Beast Quake (Taylor’s Version): analysis of seismic signals recorded during two Taylor Swift concerts

Jacqueline Caplan-Auerbach (caplanj@wwu.edu)  
Western Washington University

Kyla Marczewski  
Pacific Northwest Seismic Network

Gavin Bullock  
Pacific Northwest Seismic Network

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Abstract

Taylor Swift concerts at Lumen Field, Seattle in July 2023 were detected seismically by an accelerometer located proximal to the stadium. The signals were nearly identical over the two nights, consistent with a repeated set list. Ground shaking is recorded in two primary frequency bands: broadband energy between 30-80 Hz, and harmonic low frequencies between 1-8 Hz. Discrete songs are clearly visible within the data, with narrow-band low frequency signals matching the published tempo of each song. Signals recorded in association with the sound check contain little to no low-frequency energy, suggesting that low frequency energy is associated with the synchronous motion of a dancing crowd. High frequency energy is observed only during songs that include a full band as opposed to solo acoustic performances by Taylor Swift. Video data provided by citizen scientists in attendance at the concerts allow us to correlate changes in seismic amplitude with observations of crowd motion. The synchronized motion of 72,000 fans created sustained energy that exceeded the iconic “Beast Quake” in 2011.

INTRODUCTION

On January 8, 2011, in the final minutes of an NFL Wild Card Game between the Seattle Seahawks and New Orleans Saints, Seahawk running back Marshawn Lynch broke through the Saints defense and scored a touchdown that resulted in a victory for the Seahawks. The crowd response was captured on a seismometer deployed proximal to the stadium (then called Qwest Field, now called Lumen Field). The seismic signal became known as the “Beast Quake”, in homage to Lynch's nickname “Beast Mode”, and is considered to be among the iconic moments in Seattle sports history (e.g. https://bleacherreport.com/articles/2587182-the-10-greatest-seattle-sports-moments).

That the Beast Quake was detected seismically is likely due to a combination of factors. Most importantly, station KDK (named for the Kingdome, which preceded the current stadium at that location) is located in close proximity to the stadium (~150 m from the stadium's center). The subsurface geology in the area is primarily artificial fill, sands and silt [1] which amplifies ground shaking at seismic frequencies. Some stadiums have been observed to be set into resonance by crowd behavior and to vibrate nearby buildings [2], which could also have contributed to the activity observed on the seismometer. The conditions at Lumen Field are therefore optimal for the recording of seismic waves associated with stadium events.

On July 22 and 23 2023, shaking from Lumen Field was once again detected on KDK, this time during two concerts by pop singer Taylor Swift. At station KDK, the maximum shaking during the concert exceeded that of the Beast Quake by a factor of ~2.5 (Figure 1). While the two events are substantially different, the potential for bragging rights between Swifties and Seahawks fans caused us to wonder if in fact fan activity was the cause of the seismic activity recorded during the concerts, or whether the ground motion was primarily caused by stadium resonance or the sound system.
In this study we first address this issue by showing that seismic energy detected on KDK correlates precisely with the two concerts. Crowd-sourced information about the concerts (Supplementary Table S1) allowed us to precisely link the waveform with unique songs, and to show that each song’s tempo is captured in the data. We present evidence that crowd motion, including dancing, jumping, and swaying, is the primary cause of low-frequency energy recorded seismically, while higher frequency energy relates directly to amplified music. We show that the strongest seismic signals correlate with fan behavior and conclude that indeed, fans at the Taylor Swift concert were responsible for the bulk of the ground shaking.

BACKGROUND

Anything that shakes the ground has the potential to be detected by seismometers. Observations of non-earthquake-related signals in seismic data include anthropogenic activity, animals, and surf, the primary cause of microseismic energy in seismic data [3]. Human activity is ubiquitous in urban data, with seismic signals generated by sources such as trains, cars, aircraft, and pumps [4,5].

Of interest are seismic signals recorded during large concerts: researchers have debated whether such signals are caused by crowd motion, stadium vibration, or the sound system itself. Erlingsson and Bodare (1995) modeled shaking in Nya Ullevi stadium in Sweden and suggest that crowds dancing during concerts set both the stadium and the underlying clays into resonance [2]. Green and Bowers (2008) attribute narrow-band signals recorded during two Electronic Dance Music (EDM) festivals to energy imparted into the ground by the loudspeakers [6]. In response to an inquiry about the study [7], Green and Bowers (2009) further explain that at EDM concerts, there is no traditional band and music is generated electronically, making highly consistent rhythms not only plausible, but likely [8].

The behavior of a crowd can generate two types of seismic noise: narrow-band shaking is caused by synchronous motion, while random energy generated a noisy, broadband signal [9]. These two behaviors were also described by Malone et al. (2015) for crowd noise at football games: they showed that the original Beast Quake, caused by unsynchronized crowd motion, resulted in strong broadband shaking, whereas the same crowd jumping in time to the chant of “defense now!”, was captured seismically as a narrow band signal with a rhythm identical to that of the chant [10].

Other studies focus on crowd dancing and swaying. Denton (2014) examined seismic signals generated by the audience at a Madness concert and concluded that the shaking was caused by the audience dancing in time to the music (with energy fading over time as might be expected of an aging crowd) [11]. A study of seismic signals recorded during a Bruce Springsteen concert in Barcelona showed that seismic spectra correlated with the beat of individual songs [4]. The authors of that study suggest that observed shaking was likely caused by synchronized crowd motion which may have triggered resonance in the stadium itself [4].

THE CONCERTS
Taylor Swift’s Eras Tour began in the summer of 2023. Attendance at the two Seattle concerts averaged over 70,000 each night, which at the time set the stadium’s attendance record. Fans were allowed to enter the stadium at 16:30 PDT, and the concert was slated to begin at 18:00 PDT. The concert began with two warm-up acts: Singer Gracie Adams played six songs, after which the band HAIM played an additional six songs. Taylor Swift then played for approximately 3.5 hours (Figure 2).

As implied by the tour title, the setlist was broken into segments, or “eras”, each relating to a musical period in the artist’s history. The character of the music changed during some eras, with some eras inspiring more dancing, and others having a slower beat and more subdued nature. Other forms of media and entertainment, including video, dancing, and changes in set design, accompanied each of the eras as well: the stage was backed by a large video screen on which images were shown both between and during songs. Sets and costumes were changed between Eras, and this process took up to several minutes, resulting in times in which sound production was greatly reduced.

The setlist for all concerts in the tour was largely identical, with both the order and choreography of songs scripted. Each concert, however, included two “surprise songs” which were different on the two nights at Lumen Field. This allowed us to compare time periods in which songs were repeated, and in which they were distinct between the two concerts.

STADIUM:

Lumen Field (previously known as CenturyLink Field, Qwest Stadium, and Seahawks Stadium), is oval-shaped, with its long axis oriented north-south. It is reputed to be among the loudest in the National Football League: during a 2013 football game fans broke a Guinness World Record for sound volume (https://www.foxnews.com/sports/seattle-seahawks-fans-set-stadium-noise-record-sunday). The stadium is located on the site of the former Kingdome, which was destroyed in a controlled demolition in 2000. Seismic analysis of that implosion, as well as drill holes in the region confirm that the stadium is underlain by thick alluvial sediments, including sands and muds [1,12]. The stadium’s maximum capacity is ~69k for events in which spectators are restricted to permanent seating but can be increased if attendees are permitted on the field. The crowd at the Taylor Swift concerts was estimated to be ~72k for each of the two nights.

CITIZEN SCIENCE:

Taylor Swift has a large number of dedicated fans who refer to themselves as “Swifties”. When a local Seattle news station reported that the concert had been recorded seismically, dozens of Swifties reached out to the lead author to offer their help. We created a Google Drive to which Swifties could upload concert videos as well as a spreadsheet on which they could log song start times and personal observations of the concerts. In total we received ~80 videos and dozens of comments and observations (Supplementary Table S1). Time stamps on videos and photos allowed us to confirm song and event timing, although most were precise only to the minute. The second author attended the second concert.
We received videos from attendees seated in a variety of locations in the stadium. Videos taken from high in the bleachers allowed us to observe crowd behavior across the field, and images from near the stage provided us with a view of the two bands (located on either side of the main stage). Some Swifties sent video of the substantial crowd located outside of the stadium, and we were able to use visible landmarks to identify their location.

SEISMIC DATA:

Seismograms were recorded during the concerts on station UW.KDK [13], located ~150 m due west of Lumen Field. KDK is a 3-component TITAN accelerometer, with flat response at frequencies < ~30 Hz. Data from station KDK were downloaded from the EarthScope Data Management Center and plotted in both the time and frequency domains. We selected a time period for analysis that spanned the expected time of the concert, including several hours prior to the venue opening to capture sound checks, and several hours after the concerts were expected to end.

Waveforms for the two concerts show a prolonged (hours) series of regular, high-amplitude pulses (Figure 2). These can broadly be separated into three segments: The first significant period of increased signal strength lasts 23 minutes, the second lasts 30 minutes, and the final sequence lasts ~3.5 hours. Each of these time periods is composed of shorter duration (3-6 minute) bursts, separated by short periods of quiescence (Figure 2, inset). We propose that the first two periods represent performances by the two opening acts, followed by the headline event. The duration of the shorter segments is consistent with the length of many pop songs. Further analysis confirming that these pulses represent discrete songs is described below.

Seismic signals recorded during the concerts may be separated into two frequency bands: low frequency signals are between 1-8 Hz, and high frequency signals are broadband between 30-80 Hz (Figure 3). Signals in the high frequency band include a variety of patterns: some have short pulses at narrow frequencies while others are more smoothly broadband (Figure 3). In contrast, the low frequencies are extremely narrow-band, and they exhibit harmonics at frequencies that vary between songs (Figures 3 and 4).

Two prolonged diffuse low frequency (-5-20 Hz) signals are visible in the seismic record, beginning at ~16:30 and ~23:30 (Figure 3). The venue was opened to the public at 16:30, and both seismic and video data indicate that the concert ended at ~23:30. We attribute these signals to fans arriving and departing. It is unclear whether the signal reflects vehicular or foot traffic.

Even when observed by eye it is apparent that data recorded over the two nights were highly similar (Figures 2 and 5). This is consistent with seismic energy generated during a repeated set list. Cross-correlation of five hours of data between the two nights reveals a maximum correlation when the data are offset by 26 minutes; subsequent conversations with concert attendees confirmed that the second night of the concert was delayed by an estimated half hour. This provides additional evidence that the seismic signals were generated during the two concerts.
To test that the waveforms represented a predictable set list played on both nights, we cross correlated signals from the shorter-duration pulses (interpreted as, and hereafter referred to as songs). Correlations of a song waveform over both nights were generally high (>0.75), with some correlations exceeding 0.95 (Figure 5a).

In each concert of the Era tour, Taylor Swift played two “surprise songs” (Figure 6). These differed each night of the concert, and thus represent an excellent opportunity to test concert correlations. Indeed, the surprise songs represent the only part of the concert that was not highly similar in time series. Because the two nights’ surprise songs differ in length, the last era of the concerts were also offset relative to one another. Unsurprisingly, the time period of the surprise songs shows the lowest correlations, with a maximum correlation coefficient of 0.03 (Figure 5b).

SONG IDENTIFICATION:

That the short-duration pulses were in fact different songs was confirmed by (a) signal duration, (b) song rhythm, and (c) sonification of the seismic signal. Concert setlists were published online (e.g. https://www.setlist.fm/setlist/taylor-swift/2023/lumen-field-seattle-wa-3ba4a0dc.html) and confirmed by videos submitted by attendees.

To first order, waveforms were correlated with songs by comparing their onset times with photos, comments, and videos sent in by attendees (Supplementary Table S1). Most videos shared by Swifties were time stamped only to the minute, which resulted in some uncertainty in the precise start times of the songs. In many cases, a clear increase in amplitude was visible in the time series near the approximated start time, but in other cases, the onset time was less certain. We were able to refine start times by viewing a complete video of the concert posted online. In many cases, we were able to compare song durations to published versions, but many songs were performed with extended intros or shortened for the concert.

Station KDK has a sample rate of 200 Hz and an anti-aliasing filter at 80 Hz. Thus the highest frequencies available in the seismic record would, at best, capture the bass portion of each song; much of the vocals, guitars, and piano music fall outside of the instrument’s detection capacity.

In nearly all cases, the seismic data have distinct, narrow-band low frequency (1-8 Hz) signals that exhibit harmonics (Figure 4). The spectral content of these signals is well below what would be expected of music, but precisely matches the rhythms of specific songs. Figure 4 shows examples in which the fundamental frequency or first harmonic of each song correlates with the published rhythm of the song. For example, Ready For It (Figure 4) has a published rhythm of 160 beats per minute (BPM), or 2.67 beats per second (Hz). The next three songs exhibit strong shaking at 1.6 Hz (96 BPM), 2.2 Hz (132 BPM), and 2.1 Hz (126 BPM) consistent with published values for Delicate (95 BPM), Don’t Blame Me (136 BPM) and Look What You Made Me Do (128 BPM).
All of the low frequency signals exhibit at least one harmonic. It is possible that part of the audience moved with a primary rhythm where others moved in double-time. Studies have shown that crowds jumping as a group are most likely to bounce at frequencies between 1-8-2.3 Hz [14]. Thus if a song has a tempo significantly outside of this range the audience may be most comfortable moving at twice or half of the song's primary rhythm.

It is most likely, however, that the harmonics result from a Dirac comb effect, in which regularly spaced pulses exhibit a comb-shaped spectrum. This effect has been invoked for a variety of natural signals that appear harmonic but are not associated with resonance, such as regularly-spaced earthquakes [15,16] and ocean swell [17]. Diaz et al. (2017) invoked the same process for harmonic signals recorded during a Bruce Springsteen concert [4]. It is unlikely that the crowd moved at frequencies much higher than 3 Hz, lending support to a model in which the harmonics are a consequence of the Fourier transform rather than audience motion.

DATA INTERPRETATION:

Concert attendees reported observations that allowed us to interpret seismic signals throughout the concert and correlate ground shaking with specific crowd and band behaviors. We begin by describing in detail the observations and seismic data observed at the beginning of the concert, and then present data for several other periods of the concert in which signals were significant.

At approximately 19:49 PDT, a cart in which Taylor Swift was hidden was brought on stage, generating an enthusiastic audience response (Figure 7). During this time, a recording of the song *Applause* by Lady Gaga was broadcast across the sound system. At 19:54:46, a large digital countdown clock was revealed on the main screen, marking the final two minutes and 23 seconds before the main event. The recorded music now switched to *You Don’t Own Me* as performed by Dusty Springfield. At 19:56:12, the countdown reached zero, and performers entered the stage area. Between the countdown clock and Taylor Swift’s first appearance at 19:58:15, several events inspired a loud crowd response: (a) the song *Miss Americana & the Heartbreak Prince* began at 19:56:38, (b) a door opened in the main screen, from which performers emerged (19:56:50), and (c) the first performer entered the stage (19:57:07).

Each of these events is visible in the seismic data (Figure 7). The moment of the cart’s arrival is poorly known: an attendee noted the time to the minute only. The song *Applause* is visible in the seismic data as a period of higher amplitude lasting 3:30, with sustained low frequencies of ~2.3 and ~4.6 Hz; these values are consistent with the song’s published duration and tempo of 140 BPM. *You Don’t Own Me* is a ballad with a more mellow cadence than that heard in *Applause*, and indeed the seismic data are lower in amplitude and low frequencies are only weakly visible.

Once the countdown clock reaches zero, video data show the crowd loudly cheering at events a-c above. This is a period in which the seismic data have no low frequency harmonics but contain brief (seconds) pulses of energy between 40-80 Hz. We propose that these reflect the screams and cheers of an enthusiastic crowd that is not moving in a synchronous manner. In contrast, once Taylor Swift begins
singing, a strong low-frequency signal initiates, as do high frequency broadband signals (Figure 7). As noted above, the low frequency signals are consistent with song rhythms, and the broadband signals likely reflect the lowest frequencies in the music.

Seismic amplitudes vary over the course of a given song, and crowd-sourced video and observational data confirm that periods with different amplitude correspond to different parts of the song, including verses, choruses and bridges. In Figure 8 we present low-frequency (1-8 Hz bandpassed) waveform data for the song Love Story. Text labels along the top denote changes from verse to chorus, or to instrumental sections of the song, with representative lyrics. Lower text labels describe observations, from video data, of crowd motion or singer/crowd energy levels. The data show a strong correlation between song structure, crowd activity, and amplitude of ground shaking. Video data show that during the chorus ("Romeo take/save me...") the audience begins to jump synchronously; these periods correspond to sharp increases in ground acceleration at KDK (Figure 8). On a qualitative scale, no significant change in the volume of the music was observed at this time. Further, seismic amplitudes remain low at the end of chorus 3, while video data show an audible increase in the energy and amplitude of the drums. This provides strong evidence that changes in seismic amplitude are associated with crowd behavior rather than the music or sound system.

We further examine the contribution of crowd behavior to low frequency seismic amplitudes by considering times when the crowd was absent. With this in mind, we evaluated seismic data recorded during periods interpreted as the concert's sound check. Assuming that we can identify songs by their seismic character, there were two sound checks prior to the July 22 concert: one at ~17:25 on July 21, and one at ~12:00 PDT on July 22 (Figure 2). A similar signal appears in the seismic record at 13:15 PDT on July 23, several hours before the second concert.

Both the presumed sound check data and the signals recorded during the concerts have strong signals between 30-80 Hz, in bursts lasting several minutes, consistent with the duration of songs (Figure 2). However, only the songs played during the actual concerts exhibit strong low frequencies (1-8 Hz). Although we were unable to find a set list for the sound checks, videos posted online suggest that some of the same songs were played in both sound check and concert. Low frequency signals were thus only recorded seismically when fans were in attendance. This provides additional support for our contention that these signals were generated by crowd activity.

The two "surprise songs" played at each concert were distinct from the rest of the setlist in that (a) they were different each night, and (b) the singer introduced them with the words “welcome to the acoustic section of the evening”. During most other songs the singer was accompanied by a band with guitars, bass, and drums, but the surprise songs were performed solo, on guitar or piano. The different character of these songs is evidenced in spectrograms: the surprise songs contain significant low-frequency energy, but the 30-80 Hz shaking is absent from the record (Figure 6). The absence of drums or other low-frequency instruments (e.g. bass guitar) does not correlate with a loss of low frequency signal, again confirming that audience motion is a sufficient seismic source. High frequency energy is lacking from
other periods of the concert, but video data confirm that these periods either involve Taylor Swift talking with the audience or playing solo (e.g. during the song *Champagne Problems*). These observations provide a window into the cause of the high frequency signals—these appear to be specifically associated with amplified music.

**BEAST QUAKE (TAYLOR’S VERSION):**

There is no means by which the 2011 Beast Quake and the 2023 Taylor Swift concerts can be directly compared. The Beast Quake represented less than a minute of ground shaking caused by an enthusiastic, but randomly moving crowd of ~66,000. In contrast, the Eras Tour concerts lasted ~3.5 hours and had significantly larger attendance. Further, thousands were on the field for the concert, where their energy could couple directly into the ground, whereas Seahawks fans were mostly confined to the stands. Most importantly the motion of the Swifties was in a uniform manner, as the crowd jumped and swayed to the beat of the music. This caused constructive interference and amplification of seismic energy at frequencies identical to the beat of the music. Studies of vibrations induced by crowd behavior show that the energy imparted into the ground by synchronized motion such as jumping or swaying is proportional to crowd size, whereas random motion scales with the square root of crowd size (Parkhouse and Ewins, 2006). The larger signals recorded during the concert are likely a function of the type of motion rather than the relative enthusiasm of the fan base.

If credit for the seismic signal is to be given to the fans, we must rule out the contribution to ground shaking from other sources. Studies of seismic data recorded in association with other stadium events have suggested shaking may reflect resonance of the stadium itself and/or the subsurface sediments [2]. Our data show no common frequencies observed throughout the concert, which might be expected of resonance, although we cannot rule out contributions from non-resonant stadium shaking induced by the crowd.

Green and Bowers (2008) state that seismic signals recorded during an electronic music festival were caused by the sound system coupling into the ground [6]. As with the Taylor Swift concert, they show that spectral frequencies are similar to the music tempo. While sound system coupling may be a contributor to the signals presented here, the lack of low frequency energy recorded during empty-stadium sound checks strongly suggests that the primary source of low-frequency energy was crowd motion.

**CONCLUSIONS**

Using seismic data as a window into crowd behavior can provide more than just bragging rights for enthusiastic fans. The relative contributions of sound system, stadium resonance, and crowd behavior has been debated in the literature, and the Taylor Swift concerts made it clear that at Lumen Field the seismic signal was dominated by crowd behavior. That the low and high frequency signals stem from different sources had not previously been described for concert-included seismicity. The constructive interference generated by synchronized crowd motion has the potential to shake the stadium at higher amplitude than stochastic crowd behavior, which could have implications for seismic engineering. But
perhaps the most important aspect of this study was the enthusiasm for science exhibited by Swifties as they volunteered their observations and videos. Concert seismicity proved to be an excellent opportunity to engage the general public in science and introduce them to a field of science with which they may not have previously been aware. Ultimately, Taylor Swift's version of the Beast Quake may have inspired a new generation both musically and scientifically.

Declarations

ACKNOWLEDGMENTS:

The authors express our deep gratitude to the communities of Swifties for generously sharing their observations and data.

AUTHOR CONTRIBUTIONS

J.C.-A. identified the concert signals, did the spectral analysis and cross-correlation, and performed the comparative analysis that allows us to distinguish the source of the low and high frequency signals. She wrote the majority of the paper's text and created the figures. K.M. attended the concert, determined song start times and durations, and contributed observations about portions of the event not captured on video. G.S.B. performed spectral analysis, contributing to song identification and timing. K.M. and G.S.B. reviewed and edited the paper's text.

DATA AVAILABILITY

The facilities of EarthScope Consortium were used for access to waveforms and related metadata used in this study. These services are funded through the Seismological Facility for the Advancement of Geoscience (SAGE) Award of the National Science Foundation under Cooperative Support Agreement EAR-1851048. Concert observations and timing are available in the Supplementary Information file provided online. Videos used to confirm timing are available from the corresponding author upon reasonable request.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing interests.

References


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**Figures**
Figure 1

Waveforms for the 2011 Beast Quake (top panel) and a portion of the two Taylor Swift concerts (bottom panel). The Beast Quake is shorter in duration and ~2.5x weaker in amplitude. Waveforms for the song “Shake It Off” are shown for the two nights, offset in time to show the high degree of similarity.
Figure 2

Waveforms for the two nights of the Taylor Swift concerts at Lumen Field. Grey fields show the two warm-up bands (Gracie Adams and HAIM), and the Taylor Swift performance. The Taylor Swift section was delayed on July 23 by ~26 minutes, as determined by cross-correlating the waveforms. Waveforms for two songs, each of which includes a 3-4 minute series of pulses, are shown in the inset.
Figure 3

Spectrogram for July 22, 2023; warmer colors are stronger amplitude. The spectral content may be broadly divided into high frequency broadband (30-80 Hz) signals, and low frequency (1-8 Hz) signals. The time window includes both the sound check and concert. Both periods include high frequency broadband signals, interpreted as the music and sound system, but the low frequency signals were recorded only during the concert when fans were in attendance. The venue opened to attendees at 16:30 and the concert ended at ~23:30. We attribute the diffuse low frequency signals at these times to the arrival and departure of the crowd.
Figure 4

Close-up of the low-frequency seismic signals. Frequencies recorded during each song are consistent with the published beats-per-minute (BPM) of each song, with overtones. Colors as in Figure 2.
Waveforms for the two concerts at Lumen Field on July 22 and 23, with data for July 23 offset by 26 minutes (panel c). The high level of similarity is consistent with a choreographed concert and repeated set list. The time offset between nights changes over the course of the concert as the singer talked with the crowd for different amounts of time between songs. Songs that were the same on both nights exhibit extremely high correlation (panel a), whereas the surprise songs are uncorrelated (panel b). The different durations of each night’s surprise songs contributes to the apparent lack of alignment after ~21:45.
Figure 6

Spectrogram for ~1 hour of the concert including songs from the standard setlist and the two “surprise songs”. The songs with high frequency signals were performed by the full band, and the surprise songs included only Taylor Swift on guitar (song 1) and piano (song 2). Colors as in Figure 2.
Figure 7

Spectrogram showing the first ~15 minutes of the concert. Labels denote times of significant on-stage events to which the crowd responded. The two songs denoted by arrows were recorded, not live performances. Colors as in Figure 2.
**Figure 8**

Waveform for the song “Love Story”. Vertical lines and text comments show distinct parts of the song (top) and moments in which video data show changes in crowd behavior (bottom). Moments of highest amplitude were shown to correlate with the highest energy crowd motion.

**Supplementary Files**

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- Supplementtable.pdf