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Abstract

The main goal of this study was to assess the motor origin of disorders in music entrainment. To this aim, we adapted the Beat Alignment Test (BAT; Iversen & Patel, 2008) and tested a large pool of typical adults as well as nine individuals with evidence of a deficit in synchronization to music. The tasks consisted of tapping (Experiment 1) and bouncing (Experiment 2) in synchrony with the beat of non-classical music that varied in genre, tempo and groove, and of judging whether a superimposed metronome sounded on or off the beat of the same selection of music. The results point to deficits in both beat synchronization and detection of a misaligned metronome, in line with the idea that the motor system plays a *causal* role in beat perception (Patel & Iversen, 2014). However, support for this theory is weakened by the co-occurrence of deficient synchronization despite normal perception and, conversely, of deficient perception with normal synchronization.

Introduction

Humans across cultures spontaneously move to music. The movement is coordinated with perceived musical regularities that correspond to the beat. Despite the apparent simplicity of this behavior, synchronizing movements to a musical beat is complex and may be unique to humans and a few animal species (Patel, 2014) . Indeed, in many musical contexts one needs to *find* the beat in the auditory signal, as there is no one-to-one correspondence between beats and sounded events. This is particularly the case for syncopated rhythms, in which accents occur at non-beat locations. Furthermore, beats are anticipated during synchronization, relying on predictive timing mechanisms (van der Steen & Keller, 2013). Thus, beat finding is likely to recruit sophisticated cognitive and neural mechanisms, and its study can advance our understanding of predictive timing, which is crucial for numerous human behaviors including communication and sports.

Accumulating evidence suggests that beat perception cannot be understood in isolation from movements. The motion, more than being a mere reaction, may play an active role for predicting the beat (Su & Pöppel, 2012; Patel & Iversen, 2014). Indeed, the way we move the whole body to a rhythm can shape the internal representation of its beat structure (Chemin, Mouraux, & Nozaradan, 2014; Phillips-Silver & Trainor, 2005; 2007). In these prior studies, the same rhythmical sequence was internally represented as a march (One-two-One-two) or a waltz (One-two-three-One-two-three), depending on whether one bent their knees every two (march) or three (waltz) beats. Conversely, occupying the motor system by a pursuit task can disrupt beat perception (Walker, Stillerman, Patel, & Iversen, 2014). Altogether these behavioral results indicate an active role of the motor system in beat perception.

The motor system also shows activity during beat *perception*, even when no overt movement is produced (Chen, Penhune, & Zatorre, 2008; Grahn & Brett, 2007; Grahn & Rowe, 2009). For instance, the perception and production of a regular rhythm both activate brain areas implicated in motor processing, including the supplementary motor area (SMA), premotor cortex (PMC), the cerebellum, and the basal ganglia (Grahn & Brett, 2007; Grahn & Rowe, 2009). According to Patel and Iversen (2014), the recruitment of the motor system, rather than being the result of co-activation with auditory regions, sharpens the perception of a beat. These authors propose the "Action Simulation for Auditory Prediction” (ASAP) model according to which prediction of upcoming beats is facilitated by the simulation of periodic movement, in the form of neural oscillations in motor planning regions of the brain. Specifically, neuronal activity in the motor system entrains to the frequency of the beat, which is communicated to the auditory region in a temporally precise way via the auditory dorsal pathway.

The ASAP model is an attractive framework because it can explain why people often experience a compelling drive to move along to the beat when listening to music (Janata et al., 2012). Moving along with music is a human universal, appearing in very young children (Drake, Penel, & Bigand, 2000; Kirschner & Tomasello, 2009) and across the world cultures (Nettl, 2000). Here, we test one straightforward prediction of the ASAP model: if motor oscillations to the beat are altered, its perception should equally suffer. Yet, in recent years, individuals showing poor beat synchronization abilities with preserved perception have been reported (Sowinski & Dalla-Bella, 2013; (Tranchant, Vuvan, & Peretz, 2016). However, the tasks used in these prior studies were not optimal for distinguishing perceptual from motor entrainment to music (Tranchant & Vuvan, 2015). Thus, the observation of intact beat perception in case of anomalous synchronization remains to be confirmed. This was the goal of the present study.

To this aim, we developed a customized version of the Beat Alignment Test (BAT; Iversen & Patel, 2008). The BAT assesses beat alignment in perception and production. It requires participants to align their taps to preselected music (production task) or to detect a misalignment of a superimposed metronome soundtrack to the beat of the same music. The musical selections varied in genre, groove and tempo. Indeed, classical music, as used in some prior tests of beat perception (Bégel, Benoit, Correa, Cutanda, Kotz & Dalla Bella, 2017; Sowiński & Dalla Bella, 2013; Tranchant et al., 2016) may not be optimal for studying motor entrainment. Other musical styles, like R&B or Jazz for example, have high groove and induce a pleasant sense of wanting to move along with the music (Janata et al., 2012). Furthermore, in high-groove contexts (e.g., dance club, music festivals), motion is rarely limited to finger tapping but typically involves whole-body motion (e.g., Butler, 2006; Van Dyck et al., 2013). Thus, here, we investigated beat alignment through both tapping (Experiment 1) and bouncing (Experiment 2). We tested eight "beat-impaired" young adults and a large group of controls. Based on previous studies (Sowiński & Dalla Bella, 2013; Tranchant et al., 2016), we expected to find a few beat-impaired cases with normal beat misalignment detection. In addition, we expected to find a few beat-impaired cases among so-called typical participants because beat finding deficiencies can occur in individuals who are not aware of their condition (Bégel et al., 2017).

Experiment 1: Beat synchronization and perception

Methods

Participants

We tested 42 young adults without suspected beat finding difficulties (typical beat finders group, 23 females, mean age: 26.6 years, range 20-39 years, *SD* = 4.4) and 9 beat-impaired cases of synchronization (7 females, mean age: 26.4 years, range 22-30 years, *SD* = 2.6). All participants were non-musicians and had no history of neurological, cognitive, hearing or motor disorders. Four beat-impaired cases (case 1, 2, 3 and 5 in Table 1) were identified on the basis of poor bouncing and clapping synchronization to music, according to the criterion described in Tranchant, Vuvan & Peretz (2016). Two cases (4 and 6) were identified in a pilot experiment investigating tapping synchronization, using the musical stimuli presented in the present study. Two cases (7, 8) were recruited on their self-declared inability to follow the beat in music. The last beat-impaired case (T.B.) was initially recruited to be part of the typical group but was shifted to the beat-impaired group because her score was two standard deviations below the mean of the typical group (see Results section) in tapping.

All participants were assessed for the presence of musical deficits with standard tools. Typical participants were tested with the On-line Test of Amusia (Peretz & Vuvan, 2017). Scores were within normal variations (Table 1), except for two participants who were subsequently tested with the Montreal Battery of Evaluation of Amusia (MBEA; Peretz, Champod, & Hyde, 2003) in the laboratory and obtained normal scores on the latter battery. Beat-impaired cases were assessed with the MBEA (Table 1). They obtained a normal melodic composite score, which is an averaged score for three tests (scale, contour and interval) assessing pitch processing in a melodic context (Vuvan et al., 2017). All beat-impaired cases obtained a normal score in the discrimination of melodies by their rhythm whereas two of them (case 6 and 7) scored two *SD* below the population mean on the Metric test (below cut-off according to Vuvan et al., 2017).

[Insert Table 1 here]

All beat-impaired individuals were tested for their ability to synchronize finger taps with a metronome. Stimulus consisted in sequences of 31 isochronous tones, with two inter-tone-intervals (476 and 506 ms, corresponding to 126 and 119 BPM respectively). Since successful period matching was observed with both metronome sequences, the presence of a basic sensorimotor deficit can be excluded in the beat-impaired group.

Stimuli

Ten songs that varied in genre (see Table 2) were selected from previous research (Janata et al., 2012; Phillips-Silver et al., 2011; Tranchant et al., 2016; Einarson & Trainor, 2016). Beats were identified by a beat tracking algorithm (Ellis, 2007) implemented in Matlab (MathWorks). Eight songs had a simple meter in 4/4 while two had a more complex one: "Sollsbury Hill" in 5/4 and "Take Five" in 7/4. In order to obtain groove information, an independent sample of 64 adults unselected for their musical experience (35 females, mean age: 24.2 years, *SD* = 5.3) had to move a slider potentiometer (10 K Ohm, 0.5W, 10 mm) controlled by customized Python scripts while the participant listened to each stimulus twice in separate blocks, in a randomized order. Slider values ranged from zero (least groovy) to 1023 (most groovy). Groove was defined as "that aspect of the music that induces a pleasant sense of wanting to move along with the music" (Janata et al., 2012). Ratings were averaged across the two presentations then transformed into z-scores within participant. These values were then averaged across participants in order to obtain a groove score for each song (Table 2).

[Insert Table 2 here]

For the perception test, the 10 songs were presented with a metronome track constituted of pure tones (100ms, 1000Hz) that was superimposed on the last 24 beats of each stimulus, except for "Take Five" where 36 beats were considered because it had a faster tempo. In order to give participants some time to build their internal representation of the beat, the metronome track started five seconds after the beginning of each stimulus. Each song was presented eight times, four times with misaligned metronome tones (off-beat conditions) with ±15% phase shift or ± 5% period shift, and four times with aligned metronome tones (on-beat conditions), twice on each beat and once for each of two alternating beat arrangements, for a total of 80 trials. The two alternating arrangements (on-beat conditions) consisted of metronome tones occurring every two beats, either starting on the first or the second beat of the song. Creating more than one on-beat condition was done to equate the ratio of on-beat and off-beat conditions without presenting the same condition more than twice. A schematic description of on-beat and off-beat conditions is provided in Figure 1.

[Insert Figure 1 here]

For the tapping test, the songs did not have a superimposed metronome and were 10s longer: five seconds were added at the beginning (to give participants enough time to find the beat) and at the end of the excerpt. Note that these extra seconds were not included in the analyses.

Tasks and Procedure

Participants completed the tapping test before the perception test on the same day. Tapping was always administered first in order to avoid biases or clues provided by the metronome in the perception test. Participants were instructed to tap in time with the beat of the music. There were four familiarization trials on different songs than the experiment stimuli. After each of these four trials, the participant listened to a metronome superimposed on the beat of the same song, to ensure that she/he understood the concept of beat. The actual test started right after the practice session. Each stimulus was played twice in two distinct blocks, for a total of 20 trials. Order of stimuli was randomized within each block. Participants were invited to take a short break between the two blocks.

In the perception test, participants judged whether the superimposed metronome was aligned with the beat of the music or not. The task consisted in choosing one of four choices: *always on the beat (1), mostly on the beat (2), sometimes on the beat (3)* and *rarely or never on the beat (4)*. For the analysis, the first two choices were considered as "on-beat" responses and the last two choices were considered as " off-beat" responses. We provided four choices rather than just on- or off-beat options because for off-period trials some metronome tones could happen to be on a beat (Figure 1). Participants received two on-beat trials, two off-phase trials, and two off-period trials for familiarization before the experimental trials. The songs used in the familiarization session were different from the experimental stimuli, and were identical to the tapping familiarization songs. Feedback was given after each familiarization trial to ensure that the participant understood the task. The actual test started right after, with no feedback. The test was divided in four blocks, with 20 trials in each block. The order of presentation of the stimuli was pseudo-random so that no song was presented twice consecutively. Participants were instructed not to move to the music in order to reduce the contribution of body movements to the perception task. There were three breaks of at least five seconds between blocks and participants were given the opportunity to take longer breaks if needed.

The tapping test lasted for approximately 20 minutes, and the perception test lasted for approximately 40 minutes. The tapping test was programmed with MAX/MSP (Cycling' 74) and the perception test was programmed with Matlab. Taps were made on a square force sensitive resistor (3.81 cm, Interlink FSR 406) connected to an Arduino Duemilanove (arduino.cc) transmitting timing information to the computer via the serial USB port. This system had a 1-ms temporal resolution. The square resistor was placed on a table in front of the participant. Stimuli were delivered through headphones (DT 770 PRO, Beyerdynamics).

Participants provided written informed consent and received financial compensation for their participation. The research was approved by the local ethics committee at Université de Montréal.

Data analyses

We used Matlab for data processing and R for statistical analyses. There was no missing data in the perception test, with 80 responses (10 per stimulus) recorded per participant. For the tapping test, six trials (0.5% of the total) from three typical participants were missing due to a technical error. Trials for which less than eight taps were recorded (0.8% of the total) were also excluded from the analyses. This happened in one trial of a beat-impaired case and in eight trials from five typical participants. Tapping data were analyzed with circular statistics, using the Circular statistics Toolbox for Matlab (Berens, 2009). Mixed effects models were computed using the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) in R. Degrees of freedom were calculated with the Satterthwaite approximation using the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017).

Results

Synchronization

We used the Rayleigh test to assess whether taps were period-matched with the beat period of each musical stimulus, after transforming taps into vectors on the circle. A significant Rayleigh test ($p < .05$) indicates success in matching the inter-tap intervals with the stimulus inter-beat-interval (i.e., the period). Less than three out of 20 trials per participant failed to be period-matched in the typical group to one notable exception (Figure 2). One participant initially from the typical group (T.B.) failed to period-match her taps in seven trials. As it turned out that the synchronization performance of this participant was characteristic of the beat-impaired group (Figure 2), we shifted her in this latter category, as mentioned previously.

[Insert Figure 2 here]

Synchronization of the taps to the song beat was calculated with circular statistics. Individual taps were expressed as angles on a polar scale from 0 to 360 deg., considering that the full circle corresponds to the inter-beat interval. Angles were treated as unit vectors and used to calculate the mean resultant vector *R*. The length of vector *R*, ranging from 0 to 1, indicates *synchronization consistency* (i.e., the reciprocal of variability). A value of 1 means that all the taps occurred exactly at the same time interval before or after the pacing stimulus (maximum consistency); 0 means absence of synchronization (the taps are randomly distributed between the beats). Before statistical analyses, synchronization consistency was submitted to a log transformation, as circular variance was positively skewed, it was transformed using a log function (log score = -1*log circular variance). A higher score now indicates higher consistency. For each participant, the log-transformed score was averaged across the 20 trials. The scores are summarized in Figure 3. The beat-impaired group performed largely below the typical group. All participants from the beat-impaired group (including T.B.) obtained a score of two *SD* below the mean of the typical group.

[Insert Figure 3 here]

Synchronization varied across songs. In order to better understand which aspects of the stimuli contributed to this variability, we performed a mixed-effects regression on the transformed circular variance in the typical group, with Groove and Tempo as predictors and Participants as random factor. Block (first versus second block of tapping) was also entered in the model to assess the potential effect of practice. Note that the song "Solsbury Hill" and "Take Five" were not considered in this analysis because of their complex metrical structure. We observed a positive effect of Repetition, β = .15, *SE* = .058, $t(601)$ = 2.52, p = .012, indicating superior performance in the second block, a negative effect of Tempo, β = -.23, *SE*

= .030, $t(601) = -8.21$, $p < .0001$, indicating higher performance for slower stimuli, a negative effect of Groove, $\beta = -.12$, $SE = .056$, $t(601) = -2.17$, $p = .031$, indicating an unexpected higher performance for lower groove music, and an interaction between Tempo and Groove, $\beta = -.13$, $SE = .039$, $t(601) = -3.47$, $p < .001$. Unfortunately, the observed interaction between Tempo and Groove could not be broken down, as these factors were not manipulated independently from each other. At any rate, tempo seems to have a more linear effect than groove on synchronization (Figure 4). Similar statistical modeling for the effects could not be performed in the beat-impaired group because there were too few period-matched trials to be considered.

[Insert Figure 4 here]

Perception

The sensitivity index (*d'*) was calculated, as an unbiased measure of detection performance, based on the number of Hits (when unaligned tones were correctly detected) and False alarms (when lack of alignement was incorrectly reported). The scores are presented in Figure 5. As can be seen, the *d'* was highly variable in the typical group. Two participants obtained a near perfect score with only one or two incorrect responses out of 80 trials, while five participants from the typical group performed at chance (being 48/80, by binomial test).

[Insert Figure 5 here]

In the beat-impaired group, two participants (cases 6 and 7) performed at chance, with accuracy scores of 40 and 43/80, respectively. Interestingly, these two participants were also the ones showing a deficit on the Meter Test of the MBEA (Table 1). As can be seen in Figure 5, two additional participants (cases 1 and 5) performed above chance but with a *d'* score that was below the cut-off computed from typical scores. The other five beat-impaired cases performed above the cut-off albeit with low scores, which suggests normal but low beat perception abilities. A Welch's two-sample t-test confirmed that the d' score was lower in the beat-impaired group (M = 1.22) compared to the typical group (M = 2.40), $t(15.25) = 4.17$, $p < .001$. Altogether these results indicate low perception abilities in the beat-impaired group.

Because chance performance may reflect poor understanding of task demands, the five typical individuals and the two beat-impaired ones were invited to take the test a second time, on a different day; we made sure that the instructions were clear to them. One beat-impaired participant still performed at chance (case 6, with 46/80 correct response) while the other one performed slightly above chance (case 7, with 50 correct responses). Nevertheless, the *d′* score remained below the cut-off for both of them (.41 and .78, respectively), confirming a perception deficit. Three participants from the typical group performed above chance, but only two of them (identified in Figure 6) obtained a score above the cut-off (*d*' = 2.1 and 1.88). Therefore, a perception deficit is confirmed in two participants from the typical group. The fifth participant from the typical group was unavailable for retest. Note that the two participants (cases T.N. and M.B.) from the typical group who failed the perception test twice were further tested with the MBEA; their scores were within the normal range.

A different measure of sensitivity than *d'* was used to assess the role of tempo and groove on beat perception, because there was only eight responses per stimulus and participant to consider. A correct response corresponded to "always/mostly on the beat" when metronome tones were on-beat and to "sometimes/rarely on the beat" when the metronome was off-beat. Participants who failed to perform above chance (five in the typical group and two in the beat-impaired group) were not considered in this analysis. In the typical group, we found an effect of Tempo, $\beta = -.15$, $SE = .050$, $t(249) = -3.04$, $p < .01$, indicating higher accuracy for slower tempi, no effect of Groove, $\beta = -.025$, $SE = .094$, $t(249) = -.27$, $p = .79$ and no interaction between the two factors, β = .091, *SE* = .066, $t(249)$ = 1.38, p = .17. In the beat-impaired group, there were no effect of Tempo, β = -.14, *SE* = .15, $t(46)$ = -.97, p = .34, no effect of Groove, β = -.47, *SE* = .27, $t(46)$ = -1.73, p = .091, and no interaction between the two factors, β = -.24, *SE* = .19, $t(46)$ = -1.29, p = .20.

[Insert Figure 6 here]

Despite the fact that performance in the two tasks appears related (Figure 6), the correlation obtained by the 36 typical participants performaning above chance did not reach significance, $r(34)$ = 0.26, p = 0.13.

To summarize, we confirmed poor tapping performance in eight beat-impaired cases by objective testing and discovered a new case of deficient synchronization without awareness (T.B.). Four of them showed impaired beat perception and the other five obtained a low but normal perception score. The reverse pattern - impaired perception with a low but normal tapping score - was observed in two individuals initially recruited to be part of the typical group. Nevertheless, all these participants performed poorly in general. This raises the possibility that the disturbance is not confined to either auditory or motor beat finding mechanisms but rather arises from a more central timekeeping mechanism.

Experiment 2. Bouncing

Synchronization performance was assessed with bouncing movements to the same songs in order to ascertain the generality of the beat impairment found with tapping in Experiment 1. Synchronization performance may vary somewhat across movement types (Repp & Su, 2013; Tranchant et al., 2016) and may depend on how natural the movement feels to the participant. Thus, finding a deficit in both tapping and bouncing would provide convergent evidence for the presence of a disorder and for the abstract nature of the processes involved.

Methods

Participants

The nine beat-impaired cases from Experiment 1 and nine matched control participants (6 females, 3 males; mean age: 27 years, range: 22-32 years) participated to the bouncing task. This control group did not differ from the other typical participants tested in Experiment 1 on tapping performance, $t(19.73) = 1.67$, $p = .11$ (Welch's two-sample t-test).

Material and Procedure

Participants were standing in the middle of a large room, facing away from the experimenters. The room was equipped with an optical infrared motion capture system (Qualisys Oqus). The cameras detected three-dimensional positions of the markers, at a 200 Hz sampling rate. The 10 songs were delivered at a comfortable volume through two loudspeakers (Genelec 8040A) controlled by an audio interface (RME Fireface 800). Data from the markers was synchronized with the stimuli via a Qualisys Analog interface, and recorded by the Qualisys Track Manager software (http://www.qualisys.com).

Participants wore a reflective marker on the right knee, which served to measure bouncing. The bouncing consisted in a vertical full-body movement by bending the knees. Participants were instructed to bounce in time with the beat of the music, keeping the knees parallel and hips facing forward with the arms resting at their sides. Before starting with the music, participants were instructed to bounce in a regular fashion for 40 seconds in silence ("spontaneous"), to confirm that they could perform the movement. Then a procedure similar to the tapping test (Experiment 1) was followed, except that the stimuli were presented only once (10 trials in total). Stimulus order differed for each participant, and matched the order followed for Experiment 1 first tapping block. There were four practice trials. After each practice trial, the participant was presented with the same stimulus but this time with a metronome track aligned with the beat. The actual test without metronome started right after the practice. The session had a duration of approximately 40 minutes. The bouncing test was performed one to two weeks after Experiment 1.

Data Analyses

The Qualisys Track Manager software for markers identification and the Motion Capture (MoCap) Toolbox (Burger & Toiviainen, 2013) in Matlab, and Matlab and R were used for data processing and statistical analyses. For each trial, displacement data of the marker placed ont the right knee was extracted and linearly interpolated to 1000Hz in order to obtain the same resolution of 1ms as in tapping (Experiment 1). The component of maximal movement amplitude was selected, and corresponded to the horizontal direction perpendicular to the wall faced by the participant. For each trial, time points of maximal flexions of the knee were extracted (zero-crossings of the backward horizontal velocity), and were used to calculate vectors on the circle, as done for tapping.

Results

As in Experiment 1, the Rayleigh test was used to assess whether the bounces were period-matched with the stimulus beat for each song. We found a significant Rayleigh test ($p < .05$) for only 18% of the trials in the beat-impaired group and for 96% of the trials in the control group, with no overlap between the group's scores (Figure 8). Note that one case, T.B., failed to match the period of all ten songs, although she managed to synchronize with five out of ten songs in tapping in Experiment 1. This failure to bounce in-synch with the music could not be attributed to mechanical limitations. Her ability to produce a regular bouncing movement was normal in the spontaneous condition: she obtained a coefficient of variation (corresponding to the variance of the inter-bounce-intervals divided by the mean interval) of 0.034, which indicates a slightly higher regularity than the control group ($M = 0.040$). More generally, the coefficient of variation for spontaneous bouncing in the beat-impaired group ($M = 0.053$) did not differ from the control group, $t(16) = 1.44$, $p = .17$ (same result by non-parametric testing).

[Insert Figure 7 here]

In order to compare bouncing and tapping performance we used the log-transformed circular variance (log score = -1*log(circular variance)), averaged across the ten bouncing trials and across the first block of 10 tapping trials of Experiment 1. As expected, performance was lower in the beat-impaired compared to the typical controls in both experiments (Figure 9). Bouncing scores were generally lower than tapping scores in the beat-impaired group, whereas the reverse pattern was observed in the control group. This was confirmed by a mixed-design ANOVA (type III sum of squares), in which we found a main effect of Group, $F(1,16) = 759.1$, $p < .0001$, no effect of Condition, $F(1,16) = 0.040$, $p = 0.32$, and an interaction between the two factors, $F(1,16) = 16.15$, $p < 0.001$. The difference between tapping and bouncing scores within each group was confirmed by post-hoc comparisons (with bonferroni correction): $t(8) = 2.80$, $p = 0.047$ in the beat-impaired group and $t(8) = -2.91$, $p = 0.039$ in the control group.

Correlations between tapping and bouncing performances did not reach significance in the beat-impaired, $r(7) = -.38$, $p = .32$ nor in the control group, $r(7) = -.22$, $p = .58$ ($r = -.35$, $p = .36$ and $r = -.27$, $p = .49$ by non-parametric tests).

[Insert Figure 8 here]

In sum, the deficits in aligning taps to the musical beat generalize, and are even amplified, in aligning whole body movements. In contrast, typical synchronization was higher in bouncing than in tapping.

Discussion

The goal of this study was to test the reliance of perception on motor entrainment to a musical beat, as framed in the "Action Simulation for Auditory Prediction" (ASAP) model of Patel & Iversen (2014). To this aim, we used a classic neuropsychological procedure which consists in testing whether dissociations can be found between beat perception and production in nine individuals with clear evidence of a deficit in motor entrainment. According to the ASAP model, a deficit in motor entrainment should impair beat perception. This prediction was born out by the finding of a co-occurrence of deficit in judging beat alignment of metronome tones to the same songs on which the beat-impaired cases exhibited problems in tapping and bouncing to the beat. This poor performance in both production and perception suggests that poor motor entrainment might be at the root of the deficit.

However, typical performance in beat tracking production and perception did not correlate. Moreover, in some cases, perception did not appear as off-synch as movements were, which suggests a dissociation according to the usual criterion of a score below two standard deviations of the normal population's mean as indicative of a deficit. In particular, five individuals with severe motor entrainment deficits managed to perform in the normal range in the detection of an off-beat metronome tone. Conversely, we found two cases who were unable to detect the off-beat tones but tapped to the beat within normal variations. Note that the evidence is not strong because these seven cases performed poorly in general. Thus, these dissociation patterns may question the ASAP model, albeit not firmly so.

This raises the thorny question concerning the diagnostic test that should be used in the future to identify disorders in musical beat processing. In this respect, it is worth mentioning that the meter test of the MBEA, which is the current standard tools for the identification of musical disorders, is not sensitive enough to the presence of a deficit. Two of the four cases with a clear-cut deficit in beat perception on the Beat Alignment Test also failed the MBEA Meter test. The rhythm test of the MBEA had even less, if no, sensitivity to the presence of the beat processing impairment; all beat-impaired participants performed in the normal range, including those with deficient beat perception on the BAT test. This shows that the Rhythm test of the MBEA is not appropriate to prove normal beat perception abilities as done in prior research (Sowinski & Dalla Bella, 2013). The findings suggest that MBEA meter test might constitute a good complement but cannot replace the Beat Alignment Test for the diagnosis of beat perception deficits.

For synchronization, both tapping and bouncing to the music were diagnostic of a problem. The evidence is compatible with the idea that the difficulty is more cognitive than motoric, in accordance with the ASAP model and with previous research (Iversen & Patel, 2008; Fujii & Schlaug, 2013; Leow, Parrot, & Grahn, 2014). It is also consistent with the normal performance found in spontaneous tapping and bouncing without metronome or music. The movements were as regular in the individuals with a synchronization deficit as in the matched controls. Therefore, little support for a basic timing deficit was found in the present study. However, by collecting larger amounts of tapping sequences we observed a difficulty to maintain regularity and limited flexibility in tapping speeds among beat-impaired cases (Tranchant & Peretz, in preparation).

To conclude, our study confirms that beat perception and synchronization abilities are tightly coupled so that a congenital anomaly can hardly dissociate them. Now that we have a good description of the beat impairment at the behavioral level, future research should be brought to the next level by delineating its neural correlates and its training potential.

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Disclosure statement

The authors declare no competing interests

References

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1-48.

Berens, P. (2009.). CircStat: a MATLAB toolbox for circular statistics. *Journal of Statistical Software*, *31*(10), 1-21.

Bégel, V., Benoit, C.-E., Correa, A., Cutanda, D., Kotz, S. A., & Dalla Bella, S. (2017). "Lost in time” but still moving to the beat. *Neuropsychologia*, *94*, 129–138. http://doi.org/10.1016/j.neuropsychologia.2016.11.022

Burger B, & Toiviainen P. (2013) MoCap Toolbox—a Matlab toolbox for computational analysis of movement data. In Proc. In R. Bresin (Ed), *10th Sound and Music Computing Conference.* Stockholm, Sweden: KTH Royal Institute of Technology.

Butler, M. J. (2006). Unlocking the Groove. Indiana University Press.

Chemin, B., Mouraux, A., & Nozaradan, S. (2014). Body movement selectively shapes the neural representation of musical rhythms. *Psychological Science*, *25*(12), 2147–2159. http://doi.org/10.1177/0956797614551161

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Listening to musical rhythms recruits motor regions of the brain. *Cerebral Cortex*, *18*(12), 2844–2854. http://doi.org/10.1093/cercor/bhn042

Drake, C., Penel, A., & Bigand, E. (2000). Tapping in time with mechanically and expressively performed music. *Music Perception: An Interdisciplinary Journal*, *18*(1), 1-23.

Einarson, K. M., & Trainor, L. J. (2016). Hearing the beat: Young children’s perceptual sensitivity to beat alignment varies according to metric structure. *Music Perception: An Interdisciplinary Journal*, *34*(1), 56-70.

Ellis, D. P. (2007). Beat tracking by dynamic programming. *Journal of New Music Research*, *36*(1), 51-60.

Fujii, S., & Schlaug, G. (2013). The Harvard Beat Assessment Test (H-BAT): a battery for assessing beat perception and production and their dissociation. *Frontiers in Human Neuroscience*. http://doi.org/10.3389/fnhum.2013.00771/abstract

Grahn, J. A., & Rowe, J. B. (2009). Feeling the beat: Premotor and striatal interactions in musicians and nonmusicians during beat perception. *Journal of Neuroscience*, *29*(23), 7540–7548. http://doi.org/10.1523/jneurosci.2018-08.2009

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*(5), 893–906. http://doi.org/10.1162/jocn.1996.8.1.29

Iversen, J. R., & Patel, A. D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. In K. Miyazaki, Y. Hiraga, M. Adachi, Y. Nakajima, & M. Tsuzaki (Eds.). *10th International Conference on Music Perception and Cognition*, Sapporo, Japan.

Janata, P., Tomic, S. T., & Haberman, J. M. (2012). Sensorimotor coupling in music and the psychology of the groove. *Journal of Experimental Psychology: General*, *141*(1), 54–75. http://doi.org/10.1037/a0024208

Kirschner, S., & Tomasello, M. (2009). Joint drumming: Social context facilitates synchronization in preschool children. *Journal of Experimental Child Psychology*, *102*, 299–314.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, *82*(13), 1–26.

Leow, L.-A., Parrot, T., & Grahn, J. A. (2014). Individual differences in beat perception affect gait responses to low- and high-groove music. *Frontiers in Human Neuroscience*, *8*, 811. http://doi.org/10.3389/fnhum.2014.00811

Nettl, B. (2000). An ethnomusicologist contemplates universals in musical sound and musical culture. In: N. L. Wallin, B. Merker, & S. Brown S. (Eds.), *The origins* *of music*. Cambridge: Mass: MIT Press 463-372.

Patel, A. D. (2014). The evolutionary biology of musical rhythm: Was darwin wrong? *Plos Biology*, *12*(3), e1001821. http://doi.org/10.1371/journal.pbio.1001821

Peretz, I., & Vuvan, D. T. (2017). Prevalence of congenital amusia. *European Journal of Human Genetics*, *25*(5), 625–630. http://doi.org/10.1038/ejhg.2017.15

Peretz, I., Champod, A. S., & Hyde, K. (2003). Varieties of musical disorders. The Montreal Battery of Evaluation of Amusia. *Annals of the New York Academy of Sciences*, *999*(1), 58–75.

Peretz, I., Peretz, I., Gosselin, Tillman, B., Cuddy, L. L., Gagnon, B., Trimmer, S. et al. (2008). On-line identification of congenital amusia. *Music Perception: an Interdisciplinary Journal*, *25*(4), 331–343.

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the beat: Movement influences infant rhythm perception. *Science*, *308*(5727), 1430–1430. http://doi.org/10.1126/science.1110922

Phillips-Silver, J., & Trainor, L. J. (2007). Hearing what the body feels: Auditory encoding of rhythmic movement. *Cognition*, *105*(3), 533–546.

Phillips-Silver, J., Toiviainen, P., Gosselin, N., Piché, O., Nozaradan, S., Palmer, C., & Peretz, I. (2011). Born to dance but beat deaf: A new form of congenital amusia. *Neuropsychologia*, *49*(5), 961–969. http://doi.org/10.1016/j.neuropsychologia.2011.02.002

Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20*(3), 403–452. http://doi.org/10.3758/s13423-012-0371-2

Sowiński, J., & Dalla Bella, S. (2013). Poor synchronization to the beat may result from deficient auditory-motor mapping. *Neuropsychologia*, *51*(10), 1952–1963. http://doi.org/10.1016/j.neuropsychologia.2013.06.027

Su, Y. H., & Pöppel, E. (2012). Body movement enhances the extraction of temporal structures in auditory sequences. *Psychological Research*, *76*, 373–382. http://doi.org/10.1007/s00426-011-0346-3

Tranchant, P., & Vuvan, D. T. (2015). Current conceptual challenges in the study of rhythm processing deficits. *Frontiers in Neuroscience*, *9,* 197. http://doi.org/10.3389/fnins.2015.00197

Tranchant, P., Vuvan, D. T., & Peretz, I. (2016). Keeping the beat: A large sample study of bouncing and clapping to music. *Plos One*, *11*(7), e0160178.

van der Steen, M. C. M., & Keller, P. E. (2013). The ADaptation and Anticipation Model (ADAM) of sensorimotor synchronization. *Frontiers in Human Neuroscience*, *7,* 253. http://doi.org/10.3389/fnhum.2013.00253

Van Dyck, E., Moelants, D., Demey, M., Deweppe, A., Coussement, P., & Leman, M. (2013). The impact of the bass drum on human dance movement. *Music Perception: an Interdisciplinary Journal*, *30*(4), 349–359. http://doi.org/10.1525/mp.2013.30.4.349

Vuvan, D. T., Paquette, S., Mignault Goulet, G., Royal, I., Felezeu, M., & Peretz, I. (2017). The Montreal Protocol for Identification of Amusia. *Behavior Research Methods*, 1–11. http://doi.org/10.3758/s13428-017-0892-8

Walker, E., Stillerman, B., Iverson, J., Patel, A., & Bergen, B. (2014). Does beat perception rely on the covert use of the motor system. In *Proceedings of the Annual Meeting of the Cognitive Science Society,* 36(36).

Article 2: Tableaux et Figures

Tableau I. A2: Résultats à la MBEA et au Test en Ligne .

Table 1. Musical Processing. Beat-impaired participants' scores on the Montreal Battery of Evaluation of Amusia (MBEA) and scores of the typical group (N = 41) on the Online Test of Amusia. Scores below the cut-off are in bold.

Beat-Impaired Participants	**Melodic Composite Score (/30) cut-off : 21.4**	**Rhythm (/30) cut-off : 22**	**Meter (/30) cut-off : 17**
1	26	22	25
2	24.7	26	24
3	26.3	28	20
4	25	26	19
5	24.3	25	21
6	23. 7	27	**13**
7	23	26	**16**
8	25.3	25	23
9 (T.B.)	29	25	23
Typical Group (N = 40)	**Scale (%)**	**Off-beat (%)**	**Off-key (%)**
Mean	90.5	84.5	82.6
SD	7.2	6.5	11.5

Tableau II. A2: Description des stimuli.

Table 2. Description of stimuli.

Song Name	Genre	Tempo (BPM)	Duration (in s)	Groove mean (*SD*)
Party at your mama's house	Rock	82	22	-1.0 (.76)
Superstition	Pop	100	19	.86 (.62)
Solsbury hill	Rock	103	18	-.33 (.73)
Since you've been gone	Soul	117	17	.00 (.68)
The flow	Dance lounge	129	16	.02 (.70)
Suavemente	Merengue	124	16	.63 (.91)
Brand New Carpet	Pop rock	126	16	-.70 (.60)
What a feeling	Pop dance	132	15	-.01 (.91)
Don't stop me now	Rock	156	14	.63 (.80)
Take five	Jazz	170	17	-.02 (.94)

Figure I. A2: Représentation schématique de l'alignement du métronome sur le beat des stimuli.

Figure 1. Schematic representation of beat alignment of the metronome soundtrack (Experiment 1).

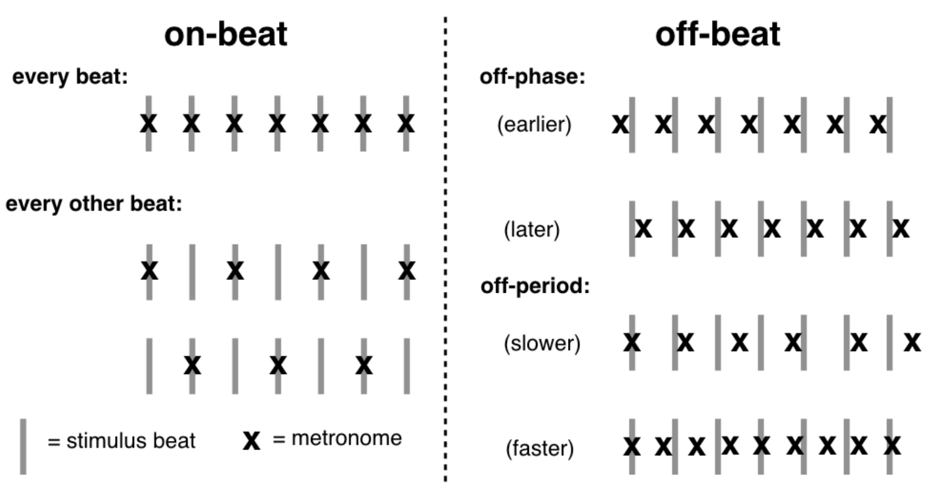


Figure II. A2: Nombre d'essais alignés à la période par participant (tapping).

Figure 2. Number of period-matched trials (out of 20) in the tapping test. Each dot corresponds to a participant.

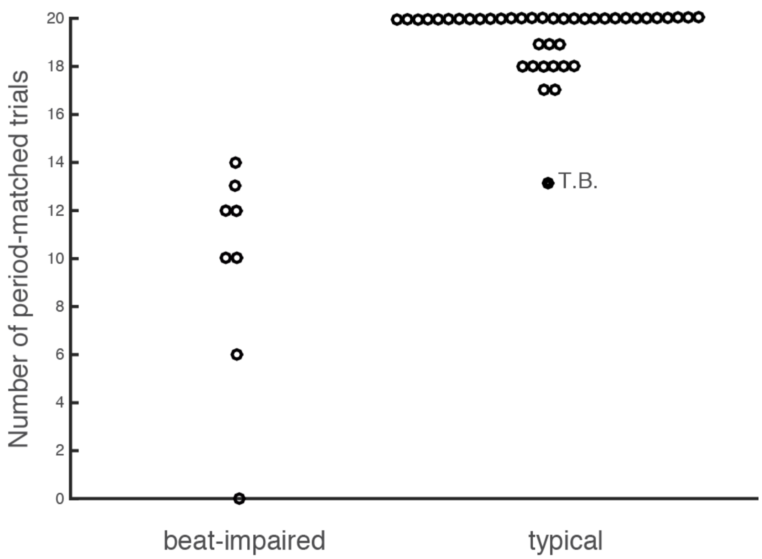


Figure III. A2: Performance en tapping dans les deux groupes.

Figure 3. Tapping performance. Scores in beat-impaired cases (*N* = 9) and in the typical group (*N* = 41). The vertical grey line indicates cut-off scores (i.e. two *SD* below the mean, as computed from the typical group).

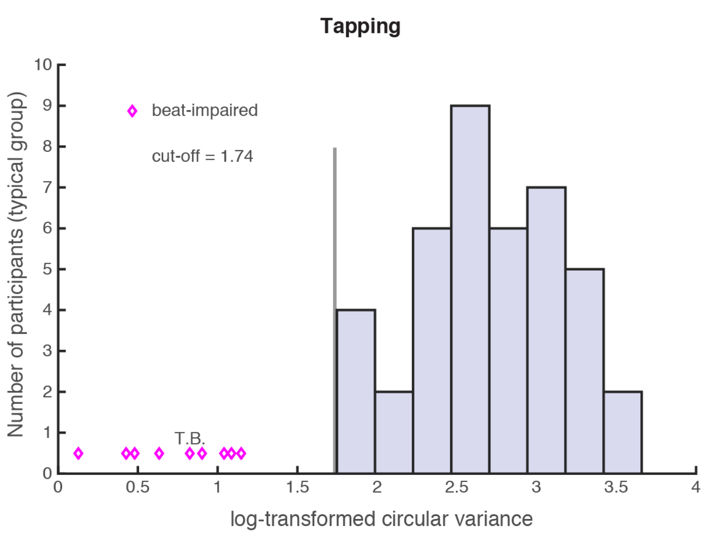


Figure IV. A2: Performance en tapping, en fonction du tempo et du groove.

Figure 4. Tapping synchronization as a function of the stimulus tempo and groove. Standard errors are represented by bars (typical group only, $N = 41$).

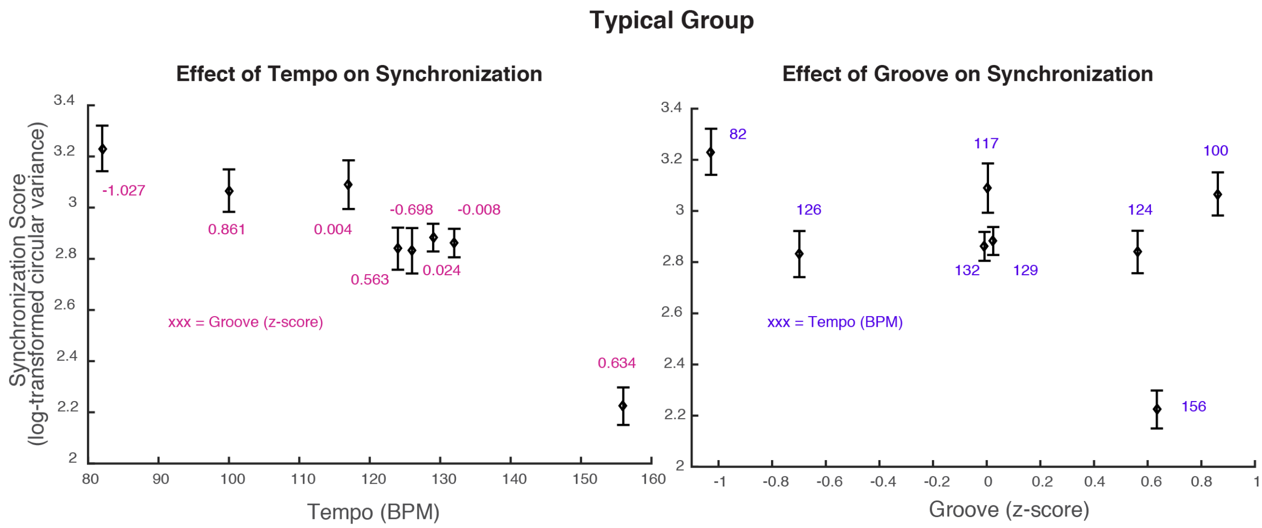


Figure V. A2: Performance au test de perception.

Figure 5. Distribution of Perception scores. The vertical grey line indicates cut-off score of 1.29 corresponding to two SD below the typical mean. Participants from the typical group who performed at chance are identified by black stars.

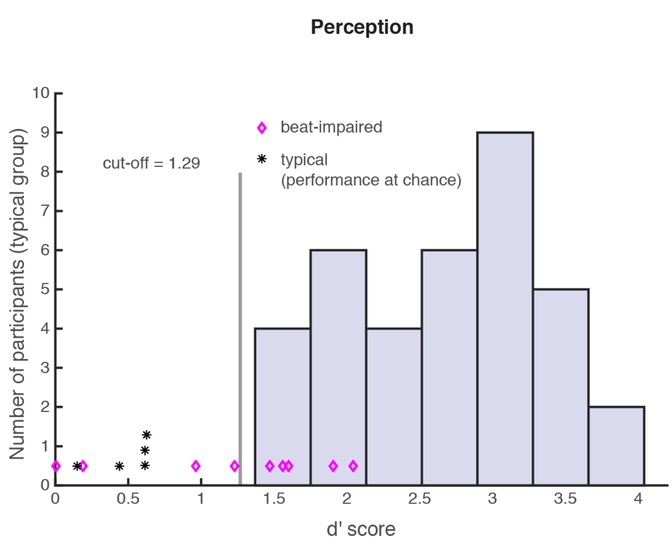


Figure VI. A2: Performance en perception, en fonction du tapping.

Figure 6. Individual scores in perception as a function of tapping. Grey lines indicate cut-off scores. Perception: participants who performed above the cut-off on re-test are identified by grey vertical arrows and the participant who has not been re-tested is identified by the grey star.

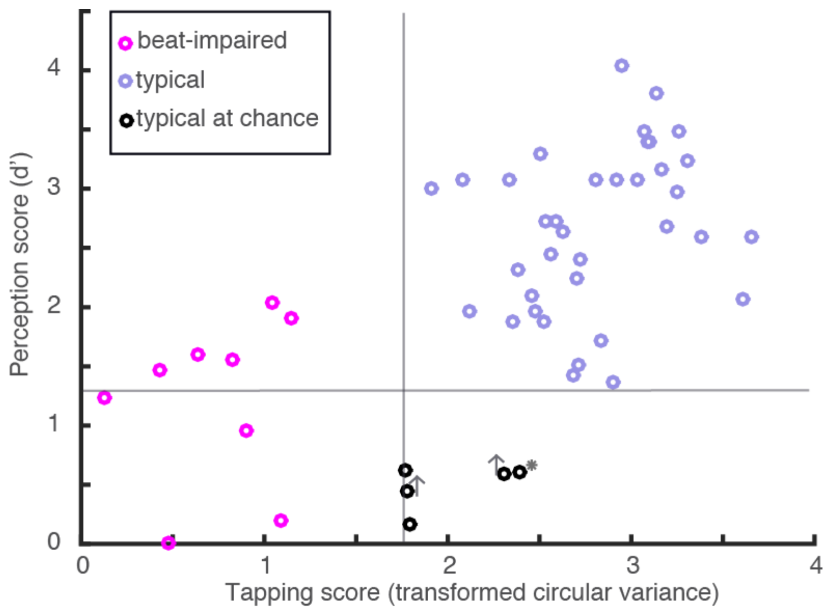


Figure VII. A2: Nombre d'essais alignés à la période par participant (bouncing).

Figure 7. Number of period-matched trials (out of 10) in bouncing. Each dot corresponds to a participant.

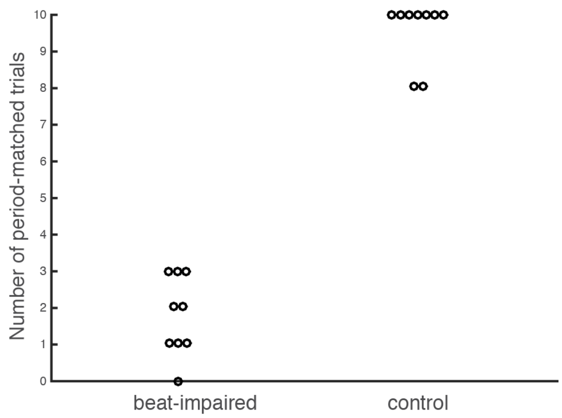
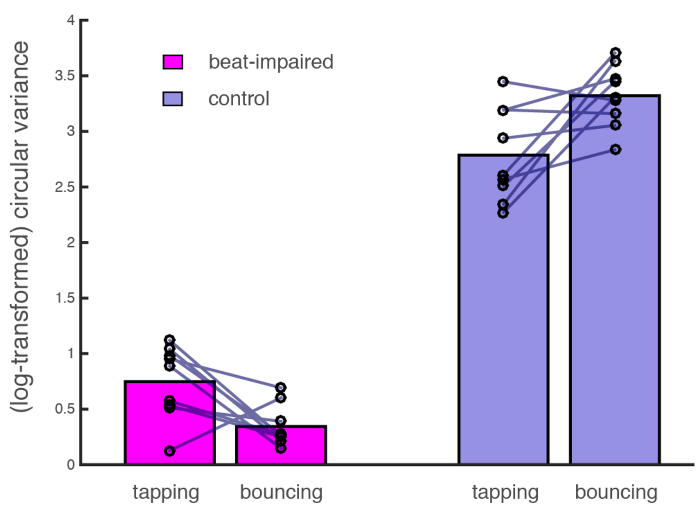


Figure VIII. A2: Performance de synchronisation: bouncing et tapping.

Figure 8. Tapping and bouncing alignment to the musical beat as a function of group. Dots indicate individual scores (averaged across stimuli).



Article 3: Faulty mechanisms of timekeeping in the beat-based form of congenital amusia

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