# Born to dance but beat deaf: A new form of congenital amusia

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## ARTICLE INFO

## ABSTRACT

Humans move to the beat of music. Despite the ubiquity and early emergence of this response, some individuals report being unable to feel the beat in music. We report a sample of people without special training, all of whom were proficient at perceiving and producing the musical beat with the exception of one case ("Mathieu"). Motion capture and psychophysical tests revealed that people synchronized full-body motion to music and detected when a model dancer was not in time with the music. In contrast, Mathieu failed to period- and phase-lock his movement to the beat of most music pieces, and failed to detect most asynchronies of the model dancer. Mathieu's near-normal synchronization with a metronome suggests that the deficit concerns beat finding in the context of music. These results point to time as having a distinct neurobiological origin from pitch in music processing.

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Humans show a natural capacity to dance – that is, to entrain to an auditory pulse or "beat" in music and to spontaneously synchronize their movement. Beat perception begins to emerge early in human development (Hannon & Trehub, 2005; Phillips-Silver & Trainor, 2005; Winkler, Haden, Ladinig, Sziller, & Honing, 2009), as does the spontaneous expression of movement in response to music (Eerola, Luck, & Toiviainen, 2006; Kirschner & Tomasello, 2009; Zentner & Eerola, 2010). These primitives of dance behavior are even present in nonhuman vocal learning species (Patel, Iversen, Bregman, & Schulz, 2009a; Patel, Iversen, Bregman, & Schulz, 2009b; Schachner, Brady, Pepperberg, & Hauser, 2009), suggesting that the biological origins of beat perception and synchronization can inform us about the origins of human communication.

Indeed, dance behavior might result from evolutionary forces. Body (and vocal) synchronization may increase group cohesion (Merker, Madison, & Eckerdal, 2009; Wiltermuth & Heath, 2009). Dance ability may also play a role in sexual selection (Darwin, 1871), since dance attractiveness may cue phenotypic quality (Brown et al., 2005). Despite the likely biological origins of dance behavior, to date, no study has addressed the importance of dancing in time to music in adults. For instance, does the general population move in synchrony with the music? Are they able to judge how well a dancer is synchronized to the music?

We predict that a general ability to dance in synchrony with music, and to judge the synchronization of others, should be widespread in the adult population. Nevertheless, cultural pressures about music and dance performance can engender fears of having "no rhythm" or "two left feet". Anecdotal reports abound of individuals who fail to detect the beat and to move in time to music; these alleged poor dancers would not be considered "tone deaf", but rather, "beat deaf". To our knowledge, such cases have never been documented. The discovery and detailed study of beat deafness represents a unique opportunity to kindle research on the neurobiological origins of beat perception and synchronization.

The study of congenital amusia, or tone deafness, has provided a model with which to understand how the normal development of the musical system can be disrupted in a minority of individuals (e.g., Peretz et al., 2002). Congenital amusia is akin to other developmental disorders, such as congenital prosopagnosia, dyscalculia, and dysphasia, and is thought to result from a musical pitch disorder (Peretz, 2008). Neuro-functional investigations of this disorder have highlighted the crucial role of the network connecting the

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right auditory cortex to the right inferior frontal gyrus (e.g., Hyde et al., 2007; Hyde, Zatorre, & Peretz, 2011; Loui, Alsop, & Schlaug, 2009). In contrast, the understanding of the neural underpinnings of rhythm and beat perception is in its infancy. Thus, the neuropsychological study of beat deafness, if it exists, represents a rare chance to contribute to the understanding of the neurobiological origins of dance behavior.

To this aim, we studied full-body dance movements (bouncing up and down by bending the knees) to music, and perception of similar movements. Full-body motion was preferred over tapping because it can provide a measure of rhythmic entrainment by integrating auditory, vestibular and proprioceptive sensory information across a wide age range, without requiring fine motor coordination (Phillips-Silver & Trainor, 2008; Trainor, Gao, Lei, Lehtovaara, & Harris, 2009). An asynchrony detection task was used in order to assess perception of dance movement in the absence of motor demands on the subject. We investigated a group of occasional dancers between the ages of 18 and 50 with university education and no professional training in either music or dance, and compared their synchronization responses to the performance of Mathieu, who declared that he had difficulty keeping time in music and dance despite sustained practice and private tutoring in both.

## 1. Case history

Mathieu was discovered through a recruitment of subjects who felt they could not keep the beat in music, such as in clapping in time at a concert or dancing in a club. Mathieu was the only clear-cut case among volunteers who reported these problems. Despite a lifelong love of music and dancing, and musical training including lessons over several years in various instruments, voice, dance and choreography, Mathieu complained that he was unable to find the beat in music. Participation in music and dance activities, while pleasurable, had been difficult for him.

Mathieu is a 23-year-old male, completing a Master's degree in communication. He has a normal audiometry and no psychiatric or neurological history. Examination of Mathieu's brain with magnetic resonance imaging has not been done yet but we do not expect it to reveal any remarkable anatomical abnormalities. His scores on the Matrix (75th percentile), Picture Completion (63rd percentile), and Similarity (84th percentile) tests of the Wechsler Adult Intelligence Scale III (WAIS-III, Wechsler, 1997) are within the normal range for his age group.

Mathieu also scored in the normal range on all but one of the six tests of the Montreal Battery of Evaluation of Amusia (MBEA; Peretz, Champod, & Hyde, 2003). He performed in the low range on the meter test selectively (with 66.7% correct; range of scores for a group of 10 university students: 67–100%). The task in the meter test is to determine for short, harmonized piano pieces that vary in tempo whether the underlying pattern of strong and weak beats corresponds to a march or a waltz. In the march, the strong beat occurs on every second beat ("ONE, two, ONE, two. . ."), and in the waltz, the strong beat occurs on every third beat ("ONE, two, three; ONE, two, three. . ."). Mathieu's failure on this test indicated a possible deficit in meter perception for music, which may be due to an inability to detect an underlying beat. In contrast, Mathieu exhibited normal discrimination for the same rhythm patterns as presented in a discrimination test in which he determined whether two successive melodies were the same or different (90% correct; range of 10 students' scores: 67–99%). When the melodies differed, it was by interchanging the duration of two successive tones. As the pitch and beat period were held constant, the detection of a change could rely on temporal grouping structure exclusively. Fur-

thermore, Mathieu obtained normal scores on all the other MBEA tests that involved pitch manipulation, with 83%, 80%, and 80% on the scale, contour and interval tests, respectively (normal range: 67–100%; see Peretz et al., 2003, for further details on these tests).

Mathieu's selective meter perception difficulty in the musical standardized tests was consistent with his report of having trouble keeping the beat with music. This finding led us to test him in two novel situations requiring synchronization or perception of full-body motion with the musical beat.

## 2. Synchronization tasks

We studied full-body motion in time with a popular Merengue song, compared to motion with a metronome. The synchronization responses of Mathieu were compared to the performance of a group of adults with variable ages and musical backgrounds. In follow-up experiments, we tested whether the deficit was related to the type of body movement performed, the type of music presented, or the tempo. Synchronization is typically considered to be accurate when movements match with the musical beat in both tempo (rate) and phase. These two criteria are conceptually distinct. Tempo matching means that the period of movements matches the musical beat period, without regard to relative phase between movements and beats. Phase matching means that rhythmic movements occur near the onset times of musical beats.

### 2.1. Bouncing to merengue and metronome

In addition to Mathieu, 33 unselected normal adults (hereby referred to as "controls") participated in this study. Controls included 25 females with a mean age of 25 (range: 19–58) and a university education. The majority had a few years of musical practice (mean: 8 years) while seven had none. Informed consent was obtained from all participants, and the study was approved by the Research Ethics Board of the University of Montreal.

The control group and Mathieu were invited individually to bounce spontaneously to a popular Merengue song (Suavemente by Elvis Crespo). Participants were instructed to bounce to the "regular, strong beat" of the music, keeping their movement consistent throughout the trial, and the experimenter demonstrated how the bending of the knees could correspond to the strong beat. The Merengue song was chosen for its regular, binary beat structure. The song duration was 64 beats, and was played at two tempi (124 bpm for beats per minute, or a period of 480 ms per quarter-note beat, and 116 bpm, or a period of 520 ms per quarter-note beat). Tempi and beats were derived by the algorithm of the MIR Toolbox (Lartillot & Toiviainen, 2007). As control conditions, an auditory metronome and the visually bouncing experimenter were presented at approximately the same tempi. Thus, six stimuli were presented in the following order: Merengue 124 bpm (2.08 Hz), Merengue 116 bpm (1.93 Hz), metronome 124 bpm (2.08 Hz), metronome 112 bpm (1.86 Hz), visual model 124 bpm (2.08 Hz), visual model 112 bpm (1.86 Hz). The duration of testing was approximately 30 min. Subjects were tested in a large sound attenuated studio, with the experimenter present but facing away from the subject (except in the visual model condition). The participants listened to the auditory stimuli presented in free-field from Genelec speakers (at approximately 70 dB depending on the comfort level of each subject), except in the case of the visual model, in which they wore noise cancellation headphones while the experimenter listened to the auditory metronome over headphones and led the subjects' bouncing. In all conditions, the subject wore the motion capture device described below. In the visual bouncing condition, the experimenter also
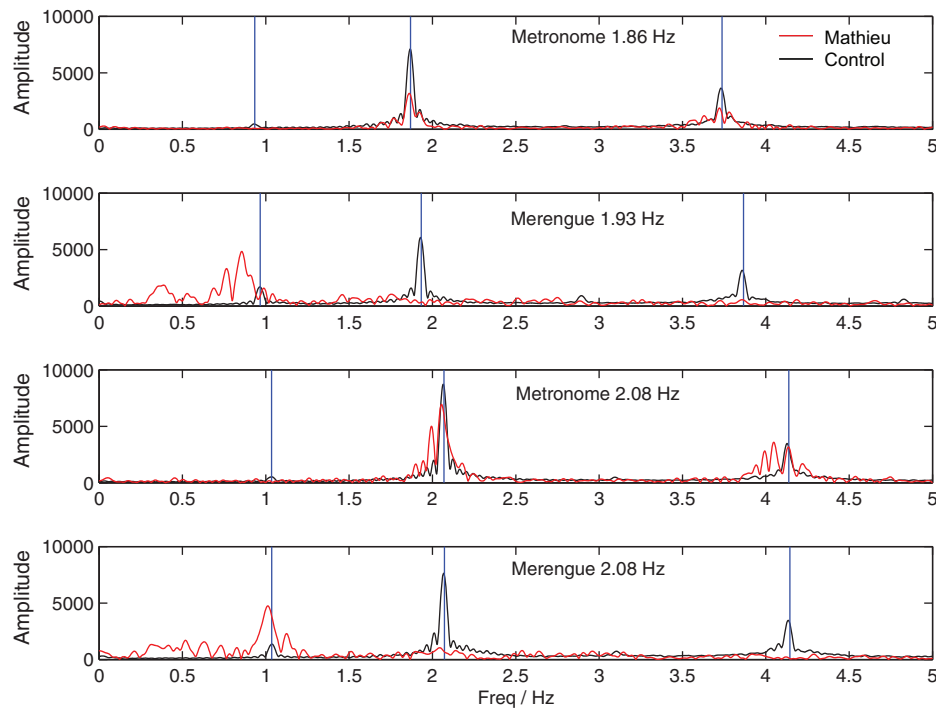
**Fig. 1.** Bouncing with Merengue and metronome, performance of Mathieu and 33 normal controls: power spectra for bouncing performance by Mathieu (red) and controls (black). Vertical lines (blue) indicate stimulus components at half-beat, beat, and twice-beat frequencies. The middle (thickened) blue line shows the stimulus beat frequency at the quarter-note level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wore a motion capture device so that her body movement could be measured.

Body motion was captured with the accelerometer contained in the remote control of the Nintendo wii, which was strapped to the trunk of the subject's body. This device measured acceleration of bouncing with a temporal resolution of 100 frames per second (10 ms), from which the beat-by-beat period of the vertical movement was computed.

We calculated the number of bounces for each subject and stimulus by counting the number of zero-crossings of the downward vertical acceleration in each data record (Toiviainen, Luck, & Thompson, 2010). This resulted in 68 bounces per control subject, on average, for the 64 beats of the Merengue stimulus and for the 64 beats of the metronome. Mathieu bounced on average 64 times to the metronome and 45 times to the Merengue. Video animations of Mathieu and a control subject bouncing to the song and the metronome are available at: www.brams.umontreal.ca/short/beatdeaf/.

We submitted the continuous movement data to a Fourier analysis, which enabled us to measure the overall proportion of power at the beat level and at related frequencies in the auditory stimuli. Frequencies between 0 and 5 Hz were taken into consideration. For each participant on each stimulus, the total proportion of power at 0.5, 1 and 2 times the beat frequency was calculated (Fig. 1). Control subjects showed significant power at the one-beat level for both the metronome and Merengue music. When bouncing to the metronome, Mathieu showed peaks at the one-beat and half-beat levels, and his proportion of synchronized power was at the level of the controls. When bouncing to the Merengue, Mathieu's movement showed some energy at the 1 Hz region (close to the two-beat period) and very little energy at the stimulus frequency (below 2 SD of the controls' mean).

We then measured to what extent the movements were phase-locked to the auditory beat. To this end, the vertical component of acceleration was first bandpass filtered using a (zero-phase)

FFT filter with a Gaussian frequency response having a center frequency equal to the beat frequency of each respective stimulus and a bandwidth of 20% of the respective center frequency. Subsequently, Hilbert transform was used to estimate the instantaneous phase of the filtered signal. The instantaneous phase was sampled at the time points corresponding to every beat in the stimulus within the interval of 5 to 30 s from the beginning of the stimulus. For Mathieu's bouncing to the Merengue stimuli, the bandpass filter was set to have a center frequency of half of the respective stimulus beat frequency, and the instantaneous phase was sampled at every other beat. The resulting discrete phase values were subjected to Rayleigh's $r$ test. While all control participants showed significant phase-locking for all stimuli (for the participant showing the weakest phase-locking for each stimulus, $r(47) = .93$, $z(47) = 19.83$; $r(52) > .93$, $z(52) = 22.87$; $r(49) = .931$, $z(49) = 12.31$; and $r(52) = .256$, $z(52) = 3.92$, for the metronome 1.86 Hz, 2.08 Hz, and Merengue 1.93 Hz, 2.08 Hz, respectively, all $p < .05$), Mathieu's bounces were only phase-locked to the metronome, with $r(24) = .789$, $z(24) = 32.78$, $p < .0001$ for the 1.86 Hz stimulus, and $r(26) = .577$, $z(26) = 19.36$, $p < .0001$, for the 2.08 Hz stimulus. For the Merengue stimuli where Mathieu shows more energy at the two-beat level (1 Hz region), the results did not reach significance ($r(25) = .202$, $z(25) = 2.14$, $p = .12$, for the 1.93 Hz stimulus, and $r(26) = .205$, $z(26) = 2.68$, $p = .07$, for the 2.08 Hz stimulus). Thus, Mathieu's bouncing was phase-locked to the metronome but not to the Merengue.

In addition, Mathieu was able to synchronize when following the experimenter visually (in tandem) with the music. We asked Mathieu to dance in tandem with the experimenter while they both listened to the song. Mathieu succeeded on this trial, with his bounces phase-locked to the musical beat ($r(52) = .536$, $z(52) = 16.76$, $p < .0001$). However, Mathieu failed immediately after, when tested alone again ($r(52) = .034$, $z(52) = .11$, $p = .89$). Thus, Mathieu can use visual imitation but cannot retain the beat in the absence of a visual stimulus.
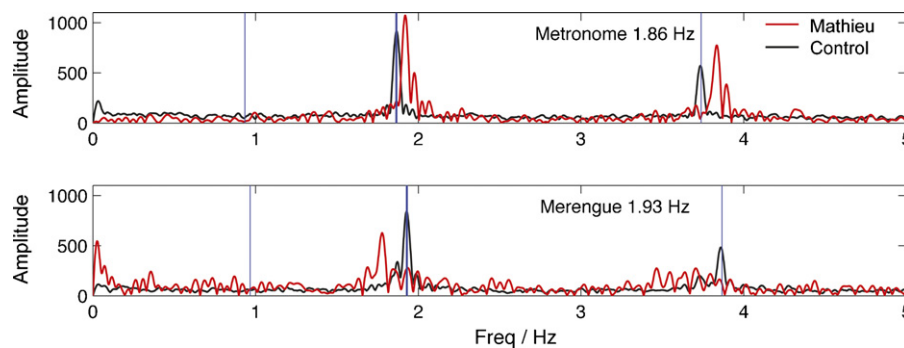
**Fig. 2.** Tapping with Merengue and metronome, performance of Mathieu and 10 normal controls: power spectra for tapping performance by Mathieu (red) and controls (black). Vertical lines (blue) indicate stimulus components at half-beat, beat, and twice-beat frequencies. The middle (thickened) blue line shows the stimulus beat frequency at the quarter-note level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 2.2. Bouncing in silence

Mathieu's spontaneous bouncing reveals that he can maintain regularity without reference to an external pulse. He showed a consistent tempo on two occasions with a period of 570 ms and 560 ms (SD of inter-beat interval = 15.0), respectively. These spontaneous tempi are slightly slower than beat periods in the Merengue (with periods of 480 ms and 530 ms), and are close to the 2 Hz frequency peak of spontaneous tempi in normal adults (i.e., 500 ms; MacDougall & Moore, 2005; Styns, van Noorden, Moelants, & Leman, 2007). These spontaneous bouncing tempi (105–107 bpm) confirm that the experimental tempi were appropriate for Mathieu.

### 2.3. Tapping to merengue and metronome

In order to ensure that Mathieu's synchronization difficulty was not limited to the bouncing movement, we asked him to tap in time to the auditory stimuli instead of bouncing. Mathieu and a subset of 10 control subjects tapped to the Merengue and the metronome using the wii, during 15 s. The subjects held the wii in one hand, and tapped a finger on the top of the vertically oriented remote: what was captured was the movement of the wii caused

by the impact of the finger tap. The location of each tap was determined to be the maximum of the acceleration during the impact. As shown in Fig. 2, controls' taps show peaks at both the beat and twice the beat level in both the metronome and Merengue condition. However, note that the energy at twice the beat frequency is probably due to the vibration of the wii in the holding hand. In general, tapping data were harder to analyze than bouncing data because of slight changes in orientation or stability of the wii during recordings.

Nevertheless, we applied the same phase-locking analysis procedure as the one used for the bouncing data. The band-pass filter applied to the acceleration data prior to the Hilbert analysis was similar to the one used previously, with a center frequency equal to the beat frequency of the respective stimulus. For both the metronome and Merengue stimuli, each control participant showed significant phase-locking (for the participant showing the weakest phase-locking for each stimulus, $r(19) = .335$, $z(19) = 14.32$, $p < .001$ and $r(20) = .164$, $z(20) = 3.16$, $p < .05$, respectively) while Mathieu's taps did not ($r(19) = .133$, $z(19) = 2.15$, $p = .12$, for the metronome, and $r(20) = .053$, $z(20) = 0.41$, $p = .66$ for the Merengue). Thus, Mathieu failed to tap in time as compared to controls.
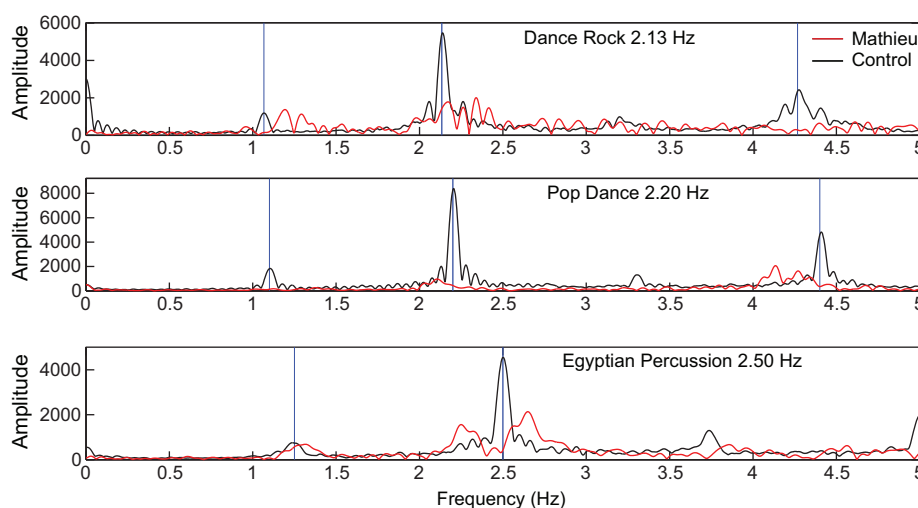


**Fig. 3.** Bouncing to a variety of music, performance of Mathieu and 10 normal controls in synchronization with eight music pieces of different genres and tempi (see Appendix): power spectra for bouncing performance by Mathieu (red) and controls (black) with three different musical stimuli. Vertical lines (blue) indicate stimulus components at half-beat, beat, and twice-beat frequencies. The middle (thickened) blue line shows the stimulus beat frequency at the quarter-note level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
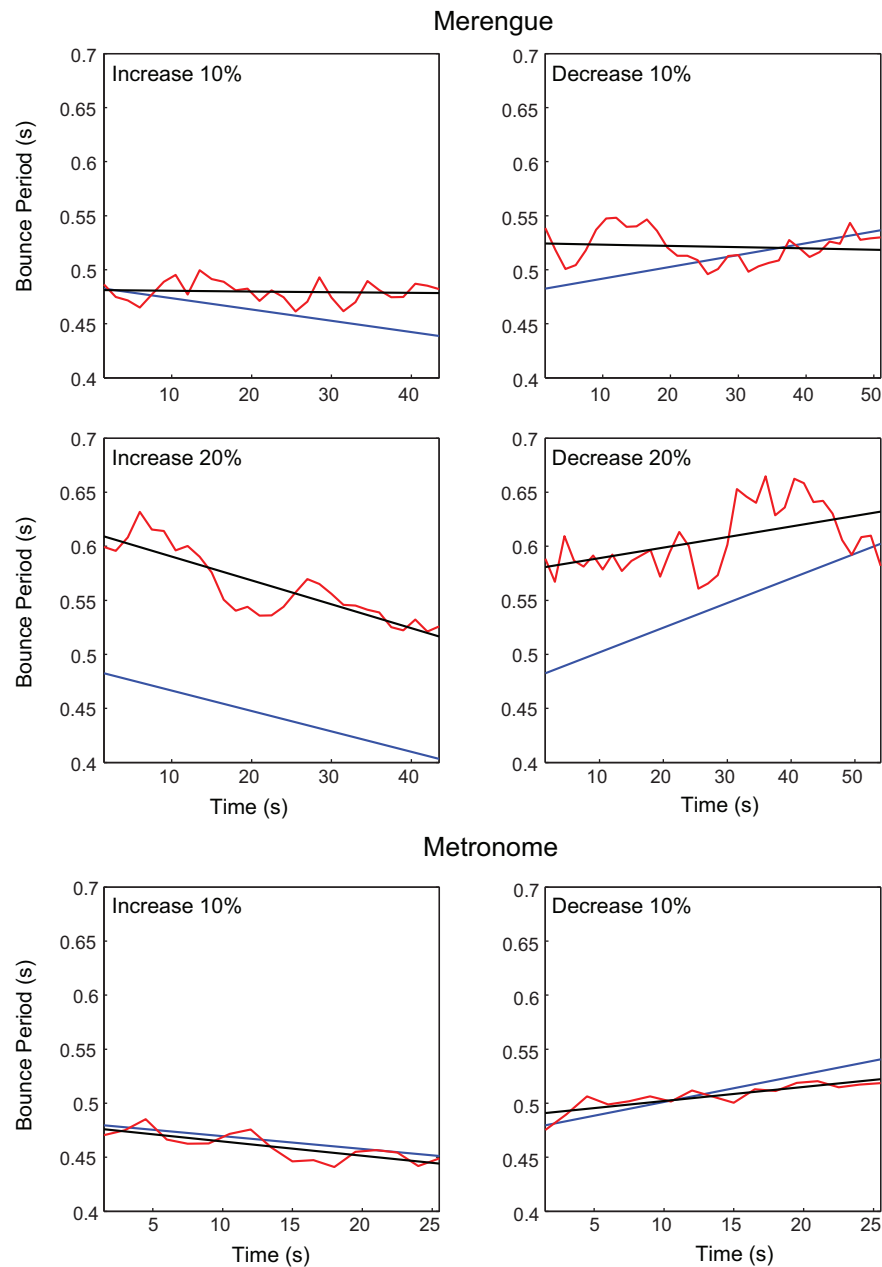
**Fig. 4.** Tempo adaptation. Mathieu's adaptation of bounce periods to gradual changes of stimulus tempo in Merengue (10 and 20%) and in Metronome (10%) condition. The blue line represents the stimulus period; the red line represents Mathieu's bounce periods, and the black line is the corresponding linear regression. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 2.4. Bouncing to various types of music

To assess the generalization of the synchronization deficit to other musical styles and tempi, we tested Mathieu and a subset of 10 controls on eight musical excerpts taken from a variety of musical genres. These stimuli included dance rock, pop dance, Egyptian percussion, swing, techno dance, dance lounge and world music, with tempi ranging from 78 to 160 bpm (see Appendix). All control participants showed significant phase-locking to the musical beat of each music, except for one control who failed to synchronize to the piece *Too darn hot*. Here again Mathieu showed a deficit with most music (Fig. 3). Thus, Mathieu's synchronization impairment is not restricted to Merengue but generalizes to other music genres and tempi. However, Mathieu was able to synchronize with

three musical excerpts, which are also the most popular ones (see Appendix).

### 2.5. Bouncing to a gradual change of tempo

Mathieu shows some coarse sensitivity to the direction of tempo change. Support for this was provided by Mathieu's performance on four versions of the Merengue stimulus in which the tempo was either increased or decreased gradually to reach a final tempo either 10% or 20% higher or lower than the starting tempo. As can be seen in Fig. 4, Mathieu failed to adapt to the tempo change when the acceleration or deceleration reached a 10% tempo change [the linear term of the regression was $-0.000096$, (95%CI: $-0.0005$, $0.0004$), and $-0.0002$ (95%CI: $-0.0007$, $0.0004$) for the increase

and decrease, respectively]. In contrast, Mathieu was able to adjust his movement tempo in the correct direction in response to a 20% tempo change in the Merengue [with a linear term of the regression of −0.0033 (95%CI: −0.0041, −0.0025), and 0.0015 (95%CI: 0.0006, 0.002), for the increase and decrease, respectively]. Note that normal subjects can track tempo changes within 10% (Drake, Penel, & Bigand, 2000; Large, Fink, & Kelso, 2002).

In contrast, Mathieu adjusted his movement in the appropriate direction for the tempo changes applied to the metronome stimuli (Fig. 4). As Mathieu was predicted to adjust his movement tempo to the metronome, we tested changes of 10% only. Mathieu was successful in adapting to the tempo changes [with −0.002 (95%CI: −0.0029, −0.0011), and 0.0046 (95%CI: 0.0036, 0.0056), for a tempo increase and decrease, respectively][1].

## 3. Detection task

Mathieu's disorder may arise from a perceptual or motor disorder, or from a failure of sensorimotor integration. In order to assess his beat perception abilities without associated action, we created a task that required no movement while similar in perceptual demands to the synchronization task. In this detection task, subjects watched 5 s video clips of the experimenter moving to the Merengue or to the metronome; viewers judged whether the dancer was "in time" with the auditory soundtrack. The audio–visual stimuli were either synchronous (e.g., the dancer was in time with the music) or asynchronous, as described below.

The audiovisual stimuli were created from two video recordings of the experimenter moving either to Merengue or to the metronome (at 124 bpm). Motion capture analyses confirmed that the movements of the dancer during the video recordings were equally synchronized with the Merengue music and the metronome. In each soundtrack condition, a 5 s clip was selected and manipulated for its tempo. Asynchronous clips had audio and video tracks unlinked and manipulated separately, so that either the audio or the video was compressed or expanded in tempo (by 80–120% corresponding to 104–156 bpm) with respect to the other track. Auditory pitch was held constant so as not to provide a cue to tempo. The asynchronies were created to be 5%, 10% and 20% of the original tempo. As the asynchronies between bounce onsets and auditory beats varied continuously in any clip, their values were between 24 ms (for a change of 5% of the 384 ms period at 156 bpm) and 288 ms (corresponding to half the longest period of 576 ms at 104 bpm). In order to maximize the perception of asynchrony, the audio–visual channels were coupled so that the asynchrony was maximal at the beginning of the clip. This procedure was applied to 12 asynchronous stimuli for both the Merengue and metronome conditions.

Eight of the twelve synchronous (unedited) clips were modified to range in tempo from 80% to 120% of the original tempo. The audio and video tracks remained linked here. Thus, the synchronous clips contained tempo change and auditory/visual distortion just as in the asynchronous stimuli, so that the only reliable cue to asynchrony detection was the disparity in tempo between the audio and visual tracks. Sample stimuli can be viewed at: www.brams.umontreal.ca/short/beatdeaf/. The 24 clips (12 synchronous, 12 asynchronous) were repeated once and presented in two blocks, with one Merengue block followed by one metronome block. The duration of the task was approximately 45 min.

Mathieu and 28 participants (8 male; mean age of 26; range: 19–53; mean of 6.6 years of musical practice with seven subjects who had no musical training) participated in the detection task.
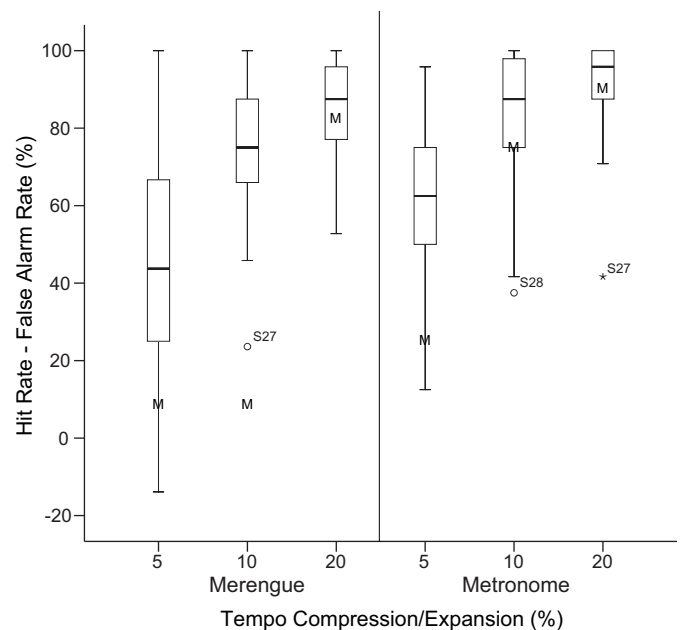


**Fig. 5.** Detection of tempo asynchrony. Detection of asynchrony between visual and auditory stimuli in audiovisual clips: hit rate (correct response to asynchronous stimuli) minus false alarm rate (incorrect responses to synchronous stimuli) at different percentages of stimulus tempo compression/expansion relative to original video clip duration, for Mathieu and 26 normal controls. Box plots show median values (horizontal lines), 25th percentiles (bottom of box) and 75th percentiles (top of box). T bars indicate 1.5 times the height of the box; stars indicate values more than 3 times the height of the box; M represents Mathieu's performance.

Subjects completed the detection task individually in a sound-treated booth, with the task presented on e-prime and viewed on a 24-inch LG Flatron computer screen. The sounds were presented in free field at approximately 70 dB, depending on the comfort level of each subject.

Hits and false alarms were computed for each participant. A hit was a correct detection of an audiovisual asynchrony and a false alarm was a judgment of asynchrony when the stimulus was synchronous. For control subjects, the hits minus false alarms were entered in an ANOVA considering condition (music, metronome) and degree of compression/expansion (5, 10, 20%) as within-subjects factors.

As shown in Fig. 5, judgments were affected significantly by the degree of tempo mismatch (or asynchrony) in both the Merengue and metronome conditions, with $F(2,54) = 65.25$, $p < .001$. Performance was higher for the metronome than the Merengue, with $F(1,27) = 16.32$, $p < .001$. There was no interaction with degree of mismatch. Mathieu showed essentially the same pattern but in an extreme manner. Mathieu showed normal sensitivity to mismatches when these were maximal (20%; $z = -0.17$, n.s.) and impaired sensitivity to smaller ones in the Merengue condition as compared to controls (10%; $z = 4.04$, $p < .0001$, by a two-tailed test). In the metronome condition, Mathieu's performance was marginally below controls at 5% ($z = 1.89$, $p = .059$) but not different at 10% and 20% ($z = .55$ and .36, respectively). Note that Mathieu's performance with the metronome soundtrack lies in the low end of the normal range, as three control subjects performed more poorly than him (Fig. 5).

## 4. General discussion

Here we report the first case of beat deafness in a university student, Mathieu, who exhibits a remarkable difficulty to synchronize with music. Despite intact motor and auditory systems, Mathieu

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[1] When the confidence interval does not cross zero, the linear term is considered to be significantly different from zero, indicating period adjustment.

is "out of time" when he synchronizes his movements with most music; furthermore, he cannot detect normally whether someone else is moving in time with the same music. These deficiencies stand in sharp contrast with the precise synchronization of full-body motion of the general (untrained) population. These problems also appear to be specific to music since Mathieu achieves near-normal synchronization with a pulse provided by an auditory metronome. Thus, this first case highlights a new form of congenital amusia that affects entrainment to music.

In the synchronization task, although Mathieu's bounces to music revealed some energy at twice the beat level, these were not phase-locked to the beat. This deficit in phase-locking was limited to music, as his performance was normal in the presence of perfect stimulus regularity (i.e., a metronome). His musical synchronization impairment generalized to tapping tasks and to most different types of dance music and tempi presented in this study. Furthermore, Mathieu displayed some sensitivity in synchronizing to gradual tempo changes of 20% but not to changes of 10%, as normal subjects can do (Drake et al., 2000; Large et al., 2002). These coarse levels of tempo adjustment may reflect a failure to adapt to temporal stimulus change, as has been documented in young children's primitive forms of synchronization to a musical beat (Drake et al., 2000; Large & Jones, 1999; Large & Palmer, 2002). A failure to adapt was most evident in Mathieu's adjustment to tempo changes of less than 20%, and least evident with the metronome. The improvement in adaptation to tempo change with the metronome may likely be explained by the absence of temporal variability.

Similarly, Mathieu's performance in the perception of asynchrony between body motion and musical beat was impaired at tempo asynchronies of 5 and 10% and was only normal at the largest level of 20%. It is worth noting that the detection task was difficult, even for normals who performed better than Mathieu. The general difficulty of judging asynchrony between visual bounces and auditory beats was surprising, as the periodicity of both the visual movements and the auditory soundtrack allowed (normal) subjects to anticipate the next occurence in each modality. Such an anticipation should facilitate asynchrony detection (e.g., Petrini, Russell, & Pollick, 2009; Vroomen & Stekelenburg, 2010). One possible explanation is that subjects tend to fuse the visual and auditory channels when their periodicities are similar. This is the case for both audiovisual musical clips and audiovisual speech (Vatakis & Spence, 2006) as well as of temporal ventriloquism (Bertelson, 1999), in which the window for temporal integration can be drastically stretched. Although observers can detect an asynchrony between the two inputs, the brain will correct for these disparities by binding the visual cues with the appropriate auditory events if the matching of both types of information could improve processing of streams that naturally belong together (Vroomen & Keetels, 2010). In our case, the brain may bind together the bimodal cues despite deviations from synchrony in order to maintain temporal coherence for dancing. However, it remains to be understood why binding seems also to occur between body motions and metronome clicks. This phenomenon should be the goal of further systematic research. For example, future research with this task should aim at disentangling the contribution of period matching relative to phase-locking. In the stituation tested here, both aspects varied.

Thus, the observation of parallel deficits in the perception and production of synchronized movements with music in Mathieu may arise either from a perceptual impairment in beat finding or from a primitive form of musical beat representation. One parsimonious account of his impairment is to ascribe it to a perceptual beat-finding problem. Beat finding is an extremely complex task and has been the topic of considerable modeling developments (Large & Jones, 1999; Large & Palmer, 2002). Although some music marks each beat explicitly, it is not always the case. Moreover, the

presence of periodicities defined at both finer and larger temporal scales than that occupied by the most salient beat makes its extraction a significant issue. Thus, ascribing Mathieu's beat deafness, as the term suggests, to perception is reasonable.

Beat deafness represents a new form of congenital amusia. Indeed, Mathieu's deficit does not affect his processing of musical pitch structure. Mathieu sings in-tune and discriminates pitch changes in melodies reliably. Mathieu succeeded in all the tests of melody discrimination on which amusic cases tested so far have failed. Moreover, the scale test, on which Mathieu obtains normal performance (25/30) is typically used as a diagnostic test in various laboratories (with scores below 22/30 indicating the presence of amusia; Peretz et al., 2008). Thus, Mathieu's pattern of impaired processing of beat structure and preserved processing of melodic structure is the reverse of what is typically observed in the cases of congenital amusia documented so far (Peretz, 2008).

Congenital amusia is ascribed to a disorder in musical pitch processing. The first reported case of congenital amusia, "Monica", demonstrated a striking deficit in pitch discrimination which rendered her "tone deaf" to musical pitch (Peretz et al., 2002). The pitch disorder has been replicated in all amusic cases tested so far (Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Hyde & Peretz, 2004; Liu, Patel, Fourcin, & Stewart, 2010; Loui, Guenther, Mathys, & Schlaug, 2008). What distinguishes amusic individuals from ordinary people is their inability to recognize a familiar tune without the aid of the lyrics, their inability to detect when they sing out-of-tune, and their difficulty judging whether two melodies are the same or different, especially on the pitch dimension. They also show little sensitivity to the presence of obvious pitch violations in melodies and to dissonant chords in classical music (e.g., Ayotte, Peretz, & Hyde, 2002). The associated rhythm deficit that is observed in about half of such individuals (Hyde & Peretz, 2004; Hyde, Zatorre, Griffiths, Lerch, & Peretz, 2006) seems to result from the presence of pitch variations in melodies. When presented with rhythmic sequences from which pitch variations are removed, amusic subjects discriminate them as well as control subjects do (Foxton, Nandy, & Griffiths, 2006). In sum, the core deficit of all prior cases of congenital amusia concerns the processing of pitch in a musical context. Thus, these cases of congenital amusia are best qualified as pitch deaf.

This pitch deafness form of congenital amusia is hereditary (Peretz, Cummings, & Dube, 2007) and is associated with abnormal connectivity between the right auditory cortex and inferior frontal cortex (Hyde et al., 2007; Hyde et al., 2011; Loui et al., 2009). Thus, we may hypothesize that this right-hemispheric neural network is intact in beat deaf cases, such as Mathieu. Lesion studies point to the left temporoparietal cortex since lesions in that region can cause selective impaiments of rhythm discrimination while sparing pitch processing (Di Pietro, Laganaro, Leemann, & Schnider, 2003; Peretz, 1990). Such a double dissociation implies the existence of anatomically and functionally segregated systems for pitch and time in music, in which the two systems can function relatively independently of each other so that one system can be selectively impaired.

Neuropsychological evidence indicates even further fractionation within the musical temporal dimension between rhythm processing (grouping structure) and meter processing (extraction of the underlying periodic beat in a hierarchical structure). In two reported cases, brain lesions affecting right temporal auditory cortex resulted in the loss of the ability to generate or tap to a regular beat, despite preserved discrimination and production of irregular sequences (Fries & Swihart, 1990; Wilson, Pressing, & Wales, 2002). Parkinson's patients with damage to basal ganglia also suffer from a loss of the abilities to produce and perceive the periodic beat in rhythm patterns, though they are no worse than con-

trols in the context of irregular sequences (Grahn & Brett, 2007, 2009).

Neuroimaging evidence also points to an important role of the basal ganglia and further highlights the connections between the auditory and motor cortices along the dorsal auditory pathway, with the dorsal premotor cortex having a particularly important role in synchronization (see Chen, Penhune, & Zatorre, 2009, for a recent review). These interconnected regions are unlikely to subserve the same functions and identifying the unique contribution of each is challenging. As neuroimaging data provide correlational, not causal, relations between brain and behavior, cases of congenital beat deafness like Mathieu represent a rare chance to identify which parts of these networks are essential for synchronization. A drawback is that the neural correlates of beat deafness can hardly be studied in a single case. Thus, one major challenge for future research will be to find further cases of beat deafness. Methodologically, the present results qualify the synchronization setup as an appropriate paradigm to identify beat deafness as it seems sensitive to the presence of the disorder and can be easily used in a wide variety of neurological conditions across the life span.

In conclusion, beat deafness could present a new form of congenital amusia related to time and not to pitch. Further study of such cases should inform us about the neural circuits that are essential for beat finding as well as about evolutionary origins of dance. Beat tracking has many human uses besides dance such as in rowing, marching, and coordinating the carrying of heavy objects with others. Behaviors as complex as conversational turn-taking, and as simple as adjusting one's gait to that of a friend, require sophisticated processes of temporal prediction and movement timing. Thus, discovery of the neurogenetic basis of synchronization deficits may unlock a key principle specific to the human genotype. As a first step, it is important to assess the domain-specificity of the disorder. Future studies aim to test whether Mathieu has problems with speech rhythms, gait adjustment, vocal imitation and learning, and choral singing. If the music-specificity of the disorder is confirmed, it would support the claim that reference to strict periodicity is unique to music as opposed to language (Patel, 2008). On the contrary, a shared deficit with speech rhythm, gait adjustment, or other entrained tasks would suggest a broader influence of the genetic basis of musical entrainment.

## Acknowledgments

## Appendix A.

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| Song | Genre | Tempo (bpm) | Length in s (number of beats) | Mathieu's bouncing | | |
|------|-------|-------------|-------------------------------|-----|-----|-----|
| | | | | r | z | N |
| What a feeling | Pop dance | 132 | 25 (55) | .161 | 1.12 | 42 |
| Round and round | Dance rock | 128 | 25 (53) | .297 | 3.89[*] | 39 |
| The flow | Dance lounge | 120 | 25 (50) | .107 | 0.36 | 39 |
| Oy oy emine (remix) | Techno dance | 128 | 25 (53) | .526 | 12.45[**] | 41 |
| Too darn hot | Swing | 160 | 25 (65) | .137 | 0.88 | 51 |
| I Like to move it move It | Pop dance | 124 | 25 (52) | .436 | 8.49[**] | 39 |
| Arabic drum | Egyptian percussion | 150 | 25 (63) | .113 | 0.74 | 48 |
| Jammu Africa | World | 78 | 25 (33) | .263 | 2.05 | 25 |

[*] $p < .05$.
[**] $p < .01$.

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