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PERCEIVED MOTOR SYNCHRONY WITH THE BEAT IS MORE STRONGLY RELATED TO GROOVE THAN MEASURED SYNCHRONY

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THE SENSATION OF GROOVE CAN BE DEFINED AS the pleasurable urge to move to rhythmic music. When moving to the beat of a rhythm, both how well movements are synchronized to the beat, and the perceived difficulty in doing so, are associated with groove. Interestingly, when tapping to a rhythm, participants tend to overestimate their synchrony, suggesting a potential discrepancy between perceived and measured synchrony, which may impact their relative relation with groove. However, these relations, and the influence of syncopation and musicianship on these relations, have yet to be tested. Therefore, we asked participants to listen to 50 drum patterns with varying rhythmic complexity and rate their sensation of groove. They then tapped to the beat of the same drum patterns and rated how well they thought their taps synchronized with the beat. Perceived synchrony showed a stronger relation with groove ratings than measured synchrony and syncopation, and this effect was strongest for medium complexity rhythms. We interpret these results in the context of meter-based temporal predictions. We propose that the certainty of these predictions determine the weight and number of movements that are perceived as synchronous and thus reflect rewarding prediction confirmations.

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Key words: beat perception, emotion, rhythm and timing, synchronization, expectation

THE SENSATION OF GROOVE CAN BE DEFINED as the pleasurable urge to move to music (Janata et al., 2012; Witek et al., 2014). It is the impulse to bob our heads, tap our feet, or get up and dance. This pleasurable urge is largely driven by the rhythmic component of music. Specifically, groove has been found to have an inverted U-shaped relation with syncopation: rhythms with a medium degree of complexity—operationalized here as syncopation—create a stronger sensation of groove than rhythms that are either very simple or very complex (Matthews et al., 2019; Sioros et al., 2014; Witek et al., 2014). Conversely, moving in synchrony with the beat of a rhythm becomes more difficult as the rhythms get more complex (Fitch & Rosenfeld, 2007). This suggests that the rhythms that make us want to move are not necessarily those that we are best able to synchronize with. A seminal study on groove (Janata et al., 2012), showed that groove was strongly related to how well participants synchronized with the beat and how difficult they found it to do so. Therefore, both moving in synchrony with music and perceiving that you are doing so successfully may contribute to feeling "in the groove." However, when tapping to a rhythm, participants tend to overestimate their synchrony (Franěk et al., 1987), suggesting a discrepancy between perceived and measured synchrony, which may impact their relative relation with groove. Further, the influence of syncopation and musicianship on these relations has yet to be tested. Therefore, the current study investigates the relative association between perceived synchrony, measured synchrony, and groove, along with the influence of syncopation and musicianship on these associations.

Temporal predictions are thought to play a crucial role in beat and rhythm perception, as well as in the positive affect associated with listening and interacting with rhythmic music (Koelsch et al., 2019; Vuust & Witek, 2014; Vuust et al., 2018). Both beat (the underlying regular pulse of a rhythm) and meter (the pattern of strong and weak beats), can be thought of as internal models of the temporal structure of auditory inputs. These models engender predictions regarding the timing of future onsets that are more or less certain depending on the position of the beat point within

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a metric hierarchy (Fitch & Rosenfeld, 2007; Longuet-Higgins & Lee, 1984; Vuust et al., 2018). It should be noted that metric hierarchies may differ across cultures (Hannon et al., 2012). Here we follow a hierarchy based on Western music (Longuet-Higgins & Lee, 1984) in which, for example, predictions will be more certain for notes falling on the first (stronger) beat of a phrase compared to the second (weaker) beat. Other factors also contribute to prediction certainty, including whether there was a note or silence on the previous beat (syncopation), the overall rhythmic context (i.e., its complexity), and the listener's experience with the particular musical structure.

Framing beat and meter as psychological constructs, rather than strictly bottom up perception, is supported by the fact that they are reliably perceived even when there is little or no acoustic energy on the beat (Chapin et al., 2010; Large et al., 2015). This occurs, for example, when a rhythm contains syncopations, which is when no note falls on a strong beat but instead falls on a preceding, metrically weaker beat (Longuet-Higgins & Lee, 1984). Syncopations can also modify the strength of perceived beat and meter. By de-emphasizing beat points for which one has relatively strong expectations and emphasizing beat points for which one has relatively weak expectations, syncopations can be thought of as providing counterevidence to the internal model of the meter. In this way, syncopations make the rhythm more complex, and increase the uncertainty of the resultant temporal predictions (Vuust et al., 2018). With enough syncopations, models of the beat and meter, and thus temporal predictions, cannot be generated, leading to decreased synchronization, reproduction, and recognition performance (Fitch & Rosenfeld, 2007). Recent computational modeling work supports the link between increased syncopation and the decreased certainty of temporal predictions, providing a plausible mechanism for the failure to track highly syncopated rhythms (Cannon, 2021).

Moving to the beat of music, here referred to as beat synchronization, can be thought of as externalizing beat-based predictions and can thus be seen as a way of testing beat-based predictions (Patel & Iversen, 2014). In this way, beat synchronization provides indirect but objective measures of beat and meter-based predictions (Patel et al., 2005). Under this framework, movements perceived as asynchronous generate prediction errors, indicating that the model needs to be updated, while movements judged as synchronous generate prediction confirmations, indicating that the current model is valid. Prediction confirmations may act as a reward signal and may therefore be one of the motivating factors underlying the urge to move, thus linking synchrony to the sensation of groove. One possible reason that prediction confirmations are rewarding is that they reduce uncertainty (Mencke et al., 2019; Zald & Zatorre, 2011) and thus contribute to learning, which is thought to be inherently rewarding (Oudeyer et al., 2016). However, for learning to occur, there must be some uncertainty to reduce in the first place. Therefore, stimuli or tasks that are complex enough to generate uncertainty, but not so complex as to be impossible to learn, will lead to the greatest reward. This suggests that perceived synchrony should be more rewarding, and therefore show a stronger relation with groove, when rhythms are moderately syncopated.

One wrinkle when studying perceived synchrony is that participants tend to overestimate their tapping accuracy. When tapping to an auditory pacing signal, participants consistently tap early relative to each onset, a phenomenon known as the negative mean asynchrony (NMA; Aschersleben, 2002). However, participants tend to be unaware of this asynchrony. For example, in a study where participants were asked to report whether they tapped on time, early, or late, they reported that they tapped on time, even though they tapped 39 ms early on average (Franěk et al., 1987). Small asynchronies during synchronization tasks, in the range of tens of milliseconds, are an inevitable consequence of temporal variability in both perceptual and motor processes (Repp, 2005). Evidence suggests that both the perception and correction of these small asynchronies relies on automatic motor processes (Hove et al., & Valera, 2017; Repp & Keller, 2004) and therefore may be less accessible to conscious awareness. Likewise, these small asynchronies do not reflect an invalid model and therefore may not register as the sort of prediction errors that affect learning and thus reward. Indeed, in the context of perception, larger timing deviations, such as syncopations, have been consistently linked with groove (Matthews et al., 2019; Matthews et al., 2020; Sioro et al., 2014; Witek et al., 2014), whereas the link between groove and smaller, and often subconscious, microtiming deviations has been less consistent (Butterfield, 2010; Davies et al., 2013; Frühauf et al., 2013; Kilchenmann & Senn, 2015; Madison & Sioros, 2014). Together, these results suggest a discrepancy between perceived and measured synchrony, with small deviations in tap performance—due to either inherent timing variability or the NMA—having potentially less influence on perceived synchrony and subjective ratings of groove.

Although a full explanation of the NMA remains elusive, hypotheses regarding its underlying mechanisms may be relevant to the associations between perceived synchrony, measured synchrony, and groove. One hypothesis suggests a tolerance zone within which taps are considered synchronous, and which is shifted early relative to the pacing signal, thus accounting for the NMA as well as the higher asynchrony detection thresholds for early compared to late taps (Müller et al., 1999). One possibility is that this tolerance zone reflects temporal prediction uncertainty, and thus may widen or contract depending on the strength of the metrical model determined by the rhythmic context and/or individual differences, including music training (Repp, 2005).

Several authors have suggested that rhythm-based temporal predictions and the degree of uncertainty can be modeled in terms of probability distributions (or probability density functions; Cannon, 2021; Danielsen et al., 2019; Gordon, 1987; Koelsch et al., 2019; Large & Jones, 1999). According to this idea, the predicted location of a future onset is the mean of a probability distribution while the width of this distribution; that is, its extension in time reflects the certainty of the prediction, with a wider distribution reflecting lower certainty. This has been applied in the context of microtiming, where multiple jittered onsets around a metronomic beat lead to perception of the beat as an extended "beat bin" (Danielsen, 2010, 2018). Introducing small temporal mismatches between instruments, or between tones within chords, affects tapping precision, an effect which may depend on musical experience (Danielsen et al., 2015; Hove et al., 2007). Therefore, uncertainty regarding the precise location of the beat may extend the window within which onsets are considered on the beat.

Although the beat-bin hypothesis has yet to be applied to larger temporal deviations such as syncopations, we hypothesize they will have a similar beat-bin expanding effect. That is, since syncopations entail a gap where a note is strongly expected, uncertainty regarding the location of the beat may accumulate through this gap (Cannon, 2021), thus reducing the certainty of the following predictions. In addition, this gap forces listeners to rely solely on their (potentially imprecise) metrical model to estimate the location of the beat. As with microtiming deviations, this uncertainty may expand what is perceived as on-beat. In accordance with the tolerance zone, this expansion may allow more taps to be perceived as synchronous, which may lead to more taps being registered as prediction confirmations, and thus rewarded. The effect of syncopations may also accumulate over the course of a stimuli as prediction uncertainty increases with the number of syncopations. Together, these beat-to-beat and cumulative, uncertainty-inducing effects of syncopations may provide another avenue through which the relation between perceived synchrony and groove may outweigh that between measured synchrony (relative to the metronomic beat) and groove.

As mentioned, musicianship is likely to impact the relative association between rhythmic context, perceived synchrony, measured synchrony, and groove. Indirect evidence for this comes from studies using an asynchrony detection task, in which the delay between participants' taps and the consequent sounds are manipulated, and participants judge whether or not their tap and the sound were synchronous. Detection thresholds are surprisingly large, particularly when taps precede the sound (Müller et al., 1999), but are smaller in musicians (van Vugt & Tillmann, 2014). Therefore, musicians' perceived synchrony is likely to better match their measured synchrony. Further, musicians are better at synchronizing their taps to rhythms (Matthews et al., 2016; Repp, 2010; Repp & Doggett, 2007) and have smaller negative mean asynchronies (Repp, 2010). Therefore, musicians will have less asynchrony to detect in the first place. This may shift the reward musicians receive from perceived synchrony (i.e., prediction confirmations) to more syncopated rhythms relative to nonmusicians, as only these will be complex enough to challenge their model of the meter. In a recent study, we showed that musicians have a stronger urge to move to moderately syncopated rhythms compared to nonmusicians (Matthews et al., 2019), providing initial evidence that musicianship affects the shape of the inverted U, at least in a passive perceptual context. Together, these results suggest that musicianship will influence the relation between syncopation, measured and perceived synchrony, and groove.

To investigate the relation between perceived synchrony, measured synchrony, and the sensation of groove, we asked musicians and nonmusicians to listen and then tap in synchrony to a set of synthesized drum sequences that varied in the number and strength of syncopations. First, they passively listened to the sequence and rated the degree of perceived groove. They then tapped to the beat of each sequence and rated how well they thought their taps were synchronized to the beat. The relation between groove ratings, tap ratings, circular measures of tapping performance (accuracy and precision), and number of syncopations were compared to test whether: 1) the perception of synchrony (tap ratings) shows a stronger relation with groove compared to measured tapping performance and the number of syncopations, 2) the relation between perceived synchrony and groove ratings is greatest for moderately syncopated rhythms, and, 3) whether these patterns

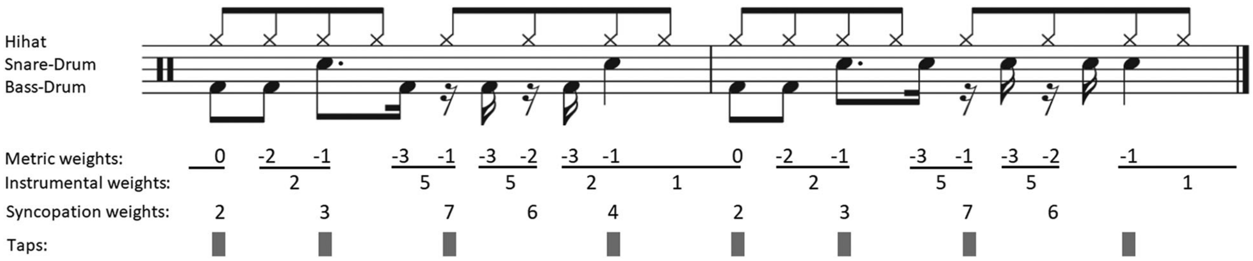

FIGURE 1. Transcription of the drum pattern from 'Telephone Girl' by Assagai (1971; Stimulus number 30; Syncopation index = 40). The metric weights and the instrumental weights were combined to calculate the per-beat syncopation weights according to the formula $S = N - Ndi + I$, where N is the metric weight of the preceding note, Ndi is the metric weight of the rest or note from a different instrument, and I is the instrumental weight of the syncopation. The per-beat syncopation weights are then summed to generate the per-stimulus syncopation index. Grey rectangles show the metric level (quarter note beat) at which participants were expected to tap. Note that in the post hoc analysis, when calculating the per-beat syncopation weights, those at the eighth note (between beat) level were averaged with the syncopation weights on the following quarter note.

differ for musicians and nonmusicians. Based on previous results (Matthews et al., 2019, 2020), musicians were expected to show a stronger inverted U-shaped relation between syncopation and groove. Additional analyses tested the relative effects of tapping precision and accuracy on perceived synchrony.

Method

PARTICIPANTS

Nineteen musicians (nine female) and twenty-four nonmusicians were recruited to participate in this study. Musicians had an average age of 25.16 ($SD = 3.86$), had an average of 13.58 years of formal music training ($SD = 3.59$), and practiced on average 12.63 hours a week ($SD = 9.67$) at the time of testing. Data of seven nonmusicians were excluded from analysis due to not having enough analyzable trials (see preprocessing section below). The final sample consisted of 17 nonmusicians (11 female) with an average of one year of formal music training ($SD = 1.03$) and an average age of 24.13 ($SD = 6.04$).

The protocol was approved by the Concordia University Human Research Ethics committee. Participants provided written informed consent in accordance with the Declaration of Helsinki and were compensated for their time.

STIMULI

The stimuli were created for a previous study (Witek et al., 2014) and consisted of 50 drum sequences generated using synthesized drum sounds (bass drum, snare drum, and hihat) in GarageBand 5.1 (Apple, Inc.). Thirty-four of these were derived from actual songs, 14 were experimenter generated, and two were templates from GarageBand. Each sequence consisted of a single two-bar pattern repeated four times in 4/4 time, had an interbeat interval of 500 ms, and lasted 16 seconds. In all sequences, the hihat maintained an isochronous pattern at twice the beat rate (interonset interval 250 ms). Therefore, the unique sequences were generated by the snare and bass drum patterns.

Rhythmic complexity was quantified using a modified version of the syncopation index (Fitch & Rosenfeld, 2007; Longuet-Higgins & Lee, 1984; Witek et al., 2014) in which the degree of syncopation depends on both the metric position and the instrument (snare or bass drum; see Witek et al., 2014, for a detailed description). According to this work, a syncopation occurs when a note on a given instrument precedes a rest, or a note from another instrument with a lesser metric weight. Therefore, each syncopation in a sequence is weighted based on its metric position and whether it involves a snare, bass drum, or both (see Figure 1). This includes syncopations that occur at the eighth note level, between the quarter note beats that participants tapped along to. These weights are then summed within a sequence providing a syncopation index ranging from 1 (low syncopation) to 81 (high syncopation). Table A1 shows the per-beat syncopation weights and sum for all stimuli.

PROCEDURE

Upon arrival participants filled out a musical experience questionnaire. Before starting the experiment, participants were given the definition of groove as the pleasurable desire to move to music. Participants then listened to all fifty drum sequences through headphones (Sony MDR 7506) in a randomized order and rated each sequence on the degree it elicited the sensation of groove on a scale from one to five. Participants then listened to the same drum sequences, in a different randomized order, and were asked to tap in synchrony with the beat. Participants were given a four-beat count-in at the start of each sequence. At the end of each sequence participants rated how well they felt they were able to synchronize their taps to the beat of the sequence on a scale from one to five.

MEASUREMENT APPARATUS

Taps were measured using a force-sensitive resistor[1] (FSR) covered by a thin layer of foam, to dampen the tapping sound. The outgoing audio stimulus was recaptured alongside the incoming force measurement using an audio interface[2] controlled by the experiment software at a sampling rate of 44.1 kHz. At this sampling rate, and with the response time of the FSR rated at less than three microseconds, we concluded that any errors in the time-alignment between the recorded stimuli and tap measurements were negligible. In the recorded force measurements, we defined a tap as the maximum force produced by the impact of the participant's finger on the sensor. Beats were extracted from the stimulus audio signal using a similar process, using the amplitude envelope of the stimulus signal to determine drum onsets. Differences between the perceived location of an onset (P-center) and its objective onset can affect synchronization (Danielsen et al., 2019). However, here, the sequences were made up of short percussive sounds, with short rise times, therefore both perceptual and objective onsets are likely to match.

PREPROCESSING OF TAPPING DATA

Data from entire trials were removed if participants tapped twice per beat, tapped too fast (more than 25% of ITIs were less than 0.3 s), or did not have enough taps in the trial for analysis (less than eight of an expected 32 taps). Data from participants with more than five excluded trials (10%) based on the above criteria were removed from analysis. This led to removal of data of seven nonmusicians. In addition, 19 trials (1.06% of all trials) were removed across seven nonmusician participants for the same reasons.

Indices of tapping precision and accuracy were calculated using circular statistics (Fisher et al., 1993) by calculating a vector on the unit circle for each tapping trial. The mean resultant length of this vector (MRL) is determined by the spread of taps around the unit circle and thus corresponds to a measure of tapping precision. MRL varies from zero to one with values closer to one indicating low spread and thus high tapping precision. The angle of the vector is calculated relative to the beat point with which participants are synchronizing and is therefore a measure of tapping accuracy. The angle is measured in radians and thus ranges from zero to 2π. Subsequent analysis on the effect of tapping performance on tap ratings and groove ratings used the absolute value of the angle subtracted from π. This measure varies from zero to π with values closer to π indicating more accurate taps.

STATISTICAL ANALYSIS

All analyses were carried out using linear mixed effects regression in R (version 4.0.3; R core team, 2020). This approach was used as it allows for analysis of trial-level data while accounting for within-subject grouping of this data. Therefore, this approach accounts for inter-individual differences in rating style and responses to the predictor variables. All analyses followed the same three steps: 1) determination of the random structure, 2) type II sum of squares *F* tests with Kenward-Roger estimation of degrees of freedom to determine the significant main effects and interactions, 3) estimating the final models using restricted maximum likelihood and including only the significant predictors from the *F* tests to test parameter estimates against zero. For all analyses, Steps 1 and 2 were carried out using the lme4 package (Bates et al., 2014) and the car package (Fox & Weisberg, 2019). The optimal random effects structure that can be supported by the data were determined by iteratively reducing the maximal random structure (Bates et al., 2015; Matuschek et al., 2017). Several final models showed non-normal and heteroscedastic residuals and were therefore re-estimated using robust linear mixed effects regression using the robustlmm package (Koller, 2016). These models are identical to the standard linear mixed effects models. However, they automatically detect, and down-weight data points contaminated by the near-ceiling effects. The degree to which these data points are down-weighted can be tuned to prioritize robustness or efficiency of the parameter estimates. Results of models tuned for higher robustness are reported here.

For models estimated using the robust approach, Wald confidence intervals were calculated for each parameter estimate. R^2 and $\eta_p{}^2$ could not be calculated for the robust models. For final models estimated using the standard approach, bootstrapped confidence intervals around parameter estimates were calculated with 5000 iterations. For these models, R^2 values for the

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[1] Model 406 Square. *Interlink Electronics FSR Integration Guide.* Accessed 2021-02-15: https://cdn.sparkfun.com/assets/4/d/0/f/7/DS-9375-Force_Sensitive_Resistor_0.5in.pdf

[2] Lexicon Omega. Accessed 2021-02-15: https://lexiconpro.com/en/products/omega

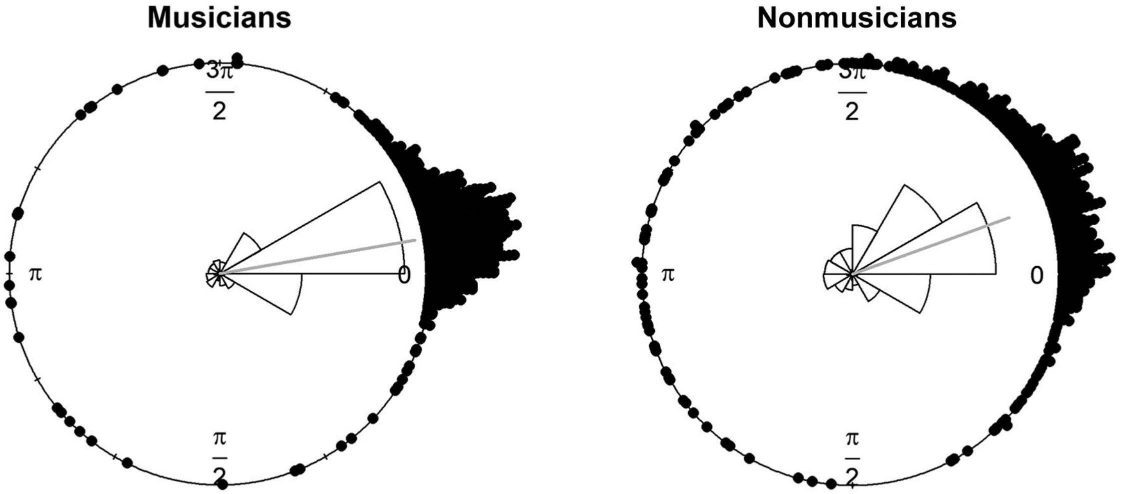

FIGURE 2. Circular plots of tapping data. A circular plot for each group showing all taps from all trials plotted on the circumference of the unit circle. The rose diagram in the center shows the relative number of taps falling in each of 12 bins. The beat is represented by zero and taps counterclockwise to zero were early and taps clockwise to zero were late, relative to the beat. Gray lines represent the mean vector. The angle of this vector represents mean group accuracy, and the length of this vector represents mean group precision.

models and partial eta-squared (η_p^2) values and associated confidence intervals were calculated using the r2glmm package (Jaeger, 2017), using the standardized generalized variance approach.

Previous work indicates that syncopation shows an inverted U-shaped relation with ratings of groove (Matthews et al., 2019; Witek et al., 2014) therefore, orthogonal polynomial (both linear and quadradic) effects of syncopation were tested in all models. Only linear effects were tested for all other variables.

EFFECTS OF SYNCOPATION AND GROUP ON TAPPING PERFORMANCE

To test the effect of syncopation, group, and their interaction on tapping performance, we conducted two sets of analyses, one for tapping precision (MRL) and one for tapping accuracy (π - absolute angle). Diagnostic plots of the final regression models showed non-normal and heteroskedastic residuals, likely because musicians exhibited a ceiling in performance, with mean absolute angles close to π and MRLs close to one (see Figure 3). Therefore, results of the models fitted with the robust approach and tuned for higher robustness are reported here.

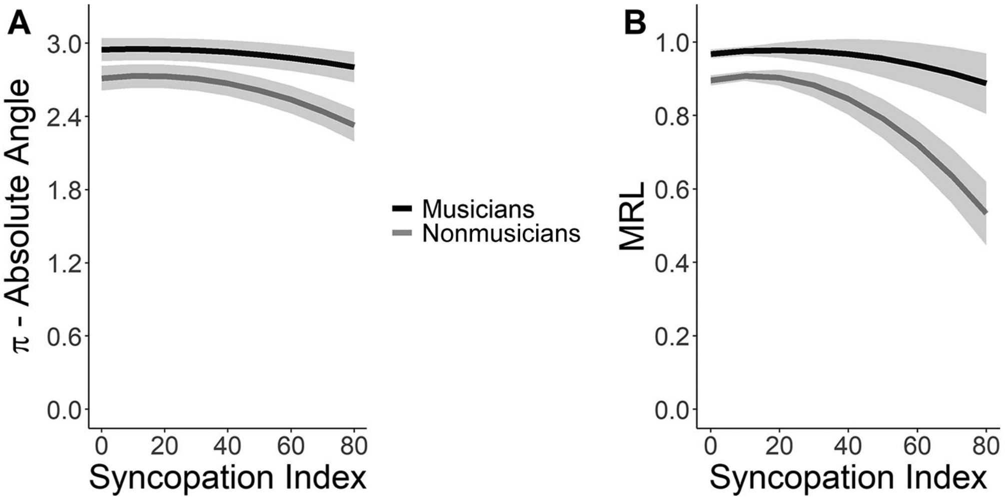

FIGURE 3. Relation between syncopation, A) tapping accuracy, and B) tapping precision. The lines represent the estimated effects of the second polynomial function from the robust regression model. Ribbons represent 95% confidence intervals. Note that in A) the absolute angle is subtracted from π so that larger values indicate higher accuracy.

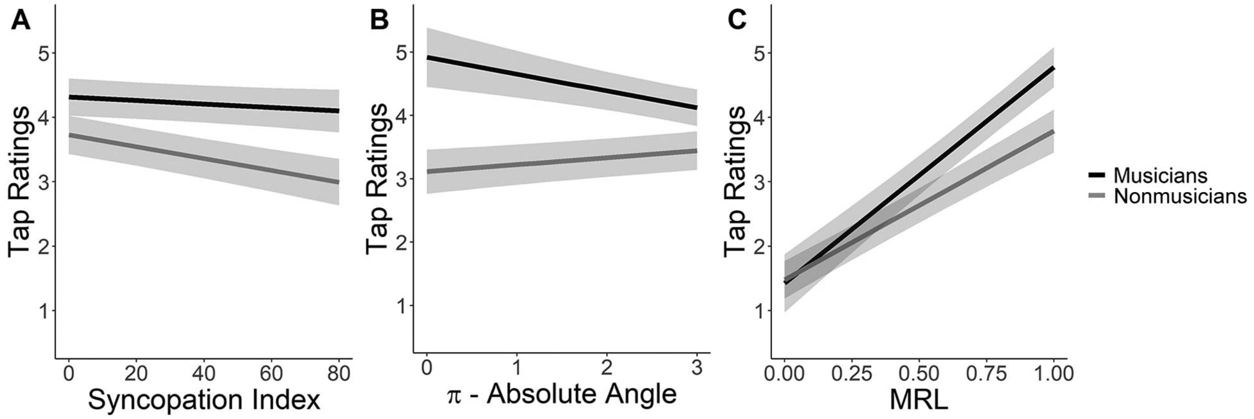

FIGURE 4. Relation between tap ratings, A) syncopation index, B) tapping accuracy, and C) tapping precision, for musicians and nonmusicians. The lines represent estimated effects of the linear function from the robust regression model. Ribbons represent 95% confidence intervals.

EFFECTS OF TAPPING PERFORMANCE, SYNCOPATION, AND GROUP ON TAP RATINGS

F tests were used to test the effect of tapping performance, syncopation, and group, as well as their interactions, on perceived synchrony. Diagnostic plots of the final model showed non-normal and heteroskedastic residuals due to the fact that musicians frequently rated their tapping performance maximally (i.e., with a rating of five; see Figure 4A). Data with many points at the upper (or lower) limit of a scale are referred to as censored. Therefore, in addition to estimating a robust model, this data was analyzed using the lme4cens package which accounts for this censoring (Kuhn & Roeder, 2018). This approach does not allow for random slopes, therefore, only by-participant random intercepts were included in this model. Results of the final model tuned for higher robustness are reported here. Results of the lme4cens model are reported in the Appendix. Finally, because musicians' tap ratings and tap performance were near ceiling, confirmatory analyses were implemented on the nonmusicians' data only, the results of which are reported in the Appendix.

EFFECTS OF TAP RATINGS, TAPPING PERFORMANCE, SYNCOPATION AND GROUP ON GROOVE RATINGS

Groove ratings underwent two sets of analyses. The first analysis tested the effects of tap ratings, tapping performance, syncopation, and group, as well as the relevant interactions. In the final model, standardized (*z*-scored) versions of the significant variables from the *F* tests were used to compare between the effects of tap ratings and tapping performance on groove ratings. Recent work has shown that music training affects the inverted U-shaped relation between syncopation and groove ratings (Matthews et al., 2019). Therefore, a second analysis tested the interaction between syncopation index and group, excluding tap ratings and tapping performance measures as predictors (i.e., ignoring the second part of each trial where participants tapped to the rhythmic pattern and rated their tapping).

Diagnostic plots of the final models showed no violations of assumptions, therefore only the results from standard linear mixed effect models are reported. However, because musicians' tap ratings and tapping performance were near ceiling and may therefore have affected the relationship to groove ratings, confirmatory analyses were implemented on the nonmusicians' data only, the results of which are reported in the Appendix.

Results

EFFECTS OF SYNCOPATION AND GROUP ON TAPPING PERFORMANCE

The circular tapping measures illustrated in Figure 2 show all taps from all trials on each unit circle. This figure shows that overall, musicians tapped more precisely (longer mean vector) and more accurately (smaller angle) compared to nonmusicians. For both groups, taps were clustered just before the beat, replicating the negative mean asynchrony (Aschersleben, 2002).

F tests were used to test the effects of group and syncopation—and the interaction between the two—on tapping accuracy (π - absolute angle) and precision (MRL). The analysis on tapping accuracy showed significant main effects of group, $F(1, 34.00) = 13.89$, $p < .001$, and syncopation (linear and quadratic together; $F[2, 88.17] = 35.00$, $p < .001$), and a significant interaction between the two, $F(2, 88.28) = 3.84$, $p = .025$. The final model tuned for higher robustness confirmed that

TABLE 1. *Results of F Tests on Model Predicting Tap Ratings*

Effect	df	*F*	*p*
Syncopation Index (Linear and Quadratic)	2, 88.90	26.73	< .001
Group	1, 35.50	3.88	.057
Absolute Angle	1, 24.08	0.29	.597
MRL	1, 41.86	169.33	< .001
Syncopation Index: Group	2, 114.86	6.32	.002
Syncopation Index: Absolute Angle	2, 1032.12	0.71	.492
Syncopation Index: MRL	2, 910.36	7.04	< .001
Group: Absolute Angle	1, 43.04	9.43	.004
Group: MRL	1, 59.84	6.92	.011
Syncopation Index: Group: Absolute Angle	2, 999.24	0.25	.782
Syncopation Index: Group: MRL	2, 1408.05	1.90	.150

nonmusicians tapped with lower accuracy overall ($b = 0.272$, 95% C[0.133, 0.410]), and that both groups showed a significant negative quadratic effect of syncopation (musicians: $b = -0.607$, 95% CI[−1.10, −0.114]; nonmusicians: $b = -1.780$, 95% CI[−2.309, −1.250]). This effect can be seen in Figure 3A, where tapping accuracy was similar for low and medium complexity in both groups, with a drop-off in accuracy for high complexity rhythms. A steeper drop-off for nonmusicians resulted in a significant interaction between groove and the quadratic effect of syncopation ($b = 1.173$, 95% CI[0.450, 1.897]).

The analyses on tapping precision showed similar results. *F* tests showed statistically significant main effects of group, $F(2, 44.62) = 52.61$, $p < .001$, and syncopation index (linear and quadratic; $F[2, 44.62] = 52.61$, $p < .001$), and a significant interaction between the two, $F(2, 44.68) = 5.50$, $p = .007$. The final model, tuned for high robustness, confirmed that musicians tapped more precisely overall ($b = 0.133$, 95% CI[0.081, 0.185]) and that both groups showed a significant negative quadratic effect of syncopation (musicians: $b = -0.477$, 95% CI[−0.657, −0.296]; nonmusicians: $b = -1.551$, 95% CI[−1.745, −1.357). As with tapping accuracy, the significant interaction was driven by a steeper drop-off in tapping precision as syncopation increased ($b = -1.075$, 95% CI[−1.340, −0.809]; see Figure 3B).

EFFECTS OF TAPPING PERFORMANCE, SYNCOPATION, AND GROUP ON TAP RATINGS

F tests were used to test the effects of tapping performance, syncopation, and group, as well as the interactions between these variables, on tap ratings. These results are displayed in Table 1. This analysis showed significant main effects of syncopation and tapping precision as well as significant interactions between syncopation index and group, tapping precision, and tapping accuracy, and between group and tapping precision, and tapping accuracy. A final model tuned for maximal robustness did not show any quadratic effects of syncopation index, therefore, this model was refitted with the linear effect only. This model showed that nonmusicians showed a stronger negative effect of syncopation ($b = 0.006$, 95% CI[0.002, 0.011]; See Figure 4A).Unexpectedly, a significant group by tapping accuracy interaction indicated that musicians showed a negative effect of tapping accuracy on tap ratings while nonmusicians showed a small positive effect ($b = -0.376$, 95% CI[−0.544, −0.208]; See Figure 4B). This result appears to be driven by the fact that musicians showed relatively low variability in their tapping accuracy and tap ratings, with high ratings even when tapping accuracy was relatively low. Finally, musicians showed a stronger positive effect of tapping precision ($b = 0.932$, 95% CI[0.258, 1.606]; see Figure 4C).

EFFECTS OF TAP RATINGS, TAPPING PERFORMANCE, SYNCOPATION AND GROUP ON GROOVE RATINGS

In a first analysis, *F* tests were used to test the effects of tap ratings, tapping performance, syncopation, and group, as well the relevant interactions on groove ratings. The results of this analysis are shown in Table 2. These results show significant main effects of syncopation index (linear and quadratic), tap ratings, and tapping precision as well as an interaction between syncopation index and tap ratings.

Results of the final model estimated using standard linear mixed effects with standardized predictor and outcome variables are shown in Table 3. Although tapping accuracy was not significant in the *F* tests, it was included in the final model for comparison with tap ratings and tapping precision. The model accounted for 28.2% (95% CI[0.251, 0.317]) of the variability in

TABLE 2. *Results of F-Tests on Model Predicting Groove Ratings*

Effect	df	*F*	*p*
Syncopation Index (Linear and Quadratic)	2, 102.92	65.28	< .001
Group	1, 38.20	1.28	.264
Absolute Angle	1, 1738.80	0.01	.923
MRL	1, 1298.33	17.19	< .001
Tap Ratings	1, 1601.42	102.02	< .001
Syncopation Index: Group	2, 149.16	0.73	.486
Group: Absolute Angle	1, 1758.28	0.04	.839
Group: MRL	1, 1644.28	0.01	.934
Group: Tap Ratings	1, 1600.12	1.80	.180
Syncopation Index: Tap Ratings	2, 1386.01	4.08	.017
Syncopation Index: Group: Tap Ratings	2, 1172.90	0.78	.46

TABLE 3. *Standardized Parameter Estimates from Regression Model Predicting Groove Ratings*

Effect	β	95% CI	η_p^2	95% CI
Syncopation Index (Linear)	−5.320	−8.01, −2.78	0.017	0.007, 0.031
Syncopation Index (Quadratic)	−9.780	−11.40, −8.10	0.058	0.039, 0.081
Tap Ratings	0.319	0.262, 0.386	0.082	0.060, 0.107
Absolute Angle	0.002	−0.053, 0.068	0.000	0.000, 0.003
MRL	0.161	0.079, 0.235	0.014	0.005, 0.026
Tap Ratings: Syncopation Index (Linear)	−0.284	−1.540, 2.290	0.000	0.000, 0.003
Tap Ratings: Syncopation Index (Quadratic)	−2.860	−4.380, −1.280	0.006	0.001, 0.016

Note: Due to the scaling effect of the orthogonal polynomial on syncopation index, the parameter estimates for this variable and its interaction with group cannot be compared to the parameter estimates for the other effects.

groove ratings. Comparing standardized regression coefficients (β) in Table 3 indicates that tap ratings showed a stronger relation with groove ratings compared to both measures of tapping performance. Due to the scaling involved in making the linear and quadratic polynomials of syncopation orthogonal to each other, the standardized regression coefficients for these variables cannot be compared to those of the other variables. However, comparing the partial eta squared values (η_p^2) shows that tap ratings were the strongest contributor to the model, followed by the quadratic effect of syncopation. Table 3 also shows a significant interaction between the quadratic effect syncopation index and tap ratings. As can be seen in Figure 5, the effect of tap ratings on groove ratings showed an inverted U-shaped curve, with the largest slope for moderately syncopated rhythms, and smaller slopes for high and low syncopation rhythms.

A second analysis tested whether there was an inverted U-shaped relation between syncopation and groove ratings, and whether this was stronger for musicians, as has been shown in a previous study (Matthews et al., 2019). *F* tests on a model with only syncopation

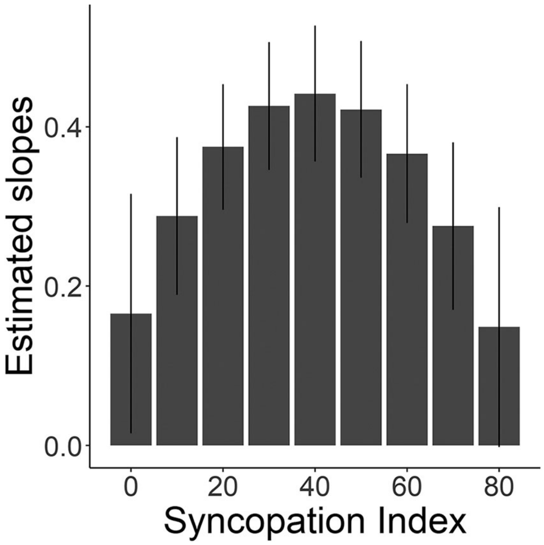

FIGURE 5. The relation between tap ratings and groove ratings as a function of syncopation index. Bars represent the estimated slopes (regression coefficients) describing the relation between tap ratings at different levels of syncopation index. Error bars represent 95% confidence intervals.

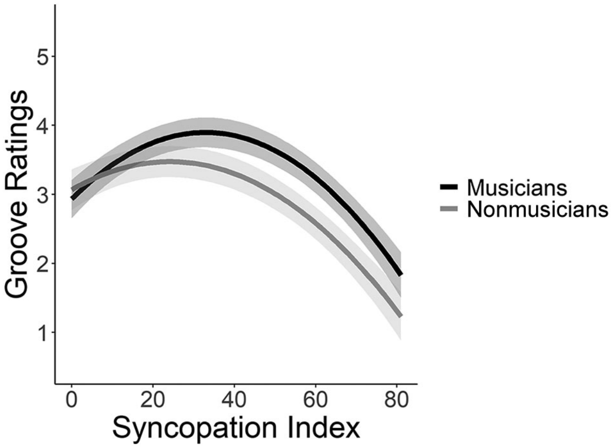

FIGURE 6. Relation between syncopation index and groove ratings in musicians and nonmusicians. The lines represent estimated effects of the second polynomial function from the final model. Ribbons represent 95% confidence intervals. Note that although both groups showed a quadratic relation between syncopation and groove, only the linear effect showed the group by syncopation index interaction.

index and group, and the interaction between the two, showed that all these effects were significant: group, $F(1, 34.00) = 7.05, p = .012$; Syncopation index, $F(2, 138.38) = 165.30, p < .001$; Syncopation index: Group, $F(2, 138.38) = 9.94, p < .001$. The final model indicated a significant negative quadratic effect of syncopation in both musicians ($b = -16.90$, 95% CI[-19.80, -13.90]) and nonmusicians ($b = -13.20$, 95% CI[-16.30, -10.10]), with musicians showing a stronger quadratic effect compared to nonmusicians, but this difference did not reach significance ($b = 3.73$, 95% CI[-0.596, 7.83]; see Figure 6). However, the nonmusicians did show a significantly stronger negative linear effect ($b = -9.06$, 95% CI[-13.70, -4.64]), indicating that higher levels of syncopation produced a more rapid drop-off in groove ratings.

EFFECTS OF SYNCOPATION WEIGHT ON BETWEEN-PARTICIPANT, PER-BEAT TAPPING PERFORMANCE

One possible interpretation of the inverted U-shaped interaction between tap ratings and syncopation index on groove ratings is that syncopations introduce uncertainty into temporal predictions, thus widening the tolerance zone within which taps are considered synchronous. One way to indirectly measure this is by testing whether syncopations affect tapping performance on a per-beat level, with stronger syncopations leading to greater reductions in tapping accuracy and precision. This is based on the hypothesis that a syncopation results in a prediction error that introduces uncertainty into the beat-based predictions, which is embodied as greater variability in the following tap. This is similar to work showing that small perturbations in a rhythm lead to automatic corrections in synchronized tapping (for a review see Repp & Su, 2013). However, syncopations are much larger temporal deviations than those used in perturbation studies. Therefore, our hypothesis assumes that syncopations affect tapping via top-down effects of prediction uncertainty, rather than automatic error correction.

To investigate this hypothesis, four post hoc analyses were implemented to test the relation between the syncopation strength of a given beat and the tapping performance on both the syncopated (lag 0) and subsequent (lag 1) beat. Absolute angle and MRL were calculated across participants for each beat, within each stimulus (because each participant only tapped once to each stimulus there was insufficient data for a within-subject measure). Therefore, 17 and 19 taps per beat were used to calculate tapping performance for nonmusicians and musicians, respectively. Syncopation weights were calculated for each beat by first summing the metric and instrumental weights and then averaging the quarter note syncopation weight with the preceding eighth note (i.e., the between beat) weight. Given that there were far fewer eighth note syncopations compared to quarter note syncopations (see Table A1), averaging their corresponding weights provides a compromise between implementing a separate analysis for the eighth note syncopations and ignoring them altogether. The resulting syncopation weights thus represent the strength of syncopation for the whole quarter note metric level, ranging from zero to seven. Analysis was performed on taps falling on the syncopated beat (lag 0) and the following beat (lag 1) separately. However, we focused on the lag 1 taps based on the assumption that it takes time for a syncopation to register as a prediction error and affect prediction certainty, therefore only those results are reported here (lag 0 results are reported in the Appendix). These stimuli were not controlled for in terms of the number and weight of different types of syncopations (e.g., eighth note syncopation with no following quarter note syncopation or quarter note syncopation with no preceding eight note syncopation, etc.). Therefore, we were not able to test assumptions regarding the effects of on-beat (quarter note) versus between-beat (eighth note syncopations) on lag 0 vs lag 1 taps.

Both tapping performance measures were skewed, therefore, robust linear mixed effects regression models were used and only results from models tuned for robustness are reported. By-stimulus random slopes and intercepts were included to account for differences

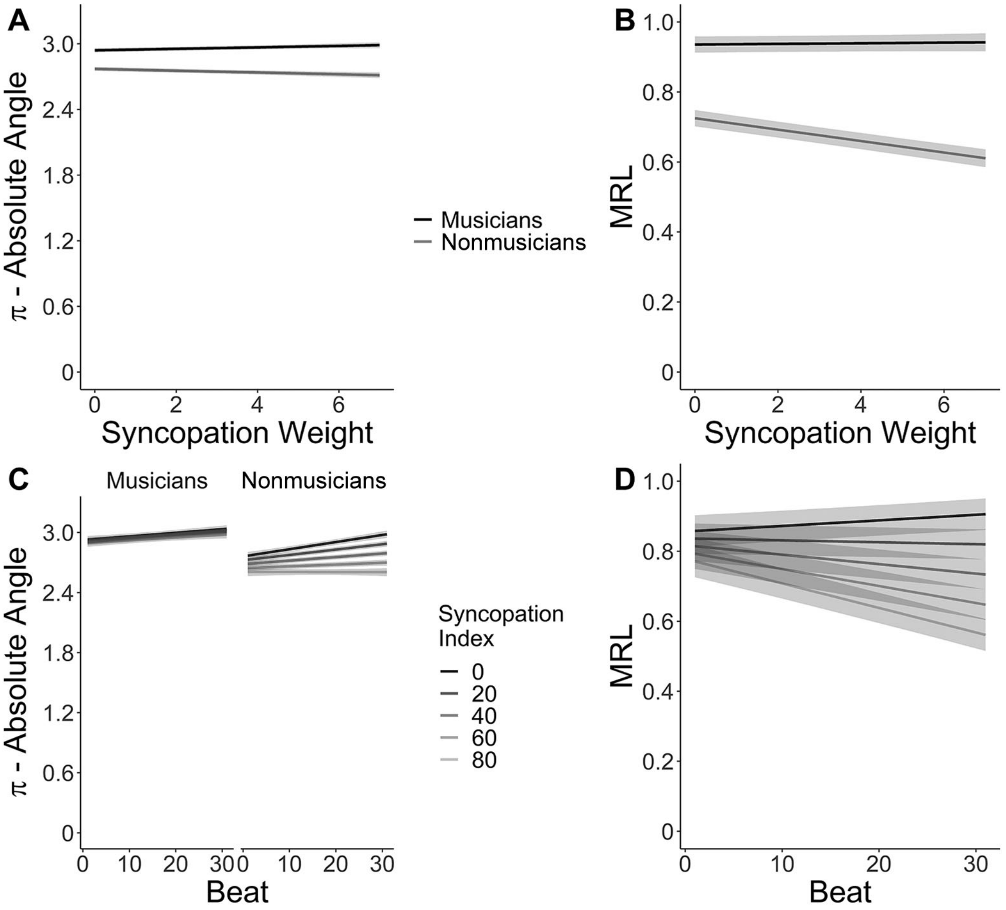

FIGURE 7. Per-beat tap performance calculated across-participants as a function of the syncopation weight of the preceding beat and the progression of the stimulus (beat). A) Tapping accuracy as a function of the weight of the preceding syncopation and group, B) Tapping precision as a function of the weight of the preceding syncopation and group, C) Tapping accuracy as a function of the progression of the stimulus (beat), syncopation index, and group, D) Tapping precision as a function of the progression of the stimulus (beat) and syncopation index. Note that tapping accuracy and precision were calculated across participants on the per-beat level. The lines represent the estimated effects from the robust regression model and ribbons represent 95% confidence intervals.

between stimuli. By-cycle random slopes and intercepts were included to account for differences between repetitions of the rhythmic pattern within a stimulus.

Analysis of the relation between per-beat tapping accuracy and lag 1 syncopation weights showed a significant group by syncopation weight interaction ($b = 0.015$, 95% CI[0.010, 0.020]; see Figure 7A). This was driven by musicians showing a small but significant positive relation ($b = 0.007$, 95% CI[0.003, 0.011]) and nonmusicians showing a small significant negative relation ($b = -0.008$, 95% CI[-0.012, -0.004]). Analysis of the relation between per-beat tapping precision and lagged syncopation weights showed a significant group by syncopation weight interaction ($b = 0.017$, 95% CI[0.014, 0.020]; see Figure 7B). This was driven by musicians showing a nonsignificant positive relation ($b = 0.001$, 95% CI[-0.002, 0.003]) and nonmusicians showing a significant negative relation ($b = -0.016$, 95% CI[-0.019, -0.014]). Analysis of tapping indices and lag 0 syncopation weights showed highly similar results (see Appendix). Together these results show that syncopation weights affected the accuracy and precision of nonmusicians' taps on a per-beat level, while musicians' taps were not negatively affected by even strong syncopations.

A follow-up analysis tested whether tapping performance increased over the course of the rhythmic pattern, as indexed by beat number, and whether this depended on the syncopation index. Robust linear mixed effects regression was used, including a random intercept accounting for differences in tapping performance due to the per-beat, lagged syncopation weight.

Analysis of tapping accuracy showed a small but significant three-way interaction between group, syncopation index, and beat number ($b = -0.00008$, 95% CI[-0.0001, -0.00003]). As can be seen in Figure 7C, musicians' tapping accuracy increased over the course of the rhythmic pattern for all levels of syncopation index, while nonmusicians' tapping accuracy only increased over the course of the less syncopated rhythms. Analysis of tapping precision showed an interaction between syncopation index and the beat number ($b = -0.00011$, 95% CI[-0.00013, -0.00008]). As can be seen in Figure 7B, tapping precision increased slightly over the course of less syncopated rhythms and decreased over the course of more syncopated rhythms, suggesting that the effect of syncopations accumulates as the stimuli progress.

Discussion

In this study we investigated the relation between perceived and measured synchrony, and the sensation of groove. To do this, musicians and nonmusicians rated the groove of rhythms that varied in degree of syncopation, and then tapped to the beat of those rhythms and rated how well they synchronized. Supporting our hypothesis, perceived synchrony showed a stronger positive relation with groove ratings than tapping precision (MRL), tapping accuracy (π - absolute angle), and syncopation. Crucially, the relation between perceived synchrony and groove was strongest for rhythms with a medium level of syncopation, thus extending work showing an inverted U-shaped relation between rhythmic complexity and groove. The effect of perceived synchrony did not differ across groups, suggesting that musicianship does not have a strong influence on the relation between perceived synchrony and groove. We also replicated previous work (Matthews et al., 2019; Witek et al., 2014) by showing an inverted U-shaped relation between syncopation and groove for both groups, with a stronger effect for musicians. Finally, in nonmusicians, between-participant tapping precision was lower following more strongly syncopated beats, supporting the hypothesis that syncopations affect tapping precision, and thus prediction certainty, on a beat-to-beat level.

PERCEIVED SYNCHRONY, SYNCOPATION, AND GROOVE

As hypothesized, the relation between perceived synchrony and groove showed an inverted U-shaped relation with syncopation, with moderately syncopated rhythms showing the strongest effect. This hypothesis was based on two proposals: 1) when rhythms are moderately syncopated, perceived synchrony evinces stronger positive feedback (i.e., more strongly weighted prediction confirmations), and 2) moderately syncopated rhythms widen the tolerance zone within which taps are perceived as synchronous, thus increasing the number of taps eliciting rewarding prediction confirmations. These proposals concern the relative weight and quantity of prediction confirmations, respectively. Therefore, these interpretations are not mutually exclusive, but are potentially compatible with each other and with the current results, as both predict a greater relation between perceived synchrony and groove for moderately syncopated rhythms. These proposed interpretations are discussed in turn.

According to the first proposal, taps that are judged to be temporally aligned with the beat generate a reward signal, which is particularly strong for moderately syncopated rhythms where the metric context is more uncertain. This is consistent with the predictive coding framework (Friston, 2010) and its treatment of groove (Koelsch et al., 2019; Vuust & Witek, 2014; Vuust et al., 2018), as well as other aesthetic emotions (Van de Cruys, 2017). According to this framework, the brain uses Bayesian inference to minimize prediction errors; for example, mismatches between meter-based temporal predictions and the timing of rhythmic onsets. Importantly, these prediction errors are weighted based on the certainty of the antecedent prediction. This weight determines the degree to which a prediction error leads to an adjustment in the metrical model. In the current context, we can invert this framing to focus on prediction confirmations, which will have stronger weights, in terms of reinforcing the model, as uncertainty increases. That is, the stronger the prediction confirmation, the more uncertainty is reduced.

Under this framework, reward is determined by the rate of prediction error or uncertainty minimization over time (Van de Cruys, 2017); in other words, how much learning occurs. This is similar to the learning progress hypothesis that suggests that making progress on a task—that is, reducing uncertainty and/or prediction errors—is intrinsically rewarding (Oudeyer et al., 2016). Therefore, prediction confirmations are rewarding only insomuch as they reduce uncertainty. Stimuli or tasks that will maximally afford this uncertainty reduction, and thus reward, will be those that are complex enough to provide reducible uncertainty (i.e., that are learnable), but not so complex as to be unlearnable (Gold et al., 2019; Koelsch et al., 2019). Therefore, the inverted U-shaped relation between complexity and pleasure (and other aesthetic emotions) can be seen as an emergent property of the intrinsic motivation to learn (Oudeyer et al., 2016). Applying this to the current context, moderately syncopated rhythms maximize reducible uncertainty, while perceived synchrony reflects the subjective perception of rewarding uncertainty reduction (i.e., prediction confirmations).

A relevant concept here is fluency, which is the degree to which one feels they can assess and act on sensory input. In the context of beat synchronization, ratings of fluency are positively related to both tapping accuracy and precision, particularly for more complex rhythms (Stupacher, 2019), suggesting a link between fluency and perceived synchrony. Fluency is one component of flow, which is a state of pleasurable absorption during a task that is optimally challenging (Csikszentmihalyi, 1990). Flow seems to be strongly linked with groove, particularly in the context of motor synchronization (Janata et al., 2012), as both are characterized by positively valenced, absorptive states while interacting with optimally complex stimuli (Danielsen, 2006; Witek, 2017). The current results provide supportive evidence of the link between flow and groove, however, as groove ratings preceded tap ratings, future work should test this link more directly with a paradigm that is more amenable to the assessment of directional hypotheses.

The second proposed interpretation of the relation between perceived synchrony, medium syncopation, and groove, suggests that syncopations add uncertainty about the location of the beat, effectively expanding the time window of what is considered on-beat. In turn, more taps fall into this wider window, are perceived as synchronous, and thus elicit a prediction confirmation and reward. According to this interpretation, moderately syncopated rhythms elicit the greatest number of prediction confirmations as they combine a pattern that is regular enough to allow for predictions, but increase uncertainty that widens the temporal window. This proposal essentially combines the notion of a tolerance zone (Müller et al., 1999), which determines which taps are perceived as synchronous, and that of temporal predictions as probability distributions, which allows for the expansion and contraction of the beat window depending on rhythmic uncertainty. Therefore, this proposal extends the beat bin hypothesis (Danielsen, 2010, 2018), which deals with smaller microtiming deviations, to larger deviations from the meter, such as syncopations. This proposal is also consistent with recent modeling work suggesting that temporal prediction uncertainty accumulates through the silent gaps created by syncopations (Cannon, 2021).

The beat bin hypothesis is based on dynamic attending theory. According to this theory, rhythm perception is supported by endogenous attentional oscillations that are entrained by rhythmic stimuli such that windows of attentional focus are temporally aligned with the beat (Large & Jones, 1999; Large & Kolen, 1994). These windows of attentional focus or "expectancy regions" expand or contract depending on the certainty for the rhythmic context, which determines the degree of synchronization between the attentional oscillator and the rhythm (Large & Jones, 1999). Therefore, in both predictive coding and dynamic attending treatments of rhythm perception, beat-based predictions are conceptualized as probability distributions whose location determines the expected beat point, and whose width reflects the certainty of the prediction. In addition, both frameworks suggest that the degree to which a violation of a prediction affects future predictions (i.e., its weight) is determined by the certainty of this prediction (i.e., the width of the probability distribution). Accordingly, both interpretations regarding the weight and number of prediction errors proposed here are consistent with both predictive coding and dynamic attending frameworks.

Indirect evidence for the second proposed interpretation is provided by the analysis showing that nonmusicians' taps were less precise (i.e., more spread out in time) following stronger syncopations, and that for both groups tapping precision declined over the course of more syncopated rhythms. Therefore, these results provide initial evidence that syncopations do increase prediction uncertainty, which leads to greater spread of taps around the beat. This greater spread may also reflect a wider tolerance zone, thus allowing more taps to be perceived as synchronous, which may in turn increase groove ratings. However, our data only allowed for indices of per-beat tap performance measured between rather than within participants, which were not amenable to direct comparison to ratings of perceived synchrony and groove. Therefore, future work should test the above interpretation directly with data that allows for within-participant measures of per-beat tap performance, and that can directly link this performance to perceived synchrony and groove.

Rhythmic context may additionally affect the temporal window for integration across sensory inputs, and thus the perception of synchrony, by affecting the comparison between haptic and proprioceptive feedback from the finger, and auditory input (Occelli et al., 2011). A recent study showed that temporal windows for integrating keypresses and the resulting auditory feedback are relatively large and that the width of this window is associated with tapping precision (van Vugt & Tillmann, 2014). Since syncopation affects tapping precision, as shown here, it could be that this integration window is also affected. In the current study, sensory feedback from movements is reduced as tapping does not result in a sound, which may further contribute to the uncertainty in perceived synchrony (Ross & Balasubramaniam, 2014).

The above interpretations focus on how syncopation affects prediction certainty and the relation between perceived synchrony and groove. However, musicianship is also likely to have an influence, and may interact with syncopation. Due to extensive experience engaging with a large variety of rhythmic structures, musicians are thought to have stronger metrical models, which generate more certain predictions (Vuust et al., 2018). This is supported by the current results showing that musicians tapped more accurately and precisely overall, and their tapping was less affected by syncopation, both at the trial and per-beat levels (see also Matthews et al., 2016; Repp, 2010; Repp & Doggett, 2007). Therefore, musicians' metrical models may only be challenged at higher levels of syncopation thus altering the relations between syncopation, perceived synchrony, and groove. Indeed, musicians showed higher groove ratings for moderately syncopated rhythms, replicating previous work (Matthews et al., 2019). However, the influence of syncopation on the relation between perceived synchrony and groove was similar for both groups, as indicated by the lack of a significant three-way interaction. This may be due to a lack of statistical power as the sample sizes are not well suited for detecting such potentially subtle effects. Therefore, further work is necessary to investigate the impact of musicianship on the relation between syncopation, perceived synchrony, and groove.

A third potential interpretation is that groove elicited by moderately syncopated rhythms itself increases perceived synchrony. This interpretation reverses the causal direction of the previous two interpretations, suggesting that the state of being "in the groove" may decrease the fidelity of judgements of the timing of one's own movements. This is supported by qualitative work describing the absorptive and immersive nature of the sensation of groove (Danielsen, 2006; Witek, 2017), which may inhibit analytical comparisons of the timing of onsets and movements. However, here we follow several influential theoretical accounts that highlight the importance of predictions in determining musical pleasure (Huron, 2006; Koelsch et al., 2019; Meyer, 1956; Salimpoor et al., 2015). From this perspective, groove, and other affective responses to music, result from the way in which music engages our predictive processes. This perspective has been given recent support from studies linking musical prediction errors (surprises) and uncertainty to affective responses and reward-related activity in the brain (Cheung et al., 2019; Gold, Mas-Herrero, et al., 2019; Shany et al., 2019). In the current context, measured and perceived synchrony are seen here as indices of the predictive processes that form the causal link between syncopation and groove. However, it is possible, and perhaps likely, that feeling "in the groove" can feed back on these predictive processes, and thus affect perceived and measured synchrony. The current results cannot determine the directionality, or bidirectionality, of the relation between medium syncopation, perceived synchrony, and groove, particularly since groove ratings were collected before tap ratings. One possible way of getting at this directionality question would be to do a similar task with "beat deaf" individuals who have difficulty synchronizing with musical rhythms, presumably indicating an inability to generate meter-based predictions.

MEASURED SYNCHRONY, PERCEIVED SYNCHRONY, AND GROOVE

For both musicians and nonmusicians, perceived synchrony showed a stronger relation with groove than measured synchrony. This suggests a discrepancy between perceived and measured synchrony, with perceived synchrony exhibiting a stronger association with affective experience. One potential insight into this discrepancy is that tapping precision (MRL) showed strong positive relations with perceived synchrony and groove, across both groups. Conversely, tapping accuracy (π - absolute angle) showed only a small positive effect in nonmusicians and a negative effect in musicians, and also showed very little relation with groove in both groups. This suggests that tapping precision is more accessible to conscious awareness, at least to the degree that it influences subjective ratings. Overall, both groups tapped quite close, and generally early, relative to the beat. Therefore, as in previous work (Franěk et al., 1987), small negative asynchronies may have generally gone unnoticed, that is, they fall within the tolerance zone (Müller et al., 1999). This is also in line with work showing that corrections of small asynchronies (i.e., phase correction) do not depend on conscious awareness (Repp & Keller, 2004). Conversely, and in line with the current results, tapping precision has been linked to the perceived difficulty of synchronizing taps (Bååth, & Madison, 2012).

These differential relations between tapping precision, tapping accuracy, and subjective ratings, may have contributed to the mixed results shown in studies relating motor synchronization performance and groove. For example, one study showed a positive relation (Janata et al., 2012), while others showed a weak relation (Stupacher et al., 2016), or no relation (Hurley et al., 2014). These studies did not look at tapping precision and accuracy separately and involved different motor effectors, which may have distinct tolerance zones. Therefore, further work is necessary to clarify which aspects of motor synchronization influence perceived synchrony and are related to groove, and to assess whether conscious awareness mediates these relationships.

Conclusion

In this study we set out to investigate the relation between perceived synchrony, measured synchrony, and the sensation of groove. We showed that perceived synchrony exhibits a stronger relation with groove than measured synchrony and even syncopation, and that this effect was strongest for moderately syncopated rhythms. This indicates that higher-order, consciously accessible prediction errors and confirmations based on metrical structure contribute to groove over and above the local fine-grained prediction errors and confirmations related to measured synchrony. In addition, both groups showed an inverted U-shaped relation between syncopation and groove, with musicians showing higher groove ratings for moderately syncopated rhythms. Together, these results align with previous work showing the primacy of moderately syncopated rhythms in eliciting groove, extending this relation to the role of perceived synchrony during beat synchronization. We also provided initial evidence of a link between syncopations and the certainty of meter-based temporal predictions, a mechanism that may also contribute to groove during perception. In sum, we provide further evidence to suggest that temporal predictions, and their certainty, may be important factors in determining our affective response to music, and the way in which perception of our actions may relate to this affective response.

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Appendix

TABLE A1. *Per-beat Syncopation Weights For All Stimuli*

Stim	Beat																♩$_{\text{sum}}$	♪$_{\text{sum}}$	Sum
	♩	♪	♩	♪	♩	♪	♩	♪	♩	♪	♩	♪	♩	♪	♩	♪			
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	0	2	0	2	0	0	0	1	0	0	0	6	0	6
4	2	0	0	0	1	0	2	0	0	0	0	0	0	0	2	0	7	0	7
5	0	0	0	0	3	0	0	0	2	0	0	0	3	0	0	0	8	0	8
6	2	0	0	0	0	0	2	0	2	0	0	0	1	0	2	0	9	0	9
7	2	0	0	0	0	0	2	0	2	0	0	0	1	0	2	0	9	0	9
8	2	0	0	0	0	6	0	0	2	0	0	0	0	0	2	0	6	6	12
9	3	0	0	0	0	0	3	0	0	0	0	0	0	0	4	3	10	3	13
10	2	0	0	0	0	0	2	0	2	0	0	0	1	3	4	0	11	3	14
11	2	0	0	0	0	0	2	0	2	0	3	6	0	0	2	0	11	6	17
12	0	0	3	0	3	0	0	0	7	0	3	0	1	0	0	0	17	0	17
13	0	0	0	0	6	0	7	0	0	0	0	0	5	0	0	0	18	0	18
14	2	0	0	0	0	0	3	6	0	0	6	0	0	0	2	0	13	6	19
15	2	0	0	0	7	0	3	0	2	0	4	0	0	0	3	0	21	0	21
16	0	0	3	0	0	0	3	0	0	0	6	0	6	0	3	0	21	0	21
17	0	0	0	0	7	0	0	0	2	0	0	0	7	0	0	6	16	6	22
18	2	0	3	0	0	0	4	0	2	0	3	6	0	0	3	0	17	6	23
19	2	0	0	0	0	0	6	0	7	2	4	0	3	0	0	0	22	2	24
20	0	0	4	0	6	0	4	0	0	0	0	0	6	0	4	0	24	0	24
21	0	0	4	0	6	0	3	0	2	0	4	0	0	6	0	0	19	6	25
22	0	0	3	0	0	0	3	6	0	0	4	0	7	0	3	0	20	6	26
23	0	0	0	0	7	0	6	0	7	0	6	0	0	0	1	0	27	0	27
24	0	0	0	0	5	0	3	0	2	0	0	0	7	0	6	6	23	6	29
25	3	0	0	0	3	0	3	0	4	0	6	0	0	6	7	0	26	6	32
26	4	0	3	6	3	0	3	0	0	0	3	0	7	2	3	0	26	8	34
27	0	0	4	0	5	0	3	0	6	0	3	6	0	0	3	6	24	12	36
28	2	0	6	0	1	6	4	0	3	0	4	0	1	6	4	0	25	12	37
29	4	0	0	0	1	6	4	0	2	6	4	0	0	6	4	0	19	18	37
30	2	0	3	0	7	6	4	0	2	0	3	0	7	6	0	0	28	12	40
31	0	0	0	0	7	6	4	6	0	0	3	0	5	6	0	6	19	24	43
32	3	0	4	6	7	6	0	2	5	6	0	2	4	0	0	0	23	22	45
33	0	0	0	0	7	2	3	0	4	0	3	0	7	6	7	6	31	14	45
34	0	0	3	6	7	0	3	6	0	0	4	0	7	6	4	0	28	18	46
35	3	0	3	0	7	2	6	0	7	2	4	0	7	2	6	0	43	6	49
36	3	0	4	6	7	6	4	3	3	6	4	6	0	0	0	0	25	27	52
37	4	0	0	0	7	6	4	0	3	6	4	6	4	0	3	6	29	24	53
38	3	0	4	6	7	0	6	0	0	0	4	6	7	3	4	3	35	18	53
39	0	6	4	6	0	0	4	6	8	6	4	0	0	0	4	6	24	30	54
40	3	0	0	0	7	6	4	6	8	0	2	6	4	2	6	0	34	20	54
41	2	0	7	0	5	6	6	6	7	6	7	0	6	0	0	0	40	18	58

(continued)

TABLE A1. *(continued)*

Stim	Beat																♩$_{\text{sum}}$	♪$_{\text{sum}}$	Sum
	♩	♪	♩	♪	♩	♪	♩	♪	♩	♪	♩	♪	♩	♪	♩	♪			
42	3	0	4	0	7	6	7	3	3	0	4	0	7	6	7	3	42	18	60
43	0	0	4	0	7	6	4	6	8	6	4	6	6	0	3	0	36	24	60
44	7	6	0	0	7	0	7	0	8	0	7	6	7	0	7	0	50	12	62
45	8	6	6	0	7	0	5	6	7	0	7	0	7	0	5	0	52	12	64
46	7	6	6	0	7	0	6	0	8	0	7	0	6	6	6	0	53	12	65
47	8	0	7	6	6	0	7	0	8	6	6	0	7	0	5	0	54	12	66
48	8	6	4	6	0	0	4	6	8	6	4	0	3	6	4	6	35	36	71
49	7	6	7	0	7	0	7	0	8	6	7	0	5	6	6	6	54	24	78
50	8	0	7	6	7	6	7	0	8	6	0	6	7	0	7	6	51	30	81
mean	2.30	0.72	2.20	1.08	3.90	1.64	3.58	1.36	3.46	1.40	3.02	1.24	3.40	1.68	2.96	1.38	24.82	10.50	35.32

Note. Columns labeled with quarter notes indicate beats on which participants were expected to tap. Columns labeled with eighth notes indicate between-beat metric positions. When calculating the per-beat syncopation weights, the weights at the eighth note level were averaged with the weights of the beat at the quarter note level. Stim = stimulus number.

Effects of Tapping Performance and Syncopation on Tap Ratings in Nonmusicians Only

Analysis of the nonmusicians' data only were generally consistent with the results of the analysis on the full sample with main effects of syncopation index: linear and quadratic, $F(2, 39) = 8.31$, $p = .001$; tapping precision, $F(1, 16) = 26.61$, $p < .001$, and an interaction between syncopation and tapping precision, $F(2, 356) = 9.36$, $p < .001$. The interaction indicated that the relation between tapping precision and tap ratings gets weaker as syncopation increases ($b = -0.017$, 95% CI[−0.026, −0.007]).

Effects of Tapping Performance, Syncopation, and Group on Tap Ratings in a Model Accounting for the Censored Nature of the Data

Using lme4cens package, a model was estimated that accounted for the fact that a large number of tap ratings were at the upper limit of the ratings scale (a rating of 5). Only the significant predictor variables from the F tests using the standard model were included. Note that due to limitations of the package, only by-participant random intercepts were estimated and only the linear effect of syncopation was included in the model. In addition, p values but not confidence intervals were estimated using a z-score approximation. Syncopation showed a significant main effect indicating a negative relation with tap ratings ($b = -0.179$, $p < .001$). The group by syncopation index was not significant ($b = -0.091$, $p = .151$). The group by tapping precision interaction was significant ($b = -0.480$, $p < .001$), while the group by tapping accuracy interaction showed a near-significant trend ($b = 0.176$, $p = .051$).

Effects of Measured Synchrony and Syncopation on Groove Ratings in Nonmusicians Only

Analyses of the nonmusicians' data only showed very similar results to those carried out on the full data set. Importantly, the F tests showed a main effect of tap ratings, $F(1, 711.35) = 79.33$, $p < .001$, and an interaction between tap ratings and syncopation, $F(2, 551.85) = 4.78$, $p = .008$. The final model showed that tap ratings ($\beta = 0.344$, 95% CI[0.278,0.425]) had a stronger relation with groove than both tapping precision ($\beta = 0.159$, 95% CI[0.067, 0.241]) and tapping accuracy ($\beta = 0.003$, 95% CI[−0.067, 0.241]).

Effects of Syncopation Weight on Between-participant, lag 1 Tapping Performance

Analysis of the relation between per-beat tapping accuracy and lag 0 syncopation weights showed a significant group by syncopation weight interaction ($b = 0.\ 021$, 95% CI[0.017, 0.026]; see Figure A1A). This was driven by musicians showing a nonsignificant positive relation ($b = 0.001$, 95% CI[−0.003, 0.004]) and nonmusicians showing a significant negative relation ($b = -0.020$, 95% CI[−0.025, −0.017]). Analysis of the relation between per-beat tapping precision and lag 0 syncopation weights showed a significant group by syncopation weight interaction ($b = 0.\ 014$, 95% CI[0.011, 0.017]; see Figure A1). This was driven by musicians showing a small but significant positive relation ($b = 0.004$, 95% CI[0.002, 0.007]) and nonmusicians showing a small significant negative relation ($b = -0.010$, 95% CI[−0.012, −0.007]).

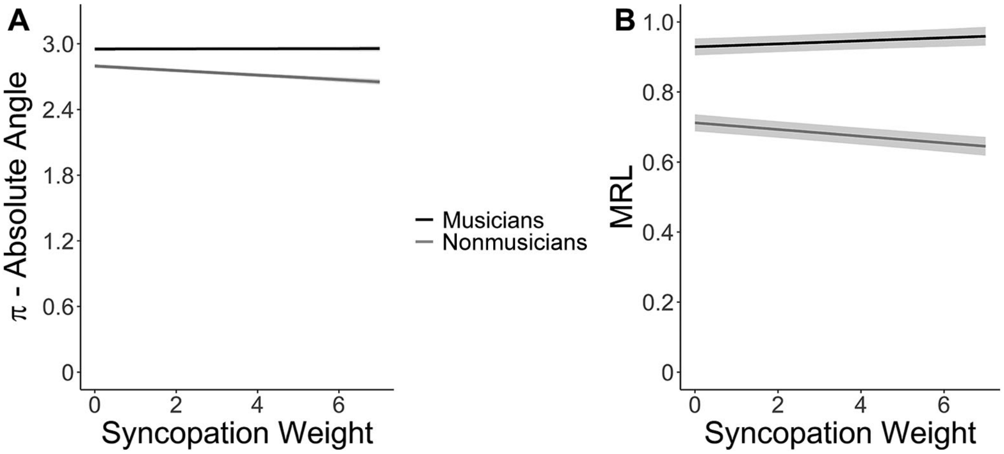

FIGURE A1. Per-beat tap performance calculated across-participants as a function of the syncopation weight of the lag 0 beat. A) Tapping accuracy as a function of the weight of the syncopation and group; B) Tapping precision as a function of the weight of the syncopation and group. Note that tapping accuracy and precision were calculated across participants on the per-beat level. The lines represent the estimated effects from the robust regression model and ribbons represent 95% confidence intervals.