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Supplementary Information for

NEURAL TRACKING OF THE MUSICAL BEAT IS ENHANCED BY LOW-FREQUENCY SOUNDS

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Main Experiment

EEG acquisition and preprocessing. The continuous EEG recordings were high-pass filtered offline at 0.1 Hz (4th order Butterworth filter) to remove very slow drifts from the signals. Artifacts produced by eye blinks were identified and removed participant-wise with independent component analysis (1) using the Runica algorithm (2, 3) applied to the concatenated epochs from all blocks segmented from 0 to 60 s relative to the trial onset. A single independent component related to eye blinks was selected and removed for each participant based on visual inspection of its waveform and topography. If the amount of variance explained by the component was less than at least 10 other components, then it was not removed from the signal (1 participant). Channels containing excessive artifacts or noise were linearly interpolated using the 3 closest channels (1 channel interpolated in 3 participants).

Beat tapping session. The main goal of the beat-tapping task performed after the EEG session was to confirm theoretical assumptions about entrainment to the beat based on a preferential grouping by four events (i.e. beat period of 800 ms) for the present rhythmic sequences and tempo (4–6), and to examine possible differences in this preferential grouping between low- and high-tone conditions. Participants were asked to tap the index finger of their preferred hand in time with the regular, isochronous, pulse-like beat that they perceived in the rhythm. The experimenter provided a short pop-music example of a beat and then short examples of tapping to the unsyncopated and syncopated rhythm (according to theoretical beat frequency). It was emphasized that there were multiple plausible pulses and starting positions, and participants were encouraged to keep the beat as naturally as possible throughout the trials. The tapping was performed on a custom-built response box containing a piezoelectric sensor that registered taps, which were recorded as an audio file using PsychToolbox, version 3.0.14 (7).

Tap-times were extracted by locating the peaks in the signal recorded from the response box. The first and last taps of each trial were discarded from further analyses. The mean and coefficient of variation (SD/mean) of inter-tap intervals (ITIs) were calculated for each trial and averaged for each condition and participant. Mean ITI provides an index of the perceived beat period while the coefficient of variation is a measure of beat tapping variability throughout the trial. Repeated-measures ANOVAs were performed for the mean ITI and the coefficient of variation, with factors tone frequency (low, high) and rhythm (isochronous, unsyncopated, syncopated).

The mean ITI for all three types of rhythm was predominantly 800 ms (as expected based on previous work; see 4, 5), which corresponds to grouping by four events (see Table S1 and Fig. S1). For the isochronous rhythm, a number of participants also tapped at a faster period of 400 ms (grouping by two events). No differences in the perceived beat period or its variability were observed between the high- and low-tone conditions for each type of rhythm, as revealed by non-significant effects involving the factor tone frequency in the ANOVAs on mean ITI and the coefficient of variation ($Ps > 0.11$).

Validity of the z-score standardization. Z-scoring the amplitudes at the 12 frequencies elicited by each rhythm (unsyncopated and syncopated) allows the relative enhancement of a particular subset of frequencies across different units, scales, and inputs to be compared. Nevertheless, z-scoring might be prone to biases to the extent that the absolute magnitudes of participants' responses are dependent on the degree of amplitude variation they exhibit across the frequency components included in the calculation. Accordingly, larger z-scores might be assigned to participants with less variability in their responses, leading to unequal weighting of participants in the group statistics independently of the experimentally manipulated factors. To ensure that this was not the case in the current study, the variability of EEG response amplitudes across the 12 peaks was subjected to a 2 x 2 ANOVA with factors tone frequency (low, high) and rhythm (unsyncopated, syncopated). There was no significant effect of tone frequency [$F(1,13) = 0.24$, $P = 0.64$, $\eta_G^2 < 0.01$) and no interaction [$F(1,13) = 1.26$, $P = 0.28$, $\eta_G^2 < 0.01$], suggesting that the observed effect of low tone in the main analysis was not due to z-scoring of the EEG amplitudes.

To address this issue further, we tested an alternative normalization method that was not dependent on the variability of EEG response amplitudes. In this method, response amplitudes were normalized by the maximum amplitude value across the 12 peaks elicited by each rhythm separately for each participant, thus rescaling the amplitudes to 1. A 2x2 ANOVA with factors tone frequency (low, high) and rhythm (unsyncopated, syncopated) revealed greater relative amplitude at the beat frequency (main effect of tone frequency) [$F(1,13) = 7.76$, $P = 0.015$, $\eta_G^2 = 0.11$] and a significant interaction between the factors rhythm and tone frequency when taking the mean across meter frequencies [$F(1,13) = 7.69$, $P = 0.016$, $\eta_G^2 = 0.06$]). Similarly, the magnitudes of the cochlear model output were rescaled to 1 and difference scores between the low- and high-tone conditions were calculated separately for the beat and meter frequencies, and the unsyncopated and syncopated rhythm. The comparison to the corresponding difference scores calculated from the EEG response amplitudes rescaled to 1 revealed significantly larger difference score in the syncopated rhythm for the beat frequency [$t(13) = 3.11$, $P = 0.03$, $d = 0.83$] and mean meter frequencies [$t(13) = 3.82$, $P = 0.009$, $d = 1.02$]. For the unsyncopated rhythm, there was no significant effect for the beat frequency nor for meter frequencies ($Ps = 1$). The similar outcome of this alternative analysis to the main analysis indicates that the z-score procedure did not artificially bias the results of the current study.

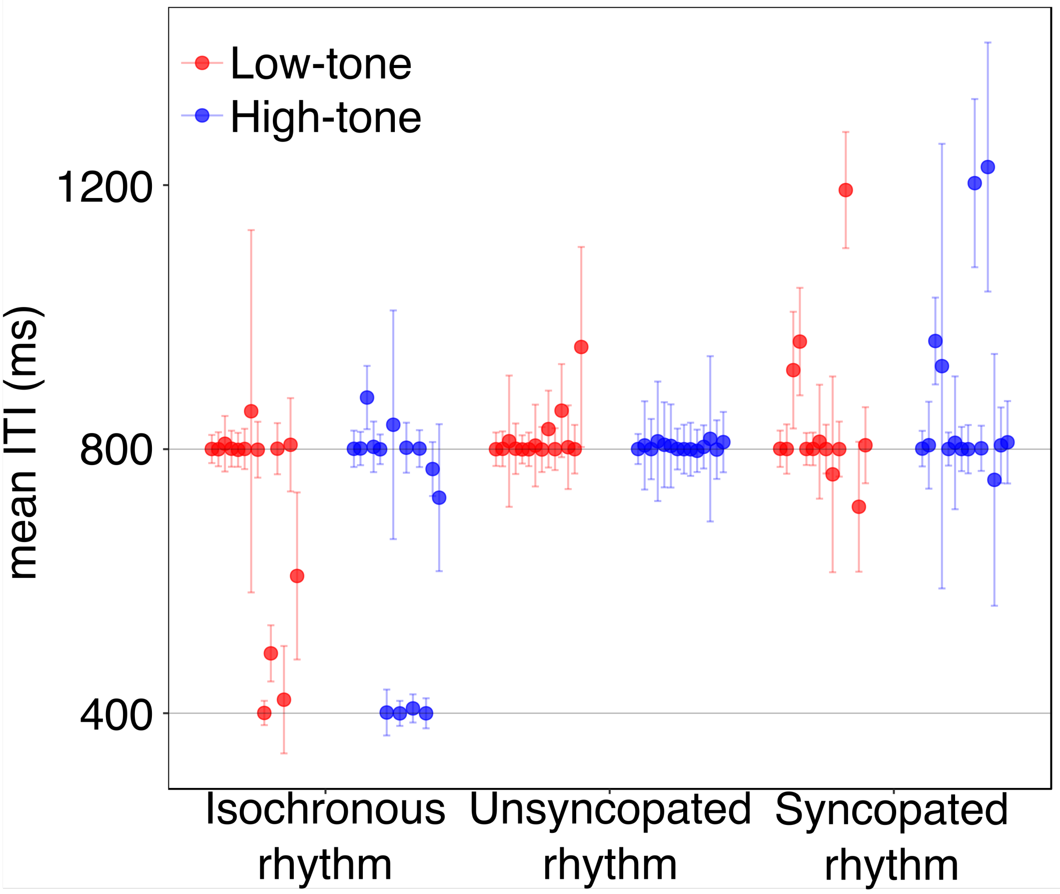

Fig. S1. Tapping responses. Mean inter-tap interval (ITI) for each participant in each condition, depicted as single data points. One data point was removed for display purposes from the low-tone syncopated condition (the participant tapped with period 2.4 s, i.e. repetition of the whole rhythmic pattern). Coefficient of ITI variation is shown as error bars for each condition and participant. Meter frequencies are shown as horizontal lines at 400 ms (grouping by 2 events) and 800 ms (grouping by 4 events). Participants' tapping predominantly converged toward grouping by 4 events, with some participants tapping a faster beat (grouping by 2) for the isochronous rhythm. No significant differences in the mean ITI or the coefficient of variation were observed between low-tone (red) and high-tone (blue) conditions.

Table S1. Descriptive statistics for the main experiment.

	Isochronous rhythm		Unsyncopated rhythm		Syncopated rhythm	
	Low-tone	High-tone	Low-tone	High-tone	Low-tone	High-tone
Temporal deviant identification task (mean % correct)	83.92 ± 24.23	79.46 ± 27.12	78.57 ± 16.57	83.93 ± 15.83	69.64 ± 20.04	84.82 ± 15.64
Tapping tempo (median ITI ± IQR in ms)	800.05 ± 145.0	800.17 ± 314.8	800.56 ± 10.51	801.83 ± 6.41	800.48 ± 92.46	805.92 ± 96.57
Tapping variability (mean coefficient of variation)	8.9 ± 8.67	6.64 ± 5.05	6.24 ± 3.60	6.55 ± 3.32	7.89 ± 4.67	10.75 ± 9.58
EEG overall response magnitude (in µV)	0.25 ± 0.12	0.18 ± 0.09	0.49 ± 0.20	0.43 ± 0.18	0.56 ± 0.21	0.54 ± 0.25
EEG beat frequency (z-score)	-	-	1.88 ± 0.98	1.42 ± 0.99	1.07 ± 0.88	0.23 ± 0.94
EEG mean meter frequencies (z-score)	-	-	0.9 ± 0.22	0.76 ± 0.19	0.75 ± 0.23	0.38 ± 0.40

Mean ± SD; ITI, inter-tap interval; IQR, interquartile range.

Control Experiment 1: Effect of sound intensity

In the main experiment, low-tone and high-tone carrier frequencies were equalized in loudness to account for the differential sensitivity of the human auditory system across the frequency range. It is, nevertheless, possible that residual loudness differences, with low-tone rhythms being perceived as louder than high-tone rhythms due to possible over-correction by the psychoacoustic model, could partly account for the effects observed in the main experiment. However, to our knowledge, there is no evidence as to whether louder rhythmic sequences induce overall larger responses or a selective enhancement at specific frequencies coinciding with perceived beat and meter. Control Experiment 1 addressed these questions by directly manipulating sound intensity.

Materials and Methods

All materials and methods were the same as in the main experiment, except as indicated below.

Participants. Thirteen individuals were recruited (mean age = 26.8, SD = 8.4, 8 females), three of whom had participated in the main experiment. The amount of formal musical training ranged from 0 (5 participants) to 17 years.

Auditory stimuli. The auditory rhythms were conveyed by a pure tone at 400.1 Hz (i.e. the geometric mean between high and low tone of the main experiment). Instead of manipulating tone frequency, we manipulated sound intensity by delivering each rhythm at either 80 dB SPL (“loud condition”) or at 70 dB SPL (“soft condition”). The 10 dB difference (corresponding approximately to doubling of the perceived loudness (see e.g. 8) was thus expected to be much larger than any possible residual loudness difference between low-tone and high-tone conditions in the main experiment. Importantly, the intensities were kept below the vestibular threshold (90-95 dB), as was the case in the main experiment.

Data analysis. During preprocessing, an independent component containing eyeblink-related artifacts was not removed for four participants. One channel was interpolated in three participants.

Results

The mean percentages of correct responses in the behavioral task (Table S2) were comparable to the main experiment. However, the ANOVA comparing behavioral responses across conditions did not show a significant main effect or interactions involving tone intensity ($Ps > 0.62$), although some participants reported the task to be more demanding in the soft condition.

The overall magnitude of the EEG response (in µV) was not significantly different between the loud and soft conditions in either rhythm ($Ps > 0.63$). Importantly, the EEG response at the beat frequency was not significantly different in loud and soft conditions (no main effect of tone intensity, $P = 0.77$), and there was no interaction between the factors tone intensity and rhythm ($P = 0.95$). Similar results were obtained for the EEG responses at meter-related frequencies ($Ps > 0.51$). Together, these results do not support the alternative hypothesis that sound intensity might have been a confounding factor driving the effects observed in the main experiment. Conversely, these results suggest that, at sound intensities well above the detection threshold (but below the vestibular threshold), the global response magnitude and the EEG responses at beat and meter frequencies are not affected by differences in sound pressure level.

Table S2. Descriptive statistics for Control Experiment 1.

	Isochronous rhythm		Unsyncopated rhythm		Syncopated rhythm	
	Loud	Soft	Loud	Soft	Loud	Soft
Temporal deviant identification task (mean % correct)	83.33 ± 15.39	84.38 ± 16.1	81.25 ± 22.3	80.21 ± 21.62	86.46 ± 17.24	81.83 ± 24.25
EEG overall response magnitude (in µV)	0.2 ± 0.08	0.19 ± 0.08	0.44 ± 0.17	0.39 ± 0.15	0.53 ± 0.18	0.48 ± 0.19
EEG beat frequency (z-score)	-	-	2.1 ± 0.59	2 ± 0.69	0.98 ± 0.98	0.92 ± 1.2
EEG mean meter frequencies (z-score)	-	-	0.83 ± 0.16	0.76 ± 0.24	0.58 ± 0.22	0.61 ± 0.24

Mean ± SD.

Control Experiment 2: Effect of behavioral task

Control Experiment 2 was conducted to address the relative contribution of endogenously generated beat-based predictions associated with the temporal deviant identification task on the effect of tone frequency observed in the main experiment. In the main experiment, the nature of the deviant identification task required focusing attention on fine-grained timing in the stimulus rhythm. It has been shown that detection performance of temporal perturbations is better in highly metrical rhythms (such as unsyncopated rhythms) compared to weakly metrical rhythms (such as syncopated rhythms, e.g. 9, 10). This is because highly metrical rhythms induce stronger representation of metric structure, where periodic beats are utilized to precisely encode temporal properties of the stimulus (11). Furthermore, the fine temporal resolution of the auditory system is slightly lower for low-frequency sounds compared to high-frequency sounds (12). These two factors in combination might have resulted in greater demands for endogenous generation of the meter in order to carry out the task in the low-tone syncopated condition of the main experiment.

In the present control experiment, the behavioral task was adapted so that participants focused their attention on broadly defined properties of the auditory stimulus (pitch, tempo, and loudness), and not on the fine temporal properties as in the main experiment. That is, whereas instructions in the main experiment encouraged focus on fine-grained event timing relative to the perceived beat (to identify shorter vs. longer deviants), instructions in the current experiment encouraged general vigilance rather than attention specifically to temporal structure. These task instructions, combined with the fact that no actual changes were present in any of the trials, were assumed to guarantee similar demands for endogenous meter generation across conditions.

Materials and Methods

Materials and methods were the same as in the main experiment, except as indicated below.

Participants. Fifteen individuals were recruited (9 females, mean age = 27.5, SD = 8.7), none of whom had participated in the main experiment. The number of years of formal musical training ranged from 0 to 17 years (mean = 2.6, SD = 5.3).

Behavioral task. The rhythmic sequences did not contain any shorter or longer sound events, in contrast with the main experiment. However, to ensure that participants were generally attentive, they were asked to listen carefully to the stimuli and report after each trial any change in pitch, loudness, or tempo that was perceived. There were in fact no actual changes in any of the trials (and therefore quantitative assessment of 'identification' performance was not conducted). However, it can be noted that, possibly due to the repetitive nature and long duration of the stimuli, participants reported hearing very subtle (apparently illusory) changes in most trials.

Data analysis. During preprocessing, an independent component containing eyeblink-related artifacts was not removed for four participants, because the variance explained by the component was smaller than at least for 10 other components. One to three channels were interpolated in six participants.

Results

The overall magnitude of the EEG response was commensurate in the low-tone and high-tone conditions for all rhythms types, as revealed by the paired-samples t-tests ($Ps = 1$, Bonferroni-corrected). As for the relative amplitude at beat frequency, there were no significant differences between conditions ($Ps > 0.52$). Similarly, the ANOVA on meter-related frequencies revealed no significant main effects or interactions ($Ps > 0.29$). These results suggest that the effect of tone frequency is dependent on the attentional focus of the listener. Together, results of the main experiment and Control Experiment 2 suggest that the EEG response at beat and meter frequencies is boosted when the behavioral task requires focusing attention on temporal properties of the stimulus, particularly in syncopated rhythms conveyed by bass sounds. Note that these results do not imply that attention exclusively to tone duration per se is necessary for the low tone benefit. In everyday contexts, attention is also directed to temporal properties of rhythm when listening to expressively timed performances, where micro-timing variations are a key determinant of performance quality (13–15), coordinating body movements with music while dancing (16), or synchronizing with others during group music making (17).

Table S3. Descriptive statistics for Control Experiment 2.

	Isochronous rhythm		Unsyncopated rhythm		Syncopated rhythm	
	Low-tone	High-tone	Low-tone	High-tone	Low-tone	High-tone
EEG overall response magnitude (in µV)	0.15 ± 0.07	0.15 ± 0.05	0.35 ± 0.16	0.37 ± 0.19	0.43 ± 0.17	0.42 ± 0.14
EEG beat frequency (z-score)	-	-	0.11 ± 0.96	0.05 ± 1.05	0.02 ± 0.91	-0.15 ± 0.92
EEG mean meter frequencies (z-score)	-	-	0.01 ± 0.55	0.03 ± 0.5	-0.04 ± 0.47	-0.04 ± 0.4

Mean ± SD.

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