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Does Training Enhance Entraining? Musical Ability and Neural Signatures of Beat Perception

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Abstract

Perception of beat and meter is a nearly universal human skill that requires little to no conscious effort. However, the extent to which music training influences this perception in the brain remains unknown. Music performance requires high sensitivity to timing and physical entrainment to external auditory stimuli. Additionally, compared to untrained individuals, musicians show higher performance on a number of auditory and speech tasks, as well as different brain morphology and fiber connections. Beat and meter perception are thought to be subtended by oscillations of groups of neurons at corresponding frequencies. Here, electroencephalography (EEG) was used to examine the magnitude of neuronal entrainment to beat and meter in individuals with high or low levels of music training. EEG signals were recorded while participants attended to a musical beat, and then imagined a binary or ternary meter over that beat. Beat-keeping ability was also assessed using a synchronous tapping task. A strong EEG signal was observed selectively at beat and meter frequencies, indicating entrainment across participants. No differences in the magnitude of entrainment were observed based on level of music training or beat-keeping ability. These results suggest that music training may not influence beat and meter perception at the level of neural networks and that entrainment could be innate. Broadly, results provide a foundation for further research into whether entrainment has evolutionary significance.

Keywords: beat perception, entrainment, music, meter

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Introduction

Human communication relies directly on the organization and perception of sounds in time. In language, the length and pacing of speech sounds informs meaning, tone, and grammar. In music, beat and rhythm form the foundation for music perception. Beat perception specifically, has become an important area of research because it is a nearly universal human skill (Merchant, Grahn, & Trainor, 2015; Palmer, Lidji, & Peretz, 2014). A "beat" is a regular change in signal amplitude, resulting in a perceived periodicity. Humans have a tendency to synchronize their behavior with perceived beats, i.e., to *entrain* to them (e.g. foot-tapping). This entrainment is further directed by beat groupings into repeating patterns of emphasis, known as meter. A well-known example of meter is a ternary or three-beat waltz meter. These temporal patterns correspond to harmonics of the original beat frequency. For example, the binary meter of a 2.4Hz beat would be perceived at 1.2Hz (2.4/2=1.2). Research has begun to examine the neural activities that subtend beat and meter perception, but further exploration is required to explore entrainment at the level of neural networks. It is currently unknown whether neuronal entrainment to beat and meter is (1) innate, (2) training-dependent, or (3) innate but enhanced by training.

Developmental studies have used event-related potential (ERP) and mismatch negativity (MMN) methodologies to demonstrate that infants are sensitive to both beat and meter, suggesting an innate human ability to perceive and hierarchically organize beats (Honing, 2012; Winkler, Háden, & Ladinig, 2009). From two to seven months old, infants can discriminate stimuli based on rhythm and meter (Hannon & Johnson, 2005; Phillips-Silver & Trainor, 2005).

By nine months, infants are able to recognize and discriminate rhythmic patterns (Bergeson & Trehub, 2006), providing evidence that beat and rhythm perception fundamentally innate and improve through early development without music training influences. However, musically trained children show earlier neural responses to music and speech, suggesting potential for training-based enhancements associated with entrainment.

In solo and ensemble performance, musicians are required to physically entrain to a steady beat. Entrainment can be defined as the adaptation of at least two oscillating agents toward a common phase and period, with the potential to reach perfect synchrony (Rosenblum & Pikovsky, 2003). Musicians therefore, entrain to successfully coordinate their behavior. Studies comparing individuals with varying levels of music training have demonstrated that musicians show entrainment-associated benefits in the brain. Research has examined neuronal entrainment as the basis of plasticity in the brainstem using a scalp-recorded auditory brainstem response (ABR). The frequency-following response (FFR) is a component of the ABR that directly represents subcortical neural entrainment to auditory stimuli in that it is phase and frequency locked to the characteristics of a sound stimulus. Musicians show earlier FFRs than non-musicians when perceiving music and speech, suggesting enhanced auditory processing abilities (Kraus & Chandrasekaran, 2010). Further, entrainment has been proposed to be the key mechanism responsible for cognitive benefits associated with music training (Miendlarzewska & Trost, 2013). For example, a study in adolescents found that the ability to tap to a beat was associated with both superior reading ability and enhanced attention (Tierney & Kraus, 2013), which have both been connected to musical training (Gordon, Fehd, & McCandliss, 2015; Roden et al., 2014; Wang, Ossher, & Reuter-Lorenz, 2015). However, this theory relies on the idea that musicians show *enhanced* entrainment, which has yet to be clarified.

In addition, a large body of research suggests that musically trained individuals show advantages in auditory perception and discrimination as well as training-associated neuroplastic changes. In comparison to untrained individuals, musicians have larger auditory cortices (Wan & Schlaug, 2010), and exhibit enhanced auditory processing of music and speech in the brainstem (Musacchia, Sams, & Skoe, 2007). Studies with children have supported training-induced plasticity over short periods. One study in 4-6 year old children used deformation-based morphometry (DBM), to examine structural brain differences between children receiving music lessons and controls. At baseline, no differences were observed between children in the music training group and controls. However, after 15 months, children in the music training group showed greater voxel size in the right precentral gyrus (motor hand area), corpus callosum, and right auditory cortex (Hyde et al., 2009). Research in adults has shown that musicians have increased grey matter in primary motor and somatosensory areas, and greater fiber density in the corpus callosum relative to non-musicians (Gaser & Schlaug, 2003). The aforementioned research supports the hypothesis that neurons in cortical areas throughout musicians' brains may show higher amplitude responses when entraining to external auditory beats. However, little research has examined training-related changes at the neural network level.

Historically, researchers have proposed that rhythm perception is directly influenced by attention, expectancy, and entrainment to specific frequencies. Beginning in 1976, Jones proposed that biological rhythms align with events in time for the purpose of generating expectancies (Jones, 1976). She expanded on this idea with Dynamic Attending Theory (DAT), suggesting that attention coordinates with external auditory stimuli to flexibly allow for the acceptance or rejection of expectancies (Jones & Boltz, 1989). The currently accepted theory of rhythm perception is the Resonance Theory, which incorporates aspects of the DAT and proposes that beat perception is subtended by the entrainment of neuronal populations oscillating at the same frequency as the beat itself (Large & Snyder, 2009).

In line with the Resonance Theory, recent research identified an EEG methodology that effectively tags beat entrainment phenomena in the brain using steady-state evoked potentials (SS-EPs) (Nozaradan, 2014; Nozaradan, Peretz, Missal, & Mouraux, 2011; Nozaradan, Peretz, & Mouraux, 2012). SS-EPs result when a stimulus is repeated at a regular rate, resulting in a strictly periodic change in voltage that is stable in both phase and amplitude over time (Regan, 1977). SS-EPs have been recorded in response to auditory (Picton, John, & Dimitrijevic, 2003), visual (Vialatte, Maurice, Dauwels, & Cichocki, 2010), and somatosensory stimuli (Colon, Nozaradan, Legrain, & Mouraux, 2012). In the case of auditory stimuli, when a periodic stimulus is played, it generates a regular change in amplitude in the electrical activity recorded on the scalp using EEG.

The current study seeks to assess whether musical training is associated with enhanced neuronal entrainment to an auditory beat. *Musical* individuals are expected to show higher amplitude SS-EPs at target beat frequencies as compared to *non-musical* individuals. It is possible that entrainment to an auditory beat is a widespread skill that is independent of training. Given this possibility, participants will also be asked to complete a meter-mental imagery task. For this task, participants will be asked to imagine a given meter (beat sub-frequency) over the original beat stimulus. *Musical* individuals are expected to mentally superimpose the given meter over the beat more easily, and therefore show enhanced (higher amplitude) entrainment at expected beat sub-frequencies. However, entrainment may be specific to beat-keeping rather than broad music training. Therefore, all participants will also complete a synchronization continuation task (SCT), which will provide a measure for beat-keeping ability. Overall, if *nonmusical* individuals perform the SCT with low accuracy, and show lower amplitude SS-EPs relative to *musical* individuals, this will provide evidence that beat tracking abilities are not independent of musical training, and that neuronal entrainment is in fact sensitive to experience.

Methods

Participants

Twenty-six participants: 16 *musical*, 14 *non-musical* (6 male, *M* = 19.81 years, *SD* = 2.09) took part in the study after providing written consent. Participants were either recruited from an introductory psychology course at Oberlin College and compensated with partial credit toward a course requirement, or from the general student body and compensated with $10. Participants were first asked to complete the self-report portion of the Goldsmith Musical Sophistication Index (GMSI) (Müllensiefen, Gingras, Musil, & Stewart, 2014; See Appendix A), online (Qualtrics, Provo, UT), for the purposes of prescreening and group assignment. Eligible participants were then assigned to a *Musical* or *Nonmusical* group based on their time spent receiving private music training or performing daily music practice. Individuals with 10 or more years of private training or daily practice on their primary instrument were assigned to the *Musical* group while those with less than three years were assigned to the *Nonmusical* group. The GMSI surveyed information related to training and measures of *musical sophistication,* which is defined by Mullensiefen et al. as, "a psychometric construct that can refer to musical skills, expertise, achievements, and related behaviors" (2014, p. 2). Higher levels of sophistication are associated with performing varied musical behaviors more frequently, and with greater ease and accuracy. Subscales of the Gold MSI include: (1) Active Engagement (2) Perceptual Abilities (3) Musical Training (4) Emotions and (5) Singing Abilities. No participants were diagnosed with or taking medications for ADD or ADHD at the time of testing.

Task 1: Synchronization-Continuation Task (SCT)

Stimuli. Stimuli were 2000Hz beats generated using Audacity 1.2.6 (http://audacity.sourceforge.net/) with five different inter-beat intervals (IBIs). Beat stimuli sounded similar to a high-pitched ticking metronome. IBIs were 450, 550, 650, 850, and 1000ms (corresponding to 60, 70, 92, 109, and 133 beats per minute, respectively). Stimuli were presented binaurally through over-ear headphones at a comfortable hearing level.

Procedure. The synchronization-continuation task (SCT) was modeled after that used previously in both human and primate research (Tierney & Kraus, 2013; Zarco, Merchant, & Prado, 2009). Participants were seated comfortably facing a CRT monitor, wearing headphones, and holding a response box with keys similar in feel to a typical computer keyboard. They were instructed to use a single finger and key consistently throughout the task, and to refrain from any physical beat-keeping (e.g. toe-tapping, head-nodding) apart from the key tapping required for the task.

Task instructions were presented on the monitor. Participants were told that they would hear a rhythmic tone stimulus in their headphones, and that their task was to tap the response key in synchrony with beat, and to continue tapping at the same rate after the tones disappeared until a “Stop!” prompt appeared on the monitor. Each trial of the task consisted of a 15s presentation of a tone beat stimulus followed by a period of silence. Five seconds before the stimulus went silent, the monitor displayed an instruction to “Keep going when the tones stop” which remained onscreen until the stimulus went silent. Presentation of the stop prompt was triggered when the participant performed the 25^{th} self-paced key tap, and thus varied as a function of the beat frequency of the stimulus (See Figure 1). A total of five trials were presented, using tone stimuli with beat frequencies of 60, 102, 92, 133, and 70 beats per minute—a pseudo random order used for all participants. After each trial, participants verbally indicated that they were ready to continue to the next trial. Accuracy was determined by calculating the absolute difference between the target inter-tap interval and the participant's actual inter-tap interval for each trial. The sum of these absolute differences was then used as an error index.

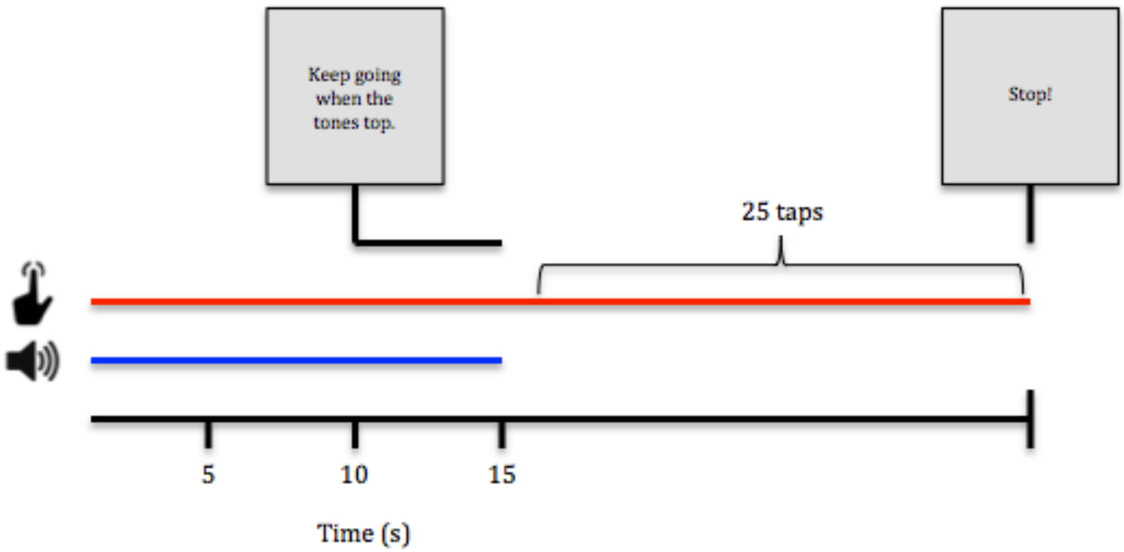

Figure 1. Schematic representation of Synchronization Continuation Task.

Task 2: Meter Mental Imagery Task

Stimuli. Stimuli consisted of a 333.3 Hz pure tone with a beat introduced by modulating the tone amplitude with a 2.4Hz periodicity (144 beats per minute). The sound was then amplitude modulated using an 11Hz sinusoidal function oscillating between 0.3 and 1. This stimuli mimics that used in a previous SS-EP study (Nozaradan et al., 2012). The stimulus was designed to have a pseudo-periodic structure[1] to (1) prevent involuntary binary meter induction bias (Pressing, 2002) and, (2) provide a better ecological representation of a musical beat. Each stimulus was 33 seconds in length.

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[1] The combination of the 11Hz and 2.4Hz frequencies together resulted in minor irregularities in both beat frequency and amplitude because 2.4Hz is not an integer ratio of 11Hz.

Procedure. The MMI task was begun following SCT completion. The task comprised three conditions—Attention Control, Binary, and Ternary—which were presented in that order for all participants. Each condition comprised a block of 10 trials. Condition-specific instructions were delivered verbally by the experimenter before each block and repeated in text on the monitor at the outset of the block. Participants were again asked to refrain from any form of physical beat-keeping, and instructed to focus during all trials on a central fixation cross on the monitor to prevent noise from eye movements or other motor activity from contaminating the EEG recording.

In the Attention Control condition, participants were asked to indicate with a key press whenever they detected an interruption in the 33s tone stimulus. Two additional trials were added to the original 10 trials in the Attention Control block (always at trials 2 and 9 within the block). These additional trials contained the interruption, a 500ms interval of silence about 10s before the end of the stimulus. The purpose of this interruption monitoring task was to ensure that participants listened attentively to the stimulus, given that there is evidence that attention modulates cortical activation in response to auditory stimuli (Chapin, Zanto, Jantzen, & Kelso, 2010). Data from the two interruption trials were excluded from analysis.

In the Binary and Ternary conditions, participants were asked to imagine a binary or ternary meter (or rather, beat-frequency sub-harmonic) over the beat stimulus. The binary meter beat frequency was, thus, 1.2Hz (2.4/2), and the ternary meter beat frequency was 0.8Hz (2.4/3) with an upper harmonic at 1.6Hz (0.8×2) (for schematic representation, See Figure 2). Prior to each meter condition, the experimenter verbally delivered the following instructions: “For this task you will be asked to imagine a [binary, ternary] meter over the stimulus, or an emphasis on every [other, third] beat. An example would be [**one** two **one** two, **one** two three **one** two three.]

Do you understand?" If the participant understood, the experimenter proceeded with the first trial of the block. If not, the experimenter provided further demonstration and explanation. Completion of all three blocks for the MMI task took participants an average of 12-15 minutes.

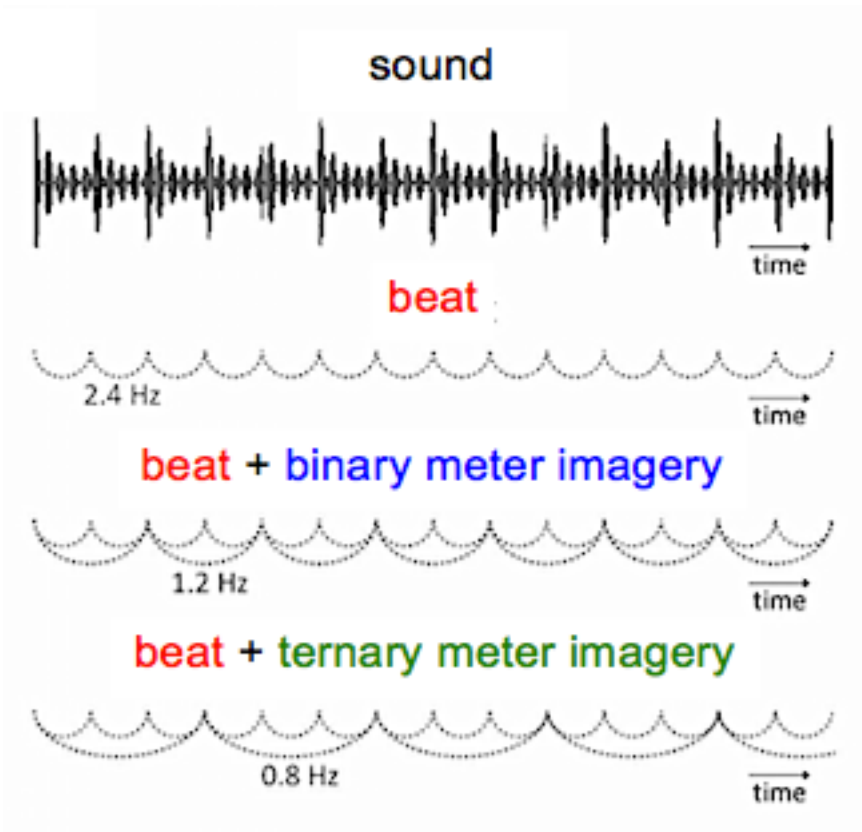

Figure 2. Schematic representation of MMI task.

EEG Recording & Preprocessing. EEG was recorded using tin electrodes in a spandex cap (ECI; Electro-Cap International, Inc., Eaton OH) from recording sites F3, Fz, F4, C3, Cz, C4 and Pz referenced to the tip of the nose. These recording sites were selected because previous research indicated that auditory SS-EPs were broadly localized to frontal and central areas (Nozaradan et al., 2011). Vertical eye movements and eye blinks were recorded from the Fp1 cap electrode vs. an electrode placed 2cm below the left eye. All electrodes were filled with ECI Electro-Gel, and impedances were kept below 10kΩ in all but a very few cases. Signals were filtered online (0.1Hz - 40Hz bandpass) and digitized at 512Hz using Contact Precision Instruments (CPI; London U.K.) hardware and software.

Preliminary processing was performed using the EEGLAB module (http://sccn.ucsd.edu) for MATLAB (The MathWorks; www.mathworks.com). EEG recordings were digitally filtered using a 0.1Hz high-pass Butterworth zero-phase filter to remove slow drifts in the signals. Epochs of 32s, beginning 1s and ending 33s after the onset of the beat stimulus, were extracted from each trial. The first second of each trial was omitted to eliminate transient signals resulting from stimulus onset. This resulted in 10 32s epochs per condition, per subject (30 total).

Subsequent processing was performed using Letswave software (Mouraux & Iannetti, 2008). Artifacts produced by eye blinks or movements were removed based on an independent component analysis (ICA) (Jung et al., 2000) using the runica algorithm (Bell & Sejnowski, 1995). EEG epochs were averaged for each subject and condition to enhance the signal-to-noise ratio. Averaged waveforms were then transformed from the time to the frequency domain using a Fast Fourier Transform (FFT) (Frigo & Johnson, 1998). Finally, signals were averaged across electrodes to avoid electrode selection bias.[2]

The amplitude of resulting SS-EPs was examined at four separate frequencies with a ±0.03Hz tolerance (0.06Hz bins), corresponding to beat and meter target frequencies: That is, 2.4Hz (bin range = 2.37-2.43Hz) for the auditory beat; 1.2Hz (bin range = 1.17-1.23Hz) for the binary meter beat sub-frequency; and 0.8Hz (bin range = 0.77-0.83Hz) and 1.6Hz (bin range = 1.57-1.64Hz) for the ternary meter beat sub-frequency.

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[2] Note: A previous study using this methodology used a dense 64-electrode array and averaged across electrodes (Nozaradan, Peretz, Missal, & Mouraux, 2011). Justification for the averaging used in the current study lies in the fact that (1) recording was limited to 8 electrodes and (2) auditory SS-EPs have broadly been localized to frontal and central areas (Nozaradan, Peretz, & Keller, 2016; Nozaradan et al., 2011; Nozaradan, Peretz, & Mouraux, 2012).

Background noise was removed from SS-EP amplitudes by subtracting the average amplitude taken from neighboring frequency bins (-0.15 to -0.09Hz and +0.09 to +0.15Hz relative to each target frequency) from the target amplitudes obtained in the bins described above. For example, for the 2.4Hz target frequency: the amplitudes from the neighboring bins (lower bin = 2.25-2.31Hz; higher bin = 2.49-2.55Hz) were averaged. This average was then subtracted from the amplitude obtained for the 2.4Hz target bin (2.37-2.43Hz, as specified above).

Results

Goldsmith Musical Sophistication Index (GMSI)

Independent samples *t*-tests were conducted to compare GMSI scores between *Musical* and *Nonmusical* individuals. *Musical* individuals showed significantly higher GMSI scores than *Nonmusical* individuals across subscales and significantly higher overall General Sophistication (See Table 1).

Table 1
Independent samples t-tests comparing GMSI scores between Nonmusical and Musical individuals.

	Nonmusical		*Musical*			
Subscale	*M*	*SD*	*M*	*SD*	*t*	Cohen's *d*
Active Engagement	29.25	7.95	35.14	7.80	2.08*	0.81
Perceptual Abilities	45.25	10.90	51.71	8.57	4.42**	1.75
Musical Training	13.70	4.88	13.35	6.24	3.31**	1.40
Emotions	32.08	5.66	35.35	5.06	2.44**	0.96
Singing Abilities	31.16	7.80	34.92	9.28	3.52**	1.38
General Sophistication	70.50	18.15	79.57	21.07	4.16**	1.74

*$p < 0.05$; **$p < 0.01$; $n = 24$

Task 1: Synchronization-Continuation Task (SCT)

Independent samples *t*-tests were conducted to compare SCT error rates between *Musical* and *Nonmusical* individuals. No significant differences in error rates were observed between *Musical* and *Nonmusical* individuals on average across individual BPM levels of the SCT. Despite non-significance, *Musical* individuals did show higher accuracy (lower error) on average at every BPM level of the SCT (See Table 2 & Figure 3).

Table 2

Independent samples t-tests comparing SCT Error rates between Musical and Nonmusical individuals.

	Nonmusical		*Musical*			
BPM	*M*	*SD*	*M*	*SD*	*t*	Cohen's *d*
60	1610.67	736.91	1436.71	882.81	0.54	0.21
70	1512.92	558.15	1086.93	564.8	1.93	0.76
92	1268.58	531.45	1177.14	648.16	0.39	0.16
109	1189.75	1325.99	778.93	389.21	1.11	0.48
133	656.75	290.89	651.86	422.4	0.03	0.01
Total	6238.67	2496.53	5131.57	2030.98	1.25	0.49

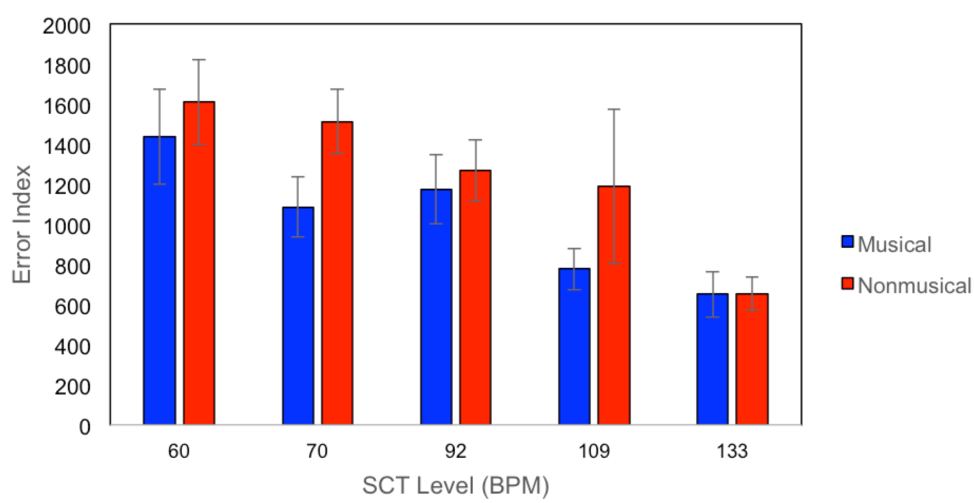

Figure 3. Mean SCT error rates for Musical and Nonmusical individuals. *Musical* individuals showed higher accuracy (lower error) across all levels of the SCT. Error bars represent one standard error.

Task 2: Meter Mental Imagery Task

Within each participant, condition, and target frequency, the amplitudes of SS-EPs were averaged across all scalp electrodes. To examine whether the auditory beat stimulus and meter-imagery induced significant steady-state responses, one-sample *t*-tests were used to determine whether noise-subtracted amplitudes at the four target frequencies were significantly different from zero within their corresponding conditions.[3] That is, an SS-EP at 2.4Hz was expected in all conditions, at 1.2Hz in the binary condition, and at both 0.8Hz and 1.6Hz in the ternary condition. This analysis relies on the fact that noise-subtracted amplitudes would tend toward zero in the absence of an SS-EP.

Results from one-sample *t*-tests show that the auditory beat stimulus elicited an increase in signal amplitude at the 2.4Hz frequency in all conditions (See Table 3). Significant SS-EPs were also observed at all meter-related frequencies in accordance with conditions. SS-EPs were observed at both 2.4Hz and 1.2Hz in the binary condition, and at 2.4Hz, 1.2Hz, and 0.8Hz in the ternary condition (See Figure 4). Most interestingly, these were the *only* significant *t*-tests observed across all frequencies in all conditions (See Figure 5).[4] In addition, the magnitude of entrainment at the auditory beat frequency with the Attention Control condition was lower than in either other condition. Although this difference is non-significant, it logically suggests that entrainment might be diminished when the auditory beat is not the focus of attention (because

[3] SS-EPs could also be examined statistically using paired-samples *t*-tests between conditions at each frequency. This analysis was also conducted and reflects the same SS-EPs as those reflected by one-sample *t*-tests with zero. However, four of the six significant SS-EPs do not remain significant with Bonferroni correction. (See Appendix A: Table A1).

[4] A Bonferroni correction for family-wise error would require that the *p*-value for statistical significance be 0.004. All SS-EP results remain significant with Bonferroni correction with the exception of the SS-EP at 0.8Hz in the ternary condition.

during the Attention Control condition, participants were focusing on finding an interruption rather than actively processing the beat itself).

Table 3

One-sample t-tests comparing SS-EP amplitudes within conditions.

	Target Frequency	*M*	*SD*	*t*	Cohen's *d*
Attention Control	2.4Hz	0.10	0.11	4.82***	1.15
	1.6Hz	0.00	0.09	-0.24	
	1.2Hz	-0.01	0.11	-0.34	
	0.8Hz	0.00	0.14	-0.12	
Binary	2.4Hz	0.15	0.12	6.51***	1.67
	1.6Hz	0.00	0.09	0.28	
	1.2Hz	0.11	0.17	3.35**	0.73
	0.8Hz	-0.02	0.15	-0.78	
Ternary	2.4Hz	0.15	0.15	5.09***	1.00
	1.6Hz	0.08	0.13	3.38**	0.66
	1.2Hz	0.01	0.11	0.60	
	0.8Hz	0.20	0.38	2.66*	0.52

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; $n = 25$

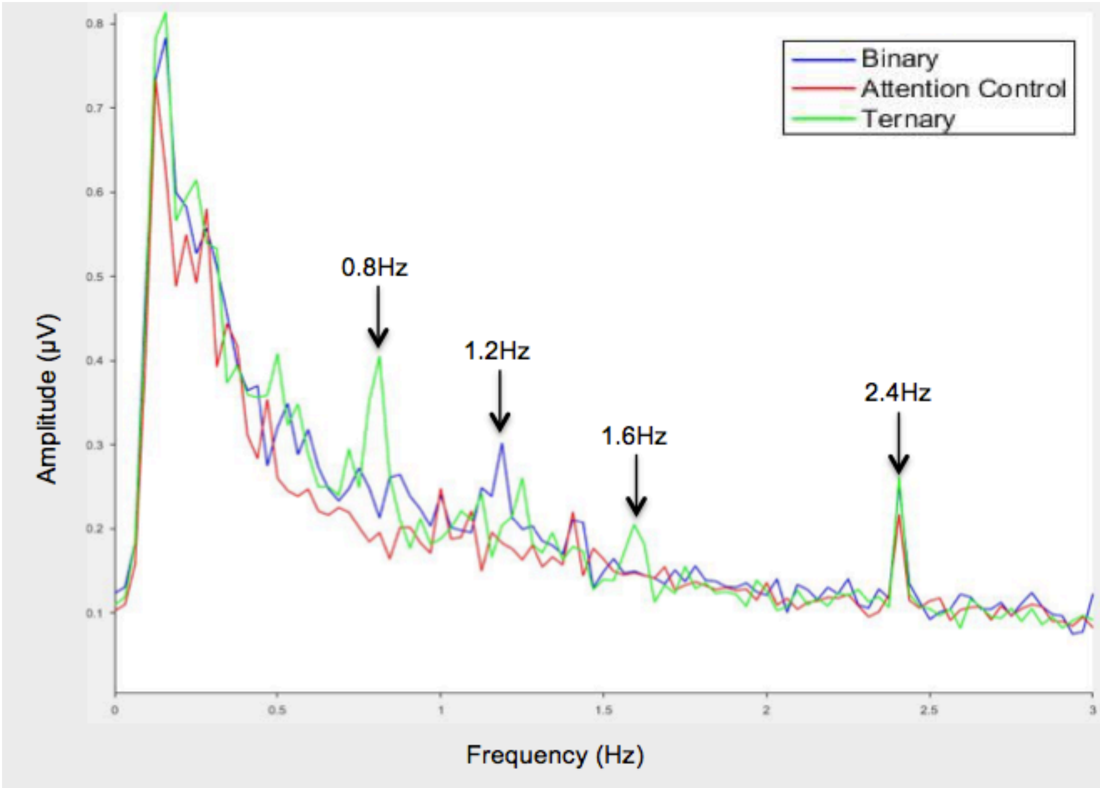

Figure 4. Grand average of EEG signal amplitudes by condition**.** SS-EPs were elicited exclusively in relation to the auditory beat stimulus and meter-mental imagery.

A one-way ANOVA was used to compare noise-subtracted amplitudes at all target frequencies between the *Musical* and *Nonmusical* groups. No significant differences in SS-EP magnitudes at target frequencies were observed between *Musical* and *Nonmusical* individuals (See Table 4).

Table 4
One-way ANOVA comparing noise-subtracted amplitudes at target frequencies between Musical and Nonmusical groups.

		Musical			*Nonmusical*				
		n	*M*	*SE*	*n*	*M*	*SE*	*F*	*p*
Control	2.4Hz	14	0.10	0.03	12	0.10	0.03	0.00	0.99
Binary	2.4Hz	14	0.15	0.03	12	0.15	0.04	0.02	0.89
	1.2Hz	14	0.10	0.04	12	0.13	0.05	0.18	0.68
Ternary	2.4Hz	14	0.13	0.03	12	0.18	0.05	0.73	0.40
	1.6Hz	14	0.10	0.04	12	0.06	0.04	0.55	0.47
	0.8Hz	14	0.26	0.13	12	0.10	0.06	1.03	0.32

A median split based on SCT error was conducted to redivide participants into two groups based on beat-keeping ability. A one-way ANOVA was used to compare noise-subtracted amplitudes at all target frequencies between Low SCT Error and High SCT Error individuals. No significant differences in SS-EP amplitudes at target frequencies were observed between Low SCT Error and High SCT Error groups (See Table 5).

Table 4

One-way ANOVA comparing noise-subtracted amplitudes at target frequencies between High SCT Error and Low SCT Error groups.

		Low Error			*High Error*				
		n	*M*	*SE*	*n*	*M*	*SE*	*F*	*p*
Control	2.4Hz	13	0.09	0.03	13	0.12	0.03	0.24	0.63
Binary	2.4Hz	13	0.16	0.03	13	0.14	0.04	0.15	0.70
	1.2Hz	13	0.15	0.05	13	0.07	0.05	1.50	0.23
Ternary	2.4Hz	13	0.13	0.03	13	0.17	0.05	0.39	0.54
	1.6Hz	13	0.12	0.04	13	0.05	0.03	1.67	0.21
	0.8Hz	13	0.32	0.14	13	0.07	0.04	3.13	0.09

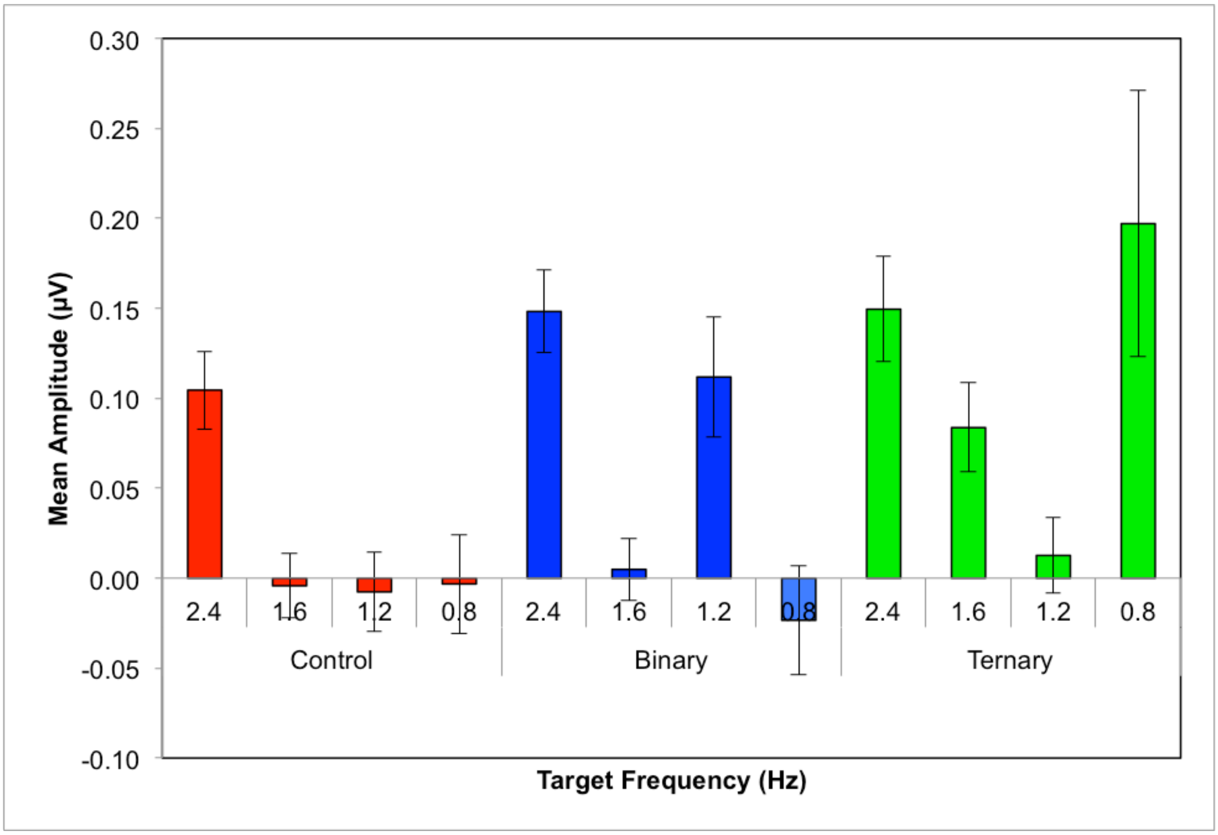

Figure 5. Mean amplitudes for all participants demonstrating SS-EPs at target frequencies. Amplitudes were significantly different from zero exclusively at target frequencies in accordance with condition. Error bars represent one standard error.

Discussion

An examination of neural entrainment to beat and meter resulted in a significant steady-state response at the auditory beat frequency, supporting the Resonance Theory that beat-perception is subtended by neuronal oscillations at beat frequencies (Large & Snyder, 2009). Significant steady-state responses were also specifically observed at imagined meter frequencies in accordance with conditions. No significant differences in the magnitude of entrainment were observed between *Musical* and *Nonmusical* individuals. Further, participants were redivided into groups based on beat-keeping ability and the magnitude of entrainment was compared between

High Error and Low Error groups. Again, no significant differences between groups were observed. Overall, results from the current study support the Resonance Theory, but suggest that entrainment may not be sensitive to music training and experience. Entrainment to beat and meter may therefore be innate and perhaps serve an evolutionary purpose.

Responses to the GMSI suggested that the arbitrary cutoffs set for group assignment effectively separated individuals based on both level of training and other levels of musical engagement and self-rated musical skills. Interestingly, the largest difference observed between groups was on the Perceptual Abilities subscale, suggesting a strong basis for a between-groups comparison of beat perception. Despite this strength, other aspects of group assignment may have prevented the detection of significant differences between groups.

Arbitrary cutoffs for *Musical* and *Nonmusical* groups did not control for all training-related variables. For the purposes of this study, primary instrument was uncontrolled, meaning that vocal musicians and instrumental musicians were included together in the *Musical* group. Previous studies suggest that instrumental music specifically results in differences in brain morphology and perceptual processing (Gaser & Schlaug, 2003; Halwani, Loui, Rüber, & Schlaug, 2011). Vocal musicians are often purposefully excluded from studies examining neuroplastic and perceptual effects because vocal music production requires comparatively less motor coordination than instrumental music production (e.g., bimanual activity). Further, vocal musicians may be less sensitive to auditory timing than other musicians due to a greater emphasis on emotionality and tempo flexibility in vocal music. Therefore, it is possible that the inclusion of vocal musicians inhibited the detection of a between groups difference.

In the SCT, non-significant differences between *Musical* and *Nonmusical* individuals could be the result of a lack of power or flawed stimulus design. The fact that *Musical* individuals showed higher accuracy at every BPM level suggests that differences between groups may have been significant with a larger sample size. Additionally, the BPM speeds chosen for this task may have been too easy for both groups. Naturally, participants overall were more accurate at faster speeds (and the smallest difference between groups was observed at 133BPM). Slower speeds require a higher level of attention and demand auditory working memory as well as internal beat subdivision for accurate performance. In fact, one *Musical* participant, prior to completing the SCT, asked if she could subdivide the beat in her head throughout the task. This ability or tendency to subdivide provides an explanation for why musicians performed with slightly higher accuracy overall. Past research has also shown that musicians tend to show a clear beat-keeping advantage over non-musicians at very slow speeds (Repp & Doggett, 2007). Future examinations of between groups beat-keeping effects therefore should use stimuli with longer inter-beat intervals.

In comparison to a previous study with similar methodology, results from this study robustly support the Resonance Theory. A 2011 study examining entrainment and meter-mental imagery used a dense 64-electrode array and merely eight participants, all with some level of musical experience (Nozaradan et al., 2011). The current study used only eight frontal and central electrodes and more than tripled the previous sample size. Given these differences, strong steady-state evoked potentials were still observed, even in a *Nonmusical* participant group. The results from this study therefore suggest that (1) a dense electrode array is not necessary to tag neuronal entrainment to beat (2) entrainment effects observed by Nozaradan and colleagues previously were not a fluke due to a small or convenient sample, and (3) untrained individuals show entrainment, possibly to the same extent as musicians.

Shortcomings in this study lie largely in the design of the MMI task. The length and attentional demands of the MMI task may have affected participants' ability to perform at an equal level across conditions. Conditions had to be presented and completed in the order of (1) Attention Control (2) Binary (3) Ternary to prevent priming effects of meter imagery from contaminating different conditions. If a participant were asked to complete the Binary condition first, they may have then experienced difficulty completing the Attention Control condition without automatically hearing or imagining a binary meter over the beat stimulus. The use of this design also meant that at the time of the Ternary condition, each participant had already been attending for approximately eight minutes to complete earlier conditions. Therefore, participants may have performed at a lower attentional level during this final condition. Additionally, the pseudo-periodic structure of the beat stimulus made the meter mental imagery in the Ternary condition more difficult than in the Binary condition. Both fatigue and subjective difficulty may therefore account for the fact that the smallest significance value was observed at 0.8Hz within the Ternary condition.

In summary, the current study successfully replicated a previous study of neuronal entrainment to beat and meter, supporting the Resonance Theory of beat-perception. No differences in entrainment were observed between groups based on level of music training or beat-keeping ability. However, detection of between groups differences may have been inhibited by a failure to control for training-related variables, and fatigue during the meter-mental imagery task. Very recent research has demonstrated that frequency-domain representations of auditory processing are highly dependent on the acoustic features of the auditory stimuli (e.g., duration, length of onset and offset in the sound envelope) and preprocessing steps applied to EEG signals in the time domain (Henry, Herrmann, & Grahn, 2017). Given this development, future research should first seek to replicate this study using stimuli within the same frequency range but with different tonal qualities to assess whether entrainment can still be observed and is represented in the same way using this methodology. More broadly, future research should examine whether neuronal entrainment has evolutionary significance in the form of coordinating group behaviors or detecting synchrony in the environment. With regard to music perception, further research should examine how neuronal entrainment might relate to pulse perception in real musical stimuli.

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Appendix A

The Goldsmiths Musical Sophistication Index, v1.0

Please circle the most appropriate category:	**1 Completely Disagree**	**2 Strongly Disagree**	**3 Disagree**	**4 Neither Agree nor Disagree**	**5 Agree**	**6 Strongly Agree**	**7 Completely Agree**
1. I spend a lot of my free time doing music-related activities.	1	2	3	4	5	6	7
2. I sometimes choose music that can trigger shivers down my spine.	1	2	3	4	5	6	7
3. I enjoy writing about music, for example on blogs and forums.	1	2	3	4	5	6	7
4. If somebody starts singing a song I don't know, I can usually join in.	1	2	3	4	5	6	7
5. I am able to judge whether someone is a good singer or not.	1	2	3	4	5	6	7
6. I usually know when I'm hearing a song for the first time.	1	2	3	4	5	6	7
7. I can sing or play music from memory.	1	2	3	4	5	6	7
8. I'm intrigued by musical styles I'm not familiar with and want to find out more.	1	2	3	4	5	6	7
9. Pieces of music rarely evoke emotions for me.	1	2	3	4	5	6	7
10. I am able to hit the right notes when I sing along with a recording.	1	2	3	4	5	6	7

Please circle the most appropriate category:	**1 Completely Disagree**	**2 Strongly Disagree**	**3 Disagree**	**4 Neither Agree nor Disagree**	**5 Agree**	**6 Strongly Agree**	**7 Completely Agree**
11. I find it difficult to spot mistakes in a performance of a song even if I know the tune.	1	2	3	4	5	6	7
12. I can compare and discuss differences between two performances or versions of the same piece of music.	1	2	3	4	5	6	7
13. I have trouble recognizing a familiar song when played in a different way or by a different performer.	1	2	3	4	5	6	7
14. I have never been complimented for my talents as a musical performer.	1	2	3	4	5	6	7
15. I often read or search the internet for things related to music.	1	2	3	4	5	6	7
16. I often pick certain music to motivate or excite me.	1	2	3	4	5	6	7
17. I am not able to sing in harmony when somebody is singing a familiar tune.	1	2	3	4	5	6	7
18. I can tell when people sing or play out of time with the beat.	1	2	3	4	5	6	7
19. I am able to identify what is special about a given musical piece.	1	2	3	4	5	6	7
20. I am able to talk about the emotions that a piece of music evokes for me.	1	2	3	4	5	6	7

Please circle the most appropriate category:	**1 Completely Disagree**	**2 Strongly Disagree**	**3 Disagree**	**4 Neither Agree nor Disagree**	**5 Agree**	**6 Strongly Agree**	**7 Completely Agree**
21. I don't spend much of my disposable income on music.	1	2	3	4	5	6	7
22. I can tell when people sing or play out of tune.	1	2	3	4	5	6	7
23. When I sing, I have no idea whether I'm in tune or not.	1	2	3	4	5	6	7
24. Music is kind of an addiction for me - I couldn't live without it.	1	2	3	4	5	6	7
25. I don't like singing in public because I'm afraid that I would sing wrong notes.	1	2	3	4	5	6	7
26. When I hear a piece of music I can usually identify its genre.	1	2	3	4	5	6	7
27. I would not consider myself a musician.	1	2	3	4	5	6	7
28. I keep track of new music that I come across (e.g. new artists or recordings).	1	2	3	4	5	6	7
29. After hearing a new song two or three times, I can usually sing it by myself.	1	2	3	4	5	6	7
30. I only need to hear a new tune once and I can sing it back hours later.	1	2	3	4	5	6	7
31. Music can evoke my memories of past people and places.	1	2	3	4	5	6	7

Please circle the most appropriate category:

32. I engaged in regular, daily practice of a musical instrument (including voice) for **0 / 1 / 2 / 3 / 4-5 / 6-9 / 10 or more** years.
33. At the peak of my interest, I practiced **0 / 0.5 / 1 / 1.5 / 2 / 3-4 / 5 or more** hours per day on my primary instrument.
34. I have attended **0 / 1 / 2 / 3 / 4-6 / 7-10 / 11 or more** live music events as an audience member in the past twelve months.
35. I have had formal training in music theory for **0 / 0.5 / 1 / 2 / 3 / 4-6 / 7 or more** years.
36. I have had **0 / 0.5 / 1 / 2 / 3-5 / 6-9 / 10 or more** years of formal training on a musical instrument (including voice) during my lifetime.
37. I can play **0 / 1 / 2 / 3 / 4 / 5 / 6 or more** musical instruments.
38. I listen attentively to music for 0-15 min / 15-30 min / 30-60 min / 60-90 min / 2 hrs / 2-3 hrs / 4 hrs or more per day.
39. The instrument I play best (including voice) is ___

Appendix B

Table A1

Paired-sample t-tests comparing SS-EP amplitudes within frequencies across conditions.

Target Frequency	Condition Pair	*t*	Cohen's *d*
2.4Hz	Control - Binary	-1.74	
	Binary - Ternary	-0.04	
	Control - Ternary	-1.33	
1.2Hz	Control - Binary	-3.33**	0.40
	Binary - Ternary	2.62*	0.06
	Control - Ternary	-0.67	
1.6Hz	Control - Binary	-0.48	
	Binary - Ternary	-3.34**	0.38
	Control -Ternary	-2.97**	0.39
0.8Hz	Control - Binary	0.47	
	Binary -Ternary	-2.81**	0.39
	Control -Ternary	-2.44*	0.38

*$p < 0.05$; **$p < 0.01$;[5] $n = 25$

[5] [5] A Bonferroni correction for family-wise error would require that the *p*-value for statistical significance be 0.004. Only the 1.6Hz Binary-Ternary (Ternary > Binary) and 1.2Hz Control-Binary (Binary>Control) comparisons remain significant with Bonferroni correction.