect of musical complexity [47]. Second, in the stimuli used in the present study, a four-beat hi-hat pattern was included in the audio in both the tapping and no-tapping conditions to assist participants in tapping. As a result, the metrical structure may already have been sufficiently emphasized even without tapping, potentially limiting the extent to which movement could reduce uncertainty. Future work should examine how tapping modulates groove sensation as a function of prediction error and uncertainty computed by the brain, using stimuli that do not include explicit beat cues.

5 | Conclusion

In conclusion, the present study demonstrated that tapping enhances groove sensation. The underlying mechanism of groove enhancement at the low degree of syncopation may not primarily reflect active inference; rather, it is more likely related to motor engagement and arousal state. However, exploratory mediation analyses indicated that, relative to the offbeat and no-tapping conditions, onbeat tapping enhanced neural and behavioral entrainment to the beat, and this entrainment was positively associated with groove ratings, partially consistent with active inference. Additional empirical studies are needed to determine whether active inference contributes to the enhancement of groove sensation through bodily movement after addressing the limitations of the present study.

Author Contributions

Kai Ishida: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing – original draft, funding acquisition, and project administration. Takahide Etani: Conceptualization, methodology, formal analysis, writing – review and editing. Hiroshi Nittono: Conceptualization, methodology, formal analysis, resources, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The sound materials used and datasets analyzed for the present paper are available at <https://osf.io/kc8x2/files>.

Peer Review

For transparency, the peer review documents associated with this article are available at <https://doi.org/10.1111/nyas.70292>.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Materials: [nyas70292-sup-0001-SuppMat.docx](#)