Université de Montréal

Beat deafness: Développement d’un outil de dépistage et nouveaux cas

par
Pauline Tranchant

Département de Psychologie
Faculté des Arts et des Sciences

Mémoire présenté à la Faculté Faculté des Etudes Supérieures
en vue de l’obtention du grade de Maître ès Sciences (M.Sc.)
en Psychologie

Août, 2013

Université de Montréal

Faculté des études supérieures et postdoctorales

Ce mémoire intitulé :

Beat deafness: Développement d'un outil de dépistage et nouveaux cas

Présenté par : Pauline Tranchant

a été évalué par un jury composé des personnes suivantes :

Marc Scoenwiesner, président-rapporteur
Isabelle Peretz, directeur de recherche
Frédéric Gosselin, membre du jury

Résumé

Le terme *beat deafness* désigne une forme d'amusie congénitale spécifique à l'aspect temporel en musique qui a été découverte récemment par l'étude d'un cas unique (Phillips-Silver et al., 2011). L'objectif principal de ce mémoire était d'identifier de nouveaux cas. Nous avons évalué, chez 100 étudiants universitaires, les capacités à percevoir le beat à se synchroniser sur celui-ci. Les capacités de perception ont été évaluées au moyen de deux tests: un test de détection de perturbations rythmiques et un test de classification de courts extraits musicaux en marches et valses. Les capacités de synchronisation ont été évaluées au moyen d'une tâche consistant à taper du doigt sur les temps forts des mêmes marches et valses. Quatre personnes se sont démarquées du groupe par des difficultés de perception et de synchronisation, et sont dès lors considérées comme des nouveaux cas de beat deafness.

Mots-clés : amusie congénitale, beat deafness, pulsation, structure métrique, synchronisation

Abstract

Beat deafness is a form of congenital amusia related to time that has been documented through a single case very recently (Phillips-Silver et al., 2011). The main goal of this study was to identify new cases. Toward this goal, we screened for deficits in beat perception and synchronization in a sample of 100 healthy university students. We assessed perception, first with an on-line test in which participants had to detect perturbations in metric structure, then with a task in which participants had to judge whether short piano pieces were marches (binary metrical structure) or waltzes (ternary metrical structure). We assessed synchronization with a finger tapping task in which participants had to tap to the strong beats of the same marches and waltzes. Four participants showed a parallel impairment in both perception and synchronization assessments and are therefore considered as new beat-deaf cases.

Keywords : congenital amusia, beat deafness, beat, metre, synchronization

Table des matières

Liste des tableaux

Liste des figures

Liste des abréviations

MBEA	Montreal Battery of Evaluation of Amusia
IBI	Inter-beat-interval
IsBI	Inter-strong-beat-interval
ITI	Inter-tap-inteval
SCC	Synchronization consistency coefficient
CV	Coefficient of variation

Remerciements

Je souhaite tout d'abord remercier chaleureusement Isabelle Peretz de m'offrir un encadrement de si bonne qualité et de m'encourager à donner le meilleur de moi-même dans la réalisation de l'ambitieux et passionnant projet *beat deafness.*

Je remercie vivement Dominique Vuvan, pour son efficacité, *to be my English teacher*, et pour l'aide qu'elle m'a apportée au cours des derniers mois. *Thank you very much Dom!*

Enfin, un immense chapeau et merci à Sébastien Bel pour la réalisation de la superbe interface MAX qui a permis de collecter une bonne partie des données présentées dans ce mémoire.

Introduction

Lorsque nous écoutons de la musique, nous 'ressentons' une pulsation musicale, ou *beat* (terme anglais généralement utilisé en cognition musicale), et avons une tendance naturelle à synchroniser nos mouvements sur celui-ci. Cela peut se manifester à travers des mouvements simples et spontanés (taper du pied, hocher de la tête) ou intentionnels et plus sophistiqués (danser dans un club). Si, pour la plupart des gens, ces comportements ne semblent pas requérir d'effort particulier, il en va autrement pour quelques-uns d'entre nous. De plus, les bases neurobiologiques et cognitives liées au traitement du beat musical sont à ce jour encore très floues. Récemment, le cas d'un étudiant universitaire épanoui, Mathieu, présentant une incapacité à synchroniser ses mouvements sur le *beat* musical a été étudié (J. Phillips-Silver et al., 2011). Ce trouble, que les auteurs ont baptisé *beat deafness*, mérite d'être étudié en profondeur. En effet, l'étude du fonctionnement cognitif déficient constitue souvent une porte ouverte sur la compréhension du fonctionnement cognitif normal, car la pathologie permet de révéler l'organisation fonctionnelle en fractionnant les éléments qui composent le système. Suivant l'étude d'un cas unique comme Mathieu, les corrélats neuronaux et fonctionnels associés au beat deafness peuvent être investigués de façon plus poussée en identifiant de nouveaux cas similaires. Un nombre plus important de sujets permettrait par exemple d'utiliser des techniques d'exploration cérébrale et des méthodes d'analyse plus puissantes que dans l'étude d'un cas unique. L'identification de nouveaux cas de beat deafness, et par cette voie la précision de la définition du trouble, constitue l'objet principal de l'article présenté dans ce mémoire.

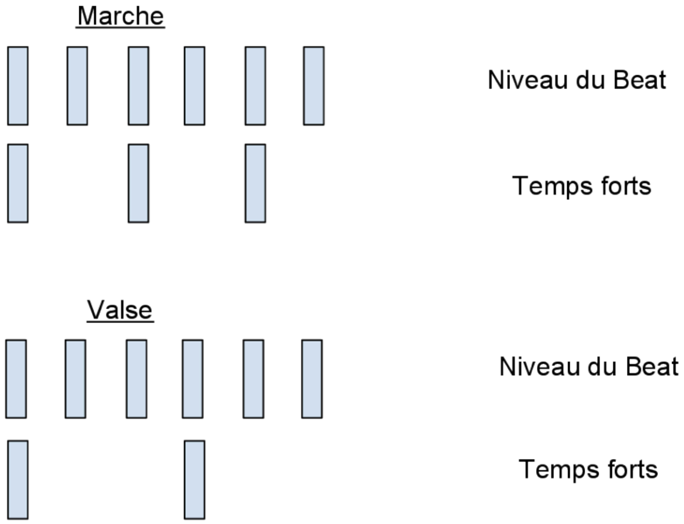
Enfin, si la notion de beat peut sembler intuitive, sa conceptualisation théorique n'est pas triviale. Dès lors, il convient de prendre quelques lignes pour en préciser la définition. De celle-ci découlera la notion, centrale dans l'article, de structure métrique en musique.

Beat et structures métriques en musique

Le rythme d'une séquence musicale désigne l'organisation temporelle des évènements sonores qui la constituent. Le *beat*, également appelé *pulse,* ou pulsation en français, renvoie à une forme de périodicité subjective émergeant de tels rythmes, lesquels ne sont généralement pas périodiques. Le beat ne constitue dès lors pas une propriété intrinsèque du stimulus musical (Epstein, 1995; Lerdahl & Jackendoff, 1983), il est une reconstruction due à notre perception. Large (2008) affine cette définition en caractérisant le beat par trois notions: périodicité non stricte, synchronie globale et constance. La périodicité est dite 'non stricte' afin que la définition inclue les changements de tempo (rubato), qui permettent notamment à l'interprète d'une œuvre musicale de véhiculer de l'émotion. On désigne par *beats* les points dans le temps à récurrence périodique qui sont la concrétisation discrète du beat. Pensons aux contacts du doigt sur la table, du pied sur le sol, lorsque l'on bat la mesure avec la musique. La synchronie signifie que la plupart de ces instants correspondent aux débuts des évènements musicaux (attaque des notes). En raison de la complexité et la diversité des rythmes en musique, cette parfaite correspondance n'est pas toujours observée, d'où le qualificatif 'globale'. Enfin, la constance réfère au fait que, une fois établie chez une personne, la sensation de beat demeure robuste et peut persister même si le stimulus qui l'a induite a cessé (Cooper & Meyer, 1960).

L’expression ‘structure métrique’ désigne, quant à elle, l’organisation des beats individuels en motifs cycliques de ‘temps forts’ et ‘temps faibles’. Bon nombre de musiques occidentales présentent soit une structure binaire de marche (1: 2, un temps fort pour deux beats) soit une structure ternaire de valse (1: 3, un temps fort pour trois beats). Les structures métriques s’organisent en différents niveaux hiérarchiques de pulsation(Palmer & Krumhansl, 1990), le niveau de base étant celui du beat, les temps forts constituant le niveau supérieur, comme indiqué dans la figure 0.

Figure 0. Structures métriques de marche et valse



Article

Beat deafness: screening test and new cases

Pauline Tranchant (1), Dominique Vuvan (1) and Isabelle Peretz (1).

(1) BRAMS, Department of Psychology, University of Montreal, Canada

Running title: beat deafness, screening test and new cases

Keywords: congenital amusia, beat deafness, beat finding, beat, metre, synchronization

Abstract

Beat deafness is a form of congenital amusia related to time that has been documented through a single case very recently (Phillips-Silver et al., 2011). The main goal of this study was to identify new cases. Toward this goal, we screened for deficits in beat perception and synchronization in a sample of 100 healthy university students. We assessed perception, first with an on-line test in which participants had to detect perturbations in metric structure, then with a task in which participants had to judge whether short piano pieces were marches (binary metrical structure) or waltzes (ternary metrical structure). We assessed synchronization with a finger tapping task in which participants had to tap to the strong beats of the same marches and waltzes. Nine participants showed a significant synchronization deficit. For three of these nine, it was not clear whether the deficit was specific to music. Among the six others, two obtained scores in a normal range on the perceptual tasks. However, we did not exclude a possible perceptual deficit for these cases because our perceptual assessment might not be adequately sensitive. Finally, four participants showed a parallel impairment in both perception and synchronization assessments and are therefore considered as new cases of beat deafness.

Beat perception in music refers to an endogenous sense of periodicity that is derived from complex sound patterns that are not necessarily themselves periodic (Large, 2008). Patterns of regularly recurring strong and weak individual beats generally arise, giving form to metrical structures or meters. As a listener must feel some beats to be accentuated relative to others in order for meter to exist, the experience of beat is necessary for the experience of meter (Meyer & Cooper, 1960). In Western music, most meters are duple (marches: alternation of one strong and one weak beat) or triple (waltzes: alternation of one strong and two weak beats).

The notions of beat and metre are tightly bound to synchronization. Indeed, across cultures, one of the most natural response to music is to spontaneously produce body movements coordinated with the beat (Nettl, 2000).This is observed, for example, in dance, hand clapping, head bouncing, and foot tapping. Beat perception and synchronization abilities are commonly referred together in the literature as beat-finding abilities. Beyond the intuitive connections between perception and synchronization, behavioral studies have shown that body movements influence whether rhythmic patterns are perceived as marches or waltzes in infants (Phillips-Silver & Trainor, 2005) and in adults (Phillips-Silver & Trainor, 2007). Moreover, imaging studies indicate that brain areas implicated in perception (i.e., posterior auditory cortex) interact with areas implicated in motor production (i.e., premotor cortex) in both meter perception and synchronization tasks (Chen, Penhune, & Zatorre, 2009). Therefore, beat perception is not easily separated, theoretically or functionally, from synchronization.

Although beat perception and its relation to synchronization constitute topics of increasing interest among the scientific community, the underlying neurocognitive mechanisms are not well known. One effective way to make inferences about normal beat finding is the study of individuals with impaired beat finding abilities. Indeed, as stated by McCloskey, ”Complex systems often reveal their inner working more clearly when they are malfunctioning than when they are running smoothly” (McCloskey, 2001, p. 594).Thus, disordered systems constitute a chance to fractionate the cognitive systems for beat-finding, and from there to infer the processors involved in this behavior.

Recently, the case of a university student, Mathieu, who is unable to synchronize simple bouncing movements to the beat of popular songs despite preserved hearing, cognitive, motor and musical pitch processing abilities has been reported (Phillips-Silver et al. 2011). Mathieu was discovered through a recruitment of subjects who declared having difficulties to keep track of the musical beat in dancing. He was the only clear-cut case among a group of volonteers in bouncing and tapping with popular songs. This deficit, named ‘beat deafness’, constitutes a rare opportunity to investigate the cognitive mechanisms underlying beat perception and synchronization. It is crucial to identify several cases similar to Mathieu in order to give as much power as possible to future experimental studies on beat deafness. To do so an effective method must be developed to screen for such cases. We did test a normal population on synchronization performances with a bouncing task (in preparation). The goal of the present study was to refine an already existing screening battery for amusia, the Montreal Battery of Evaluation of Amusia (MBEA; Peretz, Champod, & Hyde, 2003).

For more than ten years, the MBEA has been the most comprehensive behavioral test used to diagnose multiple disorders of musical abilities. The MBEA has been developed on the assumption of separable perceptual subsystems for melodic and temporal analysis in the context of music (for a review see Peretz, 2001). Thus, the MBEA contains various subtests to independently assess melodic and temporal perception. In particular, according to both cognitive models of music analysis (Lerdahl & Jackendoff, 1983) and neuropsychological dissociations (Fries & Swihart, 1990; Peretz, 1990), the temporal dimension is separated into two subtests. Two different types of temporal organizations – 'grouping' and 'meter' – are evaluated. Mechanisms related to grouping structures correspond to the tendency to group events, mostly according to temporal proximity, and are assessed with the perceptual rhythm subtest in the MBEA. In contrast, meter refers to the extraction of temporal regularity (a beat) as described above. The latter is assessed with the metric subtest of the MBEA, in which a subject has to judge short piano excerpts as being marches or waltzes. Selective disruption of grouping structure with spared metric organization has been observed in several studies (Liégeois-Chauvel, Peretz, Babaï, Laguitton, & Chauvel, 1998; Peretz, 1990; Polk & Kertesz, 1993). The opposite, i.e., the inability to extract a beat and tap along with it while maintaining intact grouping mechanisms is what was observed with Mathieu, who obtained a poor score on the metric test but performed within a normal range on the rhythm test. Subsequent unpublished observations of

Mathieu's behavior indicated that he was not able to tap to the strong beats of the march and waltz stimuli that constitute the metric test.

These findings initially led us to consider the metric test as a potential screening tool for other beat deaf cases. However, there are two issues that may prevent the metric test from detecting all beat deaf cases. First, the vast majority of participants score highly on the metric test (see results section). Therefore, it provides a qualitative judgment about metric discrimination, i.e., tells us whether the participant is normal or not, rather than discriminating a range of beat-finding ability. Then, it does not assess synchronization. We thus decided to refine the MBEA metric test by adding synchronization evaluation. We chose to assess synchronization through a finger-tapping task, which has been used in multiple previous studies on beat-finding (for reviews see Repp, 2005; Repp & Su, 2013).

This new test will thus constitute a theoretically complete measure of beat-finding that assesses a continuum of beat-finding ability. This test will also enable us to further explore the relation between perception and synchronization in beat-finding. Thus, the purpose of this study was to use our new beat-finding assessment to screen for beat deaf cases in a large sample from a normal population.

Method

Participants.

We tested 101 healthy university students (Aged 18-34, *M* = 23.4; 56 female) who provided written informed consent and received financial compensation for their participation. None of them reported any neurological problems or motor deficits. They all had normal audition (self-reported). The level of musical expertise ranged from none to professional, with a mean of 3.74 years of musical education (*SD* = 4.25). A more detailed description of musical training is presented in Table 1. Five participants had more than 10 years of formal dance training (ballet), 8 had between 5 and 10 years of dance classes (classic, jazz, modern, swing, flamenco) and 20 had between 1 and 5 years of dance classes. All of them except 3 participants in the last category were females.

(Table 1 about here)

All participants completed an on-line amusia test (MBEAPeretz et al., 2003) to screen for music processing difficulties. Fourteen individuals (2, 20, 22, 29, 36, 37, 49, 52, 53, 63, 64, 80 and 98) obtained a score below the established cut-off (67% of correct responses, see Peretz et al., 2008) at the 'off-beat' subtest, which tests the detection of local perturbation of the metre or of the beat. Individuals with poor scores on the pitch-related subtests of the on-line test were further tested with the entire MBEA. One participant had MBEA pitch score below the established cut-offs (Peretz et al., 2008) and was excluded based on this criterion. Our final sample thus did not include any pitch-impaired individuals and included 100 participants.

Tasks and stimuli.

Metric perception.

We assessed beat and metre perception with the metric task of the MBEA, in which participants were asked to judge harmonized two-phrase piano sequences as being marches (duple meter) or waltzes (triple meter). The 30 melodies were constructed in a major mode according to Western tonal-harmonic conventions. All stimuli had eight bars, and their durations ranged from 7.2 to 12 seconds (*M* = 9.09 s, *SD* = 1.2 s). Tempo values were determined with the Tempo and Beat Tracker of the Queen Mary Vamp Plugin (plugin by C. Cannam and C. Landone) in Sonic Visualiser (Peretz et al., 2003). Tempo values varied between 100 and 200 beats per minute (BPM), and thus had inter-beat intervals (IBIs) that varied from 300 to 600 milliseconds. All melodies started on the beat, except for four marches that contained an anacrusis (i.e. a note or a sequence of notes preceding the first strong beat). A complete description of tempo, IBI and inter-strong-beat-interval (IsBI) values for this set of stimuli is presented in Table 2. Half of the trials were written in duple meter and half in triple. Four practice trials preceded the 30 experimental trials; these trials were presented to all participants in the same randomized order.

(Table 2 about here)

Synchronization.

The synchronization test occurred one hour after the perception test. During this hour, several musical excerpts not presented in either the synchronization or the perception task were presented to the participants as part of another study.

We assessed synchronization abilities using a tapping task. Stimuli were identical for the perception and synchronization tasks, except for their accentuation patterns. By accentuation we refer to the phenomenal accents associated with each sounded event (Cannam, Landone, & Sandler, 2010). For the metric perceptual test, acoustic stress was systematically added to the first event of each bar by simulating increased velocity of the depression of the piano key. For the synchronization test, velocity values were controlled for all notes in the stimulus. However, note onsets occurred at regular intervals corresponding to the beat, which provided sufficient acoustic information for participants to synchronize their taps. The differences between perceptual and synchronization stimuli are visualised in Figure 1, where we present the waveforms of the same waltz for both tasks. The synchronization stimuli were synthesized from MIDI files using Ableton Live (version 8, Ableton).

(Figure 1 about here)

Each melody was presented twice, one after the other, and each time preceded by an auditory warning signal. As with the metric perceptual task, these trials were presented to all participants in the same randomized order. Participants were instructed to tap in synchrony with the strong beat of each musical excerpt. During the practice phase, the experimenter guided the participant by tapping on the first beat of each bar (i.e., on the IsBI, see table 2) for the example trials, in advance of the experimental trials. Note that one march (2 Hz) and one waltz (2.5 Hz) from the metric perceptual test were used as examples in this task. Therefore, there were four example trials (one march and one waltz both repeated twice) and 56 experimental trials (14 marches and 14 waltzes, each repeated twice).

After the tapping task, participants were asked to tap at a steady tempo without any auditory stimulus to assess regular movement production. Finally, to test basic auditory-motor synchronization abilities, participants were asked to tap in synchrony with a metronome click (2 Hz, IBI = 500 ms).

Equipment.

The study was conducted in a soundproof studio. Stimuli were presented at a comfortable volume level through Beyerdynamic DT 990 Pro headphones. The stimuli for the perception task were presented on a PC running E-Prime, and participants made their responses on a computer keyboard. For the synchronization task, key depressions were recorded by a customized program written in MAX that also controlled stimuli presentation. There was a systematic 3 ms delay between stimulus generation by Max and sound production due to buffering in the sound card. Tapping was done on a white key of a MIDI controller (a 3-octave piano keyboard), connected to the parallel port of the computer. Audible feedback was negligible, and further masked for the participants by the headphones.

Results and comments

Metric perceptual test.

The mean score for the metric evaluation test was 26.72 out of 30 (*SD* = 4.19). We present the distribution on Figure 2. This distribution looks highly asymmetric with negative skewness and a mode of 30. Therefore, as a group, participant performed very well on this task. Poor performance on this task was defined as obtaining a score at least 1.5 standard deviations below the mean adapted for a one-tailed distribution because the distribution was negatively skewed. We thus established a cut-off score of 22. Sixteen participants obtained a score inferior to this cut-off: 6, 13, 28, 44, 46, 53, 55, 59, 67, 72, 78, 81, 87, 90, 93, and 95.

(Figure 2 about here)

Synchronization with music.

We used customized Matlab (The MathWorks Inc.) scripts to analyze synchronization data. To exclude reactive taps, taps corresponding to the first bar of the piano piece were discarded. For all stimuli, participants usually selected the first beat of each bar to tap to, as instructed by the experimenter in the practice trials. Taps synchronized to the second beat (and/or third beat for waltzes) were observed in 8.4% of all trials for marches and in 2.8% of all trials for waltzes. Accordingly, most participants had little difficulty identifying the first beat of each bar as a strong beat and tapping to it.

Number of taps.

We first considered the number of taps per trial for each participant. Examination of the data revealed that 13 participants tapped along with the beat (i.e., twice the expected frequency) on 1 trial, and 1 participant did this on 2 trials. In contrast, 4 participants showed the inverse pattern (i.e., tapped at half the expected frequency) on one trial, 4 participants did it on 2 trials, and 2 participants did it on 5 trials. These two behaviours were thus observed for less than 1% of the total trials for all participants. We excluded the corresponding data when considering the number of taps.

The expected number of taps on each trial is 7 (8 bars, one tap per bar, with the first bar discarded). Recall that each stimulus was presented twice. The mean number of taps across participants for marches was 6.49 (*SD* = 0.82) on the first trial and 6.86 (*SD* = 0.54) on the second trial. For waltzes it was 6.61 (*SD* = 0.67) on the first trial and 6.81 (*SD* = 0.47) on the second trial. A two-way ANOVA with trial order and metre (march/waltz) as factors revealed no significant effect of metre but a significant effect of trial order, $F(1,99) = 49.07$, $p < 0.0001$ and a significant interaction between trial order and metre, $F(1,99) = 11.51$, $p < 0.001$, due to the fact that there was no difference between march and waltz condition for the second trials, $t(99)=1.68$, $p = 0.1$.

In general participants thus showed a tendency to miss taps or to produce too long inter-tap-intervals, rather than tapping more than necessary. Participants showing mean numbers of taps 1.5 SD above or below the mean are listed in Table 3.

(Table 3 about here)

Tapping consistency.

We used circular statistics to assess synchronization consistency (Lerdahl & Jackendoff, 1983).This class of statistics is useful for representing periodic data, such that any event can be represented as a location on a unit circle. This method presents many advantages over the standard method of alignment of stimulus and response sequence on a linear scale to quantify asynchronies between taps and beats. It is particularly useful for studies on populations with no significant musical training who perform with greater variability than populations with musical training. A detailed description of this method and its advantages is provided in (Fisher, 1995). Tap times were converted to angular values and represented by points on the unit circle with the formula:

$\text{Angle}=2\pi \times (\text{beat time}-\text{tap time})/\text{IBI}.$

Missing taps resulted in no corresponding point. The inter-beat-interval (IBI) is the time period corresponding to the beat frequency. Note that we decided to consider the IBI as the denominator in the formula presented above, and not the 'inter-strong-beat-interval' (which is 2 x IBI for marches and 3 x IBI for waltzes). This allowed us to include data from trials where rare participants tapped at the beat level (see discussion under section Number of taps).

We used a measure of synchronization consistency to evaluate synchronization. For each trial, *r* is the length of a vector, V, which is the circular mean of all the angles corresponding to the individual taps. Absolute values close to zero indicate no stable phase relationship between taps and beat times (i.e., taps are randomly distributed around the circle). Absolute values close to one indicate stable synchronization, with a unimodal distribution of taps centered around V. Note that only seven participants did miss taps on second trials according to their mean numbers of taps on marches and/or waltzes (see section Number of taps). However, disgarding missing taps does not affect much the *r* values, as it consists in a circular mean.

The distribution for the synchronization consistency coefficient (*r*) averaged over all stimuli is presented in Figure 3. The distribution shape can be described by a mirror-image log-normal function (i.e., consider 1-*r* instead of *r*). A log-normal distribution shape was not surprising as our synchronization consistency coefficient is bounded by a maximal value of 1. We thus considered Log(1-*r*) instead of *r* for each trial. Note that transforming synchronization data to meet the parametric statistical assumption of normality is common with circular synchronization measures (e.g. Kirschner & Tomasello, 2010; Sowiński & Dalla Bella, 2013). Thus, for the following analyses, "synchronization consistency coefficient" (SCC) will refer to the absolute value of Log(1-*r*), and will be our index of synchronization performance (the higher the value the better the performance).

(Figure 3 about here)

A paired-sample t-test comparing SCCs for the first versus second trial, averaged across all stimuli, revealed a significant difference, $t(99) = 5.60$, $p < 0.001$.

Performance was thus better for second (*M* = 2.65, *SD* = 0.83) than first (*M* = 2.83, *SD* = 0.83) trials. This was probably due to a practice effect.

We then assessed the impact of metre and inter-strong-beat-interval (IsBI) on synchronization performance by conducting a two-level hierarchical linear regression. We chose this method for two main reasons. First, it is robust to missing data (some participants did not tap on all trials). Second, it can accommodate unbalanced designs (IsBI values were not balanced between metre conditions and we had different numbers of trials for IsBI conditions); this is not the case for repeated-measures ANOVA. We performed this statistical analysis with the nlme package Kirschner and Tomasello (2010) in R, an open-source software platform for statistical analysis.

The first-level factors were IsBI and metre. Data were nested within participants, which constituted the second-level variable. We used a 2-level hierarchical model with IsBI, metre and the interaction between these factors as predictors, and trial order as a covariate. Fixed slopes and intercepts were estimated for IsBI and metre factors, and random intercepts were estimated for each participant.

IsBI significantly predicted synchronization performance, $b = 0.50$, $SE = 0.10$, $t(5479) = 5.01$, $p < 0.0001$, with better performance for longer intervals. Metre also had a significant effect on performance, $b = 0.42$, $SE = 0.03$, $t(5479) = 16.88$, $p < 0.0001$, indicating better performance for marches than waltzes. The interaction between IsBI and metre also predicted performance, $b = 0.5$, $SE = 0.10$, $t(5479) = 5.03$, $p < 0.0001$. Figure 4 represents synchronization consistency coefficients averaged across participants for different IsBIs and metres.

(Figure 4 about here)

We suspected no difference across IsBI for marches but a significant effect of this factor for waltzes. This pattern would explain the significant interaction between metre and IsBI. This was confirmed by simple effects hierarchical regressions for each metre condition. We found no significant impact of IsBI on performance for marches, but a significant impact for waltzes, $b = 0.99$, $SE = 0.10$, $t(2691) = 9.54$, $p < 0.0001$.

Despite their statistically significant effect, both IsBI and metre explained a very small percentage of the variability in the synchronization consistency coefficient's scores, $r^2_{\text{IsBI}} = 0.002$, $r^2_{\text{metre}} = 0.048$. The vast majority of the variability observed in the synchronization data was occurring between subjects. Accordingly, in order to identify cases of beat deafness, we computed a single global SCC for each participant, by collapsing across metre and IsBI. Additionally, we decided to include data from the second trial only (considering the first trial as practice), in order to best represent participants' synchronization abilities. The distribution of these global SCCs and descriptive statistics are provided in Figure 5.

(Figure 5 about here)

The global SCC distribution is significantly non-normal, as assessed by the Shapiro-Wilk test, $W = 0.95$, $p < 0.05$. This is a result of a slight negative skew (-0.81) in the otherwise normal-shaped distribution. This negative tail represents participants with poor synchronization scores. As with the metric test, those with scores at least 1.5 SD below the mean were considered as impaired. SCCs for the 9 impaired participants, henceforth referred to as "poor music synchronizers" are presented in Table 4.

(Table 4 about here)

We further asked whether synchronization performance was related to variability across trials, i.e., whether good music synchronizers performed consistently well and whether poor music synchronizers performed with high variability, across all trials. To do so, we calculated the correlation between the global coefficient and the standard deviation of the 28 synchronization consistency coefficients comprising the global coefficient for each participant. After excluding poor music synchronizers, we found a significant negative correlation, r = -0.48, $p < 0.001$. This indicates that synchronization performance inversely predicted variability, with better synchronizers having a general tendency to perform consistently across trials, and vice versa. This relation is presented in Figure 6. Inspection of Figure 6 suggests a possible sub-grouping of poor music synchronizers into those that perform consistently poorly (i.e., 6, 18, 53, 80 and 93), and those who perform erratically across trials (i.e., 31, 37, 54 and 97). It is worth noting that all poor music synchronizers (except 31 and 53), despite their impairment, obtained a mean score superior for marches than for waltzes. Recall that this is the pattern seen across all participants.

(Figure 6 about here)

Synchronization with the metronome.

Phase-locking and tapping consistency.

To assess performance when tapping to the metronome, we first checked, for each trial, whether taps had a common mean direction (as opposed to being uniformly distributed around the circle), using the Rayleigh test (Pinheiro, Bates, DebRoy, & Sarkar, 2007). This test asks how large the length of vector V must be to reject the hypothesis of a uniform distribution (see section Tapping consistency for a description of vector V). It provides a way to assess if taps are significantly phase-locked to the metronome clicks. We performed this analysis with the circular statistics toolbox for Matlab (Wilkie, 1983)[1]. Previous examination of the data set revealed that two participants performed in unexpected ways. Participant 21 started to tap on every click, then after eight taps switched and tapped on one click out of four clicks for the rest of the sequence. Participant 90 interrupted his taps several times (taking ~2 s breaks). The fact that participants 21 and 90's taps were significantly phase-locked to the metronome indicate a probable misunderstanding of the instruction.

All participants except 81 produced significantly phase-locked taps ($p < 0.001$). Next, for each participant we calculated the SCC to assess consistency of taps to the metronome (see section Tapping consistency for a description of how to calculate SCC). We obtained a mean coefficient of 3.2 (*SD* = 0.82). Six participants obtained a coefficient inferior to 1.5 SD below the mean, indicating low consistency: 15, 18, 22, 43, 54 and 81.

Tapping accuracy.

For participants showing evidence of entrainment (performance above chance level as indicated by a significant Rayleigh test, i.e., everyone but 81), we used φ, the relative angle of V, to measure how close the taps occurred relative to the stimulus beat. Perfect synchronization is indicated by a φ of zero. Positive φ values indicate late taps, while negative values indicate early taps. Note that before calculating V, we removed 2.16 degrees from angles corresponding to individual taps, due to the

---

[1] Note that it was not appropriate to perform the Rayleigh test on music synchronization data due to insufficient number of taps on each trial.

constant 3 ms delay in our set-up. Circular distribution of φ values is presented in Figure 7. Values ranged from -128.8 to +68.38 degrees (-179 to +95 ms, or 35.8% to 19% of the inter-onset interval). Eighty-four participants had a negative mean angle, i.e., tended to tap in advance to metronome clicks. This result is in agreement with the tapping literature, and is commonly referred to as the negative mean asynchrony (for a review, see Repp, 2005). The circular mean angle was -24.7 degrees.

(Figure 7 about here)

Finally, we asked whether tapping consistency (SCC) was related to tapping accuracy (absolute value of φ). We found a significant negative correlation, Spearman's r = -0.47, $p < 0.0001$, indicating that participants who are consistent also tend to be accurate in their taps.

We report angles of participants identified in the preceding section as 'poor music synchronizers' in Table 6. Participant 6 showed a positive angle, indicating reactive taps, while all other participants showed negative angles. It is worth noting that participant 18 had the most negative angle in the whole sample. However, as a group, the poor music synchronizers are evenly distributed in terms of metronome tapping accuracy.

(Table 5 about here)

Spontaneous tapping.

We assessed regularity of participants' spontaneous tapping with the coefficient of variation (CV) of the inter-tap intervals (ITIs), which is the standard deviation of the ITIs divided by the mean ITI. We calculated the coefficient of variation of the first 5-

35 taps for each participant. The mean CV was 0.0421 (*SD* = 0.0154). Five participants obtained a coefficient superior to 1.5 SD above the mean: 18 (CV=0.115), 35 (CV=0.074), 67 (CV=0.092), 71 (CV=0.069) and 80 (CV=0.086).

Individual differences.

Poor music synchronizers.

As described earlier, 9 participants were impaired when synchronizing with the musical excerpts: 6, 18, 31, 37, 53, 54, 80, 93 and 97. Except for participant 6, all of them had a tendency to produce less taps than what was expected. A summary of all poor music synchronizers performances described above is provided in Table 6.

Of this group, participants 18, 54, and 80 demonstrated difficulties not restricted to the beat-finding tasks. 18 and 54 performed poorly when synchronizing with the metronome, and participants 18 and 80 were irregular in their spontaneous tapping. These three participants' deficits might be due to an internal timing problem, a fine motor deficit or deficient auditory-motor mapping. Future testing is needed to further assess these deficits.

All other poor music synchronizers obtained normal scores when synchronizing to the metronome and produced regular spontaneous tapping. Accordingly, we can exclude the presence of internal timing problems, motor deficits or general synchronization impairments among participants 6, 31, 37, 53, 93 and 97. Among them, 6, 53 and 93 obtained a poor score at the metric task, and 37 and 53 were below the cut-off on the 'off-beat' subtest of the on-line amusia test. Participants 6, 37, 53 and 93 were thus impaired on both beat perception and synchronization. Therefore we will consider these four individuals as new beat deaf cases. Participants 31 and 97 are potentially beat-deaf, but since they show only a beat synchronization deficit, further testing will be required determine the extent of their beat-finding impairment.

Interestingly, participants 6, 37, 93 and 97 were not aware of any deficit related to beat-finding abilities. In fact, they replied ‘No’ to the question ‘Do you have any music-related difficulties?’ and ‘Yes’ to the question ‘Are you able to follow a musical beat ?’. Participants 31 and 53 declared to have difficulty to synchronize movements to the rhythm of music during formal dance classes and participant 53 declared that she was not able to follow the beat in music.

(Table 6 about here)

Other atypical performers.

Four participants synchronized poorly (as measured by SCC) to the metronome but not to music: 15, 22, 43 and 81. In their case, poor synchronization scores are probably due to boredom, as the task was performed at the end of a 2 hour testing session. It also might be due to poor fine motor synchronization abilities. Such an impairment might be better detected in the metronome than the music task, due to higher variability in the latter. Three participants showed poor regularity when producing spontaneous tapping despite normal synchronization abilities: 35, 67 and 71. Again, this might be due to boredom, or to an internal timing problem. Ten participants (13, 28, 44, 46, 55, 59, 72, 78, 87, 95) obtained poor scores at the metric evaluation test (perception) despite no other synchronization or movement production deficits. This might be due to a misunderstanding of the instructions.

Conclusion.

To summarize, six participants were specifically impaired when synchronizing with a musical beat. Participants 6, 37, 53 and 93 are considered as new beat deaf cases, while the nature of the difficulty experienced by participants 31 and 97 is not clear and will require further testing. Three participants (18, 54 and 80) were impaired when synchronizing with music. However, their deficit is probably not specific to beat-finding mechanisms. Finally, 10 participants obtained poor scores on the MBEA metric test while showing normal synchronization and movement production. This result supports the hypothesis that the MBEA metric test is not appropriate to diagnose beat deafness without synchronization assessment.

General Discussion

In the present study, we refined the metric perceptual test of the MBEA to screen for beat deafness in a large sample, by adding a synchronization test The vast majority (81%) of our participants performed well at both tasks, confirming that good beat-finding abilities are widespread in the normal population (e.g. Sowinski & Dalla Bella, 2013).

Nine individuals exhibited remarkable synchronization difficulties. Four of them were specifically impaired when synchronizing to musical stimuli (but not to an isochronous metronome click). Moreover, these individuals also performed poorly on the metric test and/or the on-line off-beat test. We can thus reasonably ascribe their impairment to deficient beat perception. Their deficit is very similar to what was observed with the first documented case of beat deafness (Phillips-Silver et al., 2011), and we consider these individuals to be new beat deaf cases.

Two participants were impaired for music synchronization but performed in a normal range on the metric perceptual test. This profile is quite similar to a case reported in a recent paper (Sowiński & Dalla Bella, 2013). The authors proposed the term ‘pure sensorimotor coupling disorder’ instead of beat deafness to characterize the observed deficit. The anisochrony detection task they used to assess perception, in which the penultimate beat of a musical phrase occurs earlier or later than expected based on previous inter-beat-intervals. This is very similar to the on-line ‘off-beat’ test used to pre-screen participants in our study. However, such tests might be inappropriate for beat and metre perception evaluation. Indeed, they might tap perceptual mechanisms that are not specific to beat perception (gap detection for example). Alternatively, one could use the MBEA metric test to assess perception. However, the metric perceptual test is not very sensitive, as discussed before. We thus see that these two assessments of beat perception are not reliable enough to address a possible dissociation between perception and synchronization in beat finding. To compensate, future research should exploit more direct measures of beat processing, such as those offered by neurophysiology. For example, Nozaradan, Peretz, Missal, and Mouraux (2011) recently developed a technique in electroencephalography that captures neuronal entrainment to complex rhythms by eliciting beat-related steady-state evoked potentials. For now, we argue that a deficit in beat perception should not be excluded on a permanent basis in cases showing poor music synchronization accompanied by a normal score on current tests of beat perception.

In the same way that we need to refine how we measure beat perception, we should also refine how we measure synchronization. For example, we may ask whether the observed synchronization difficulties generalize to full-body movements (bouncing, clapping, dance, etc), as we know that the vestibular system pays a role in metric encodin coupling (Jessica Phillips-Silver & Trainor, 2005, 2007, 2008). Future reasearch will examine full-body synchronization with music in normal and impaired populations.

Finally, three other participants showed poor consistency when synchronizing to a an isochronous sequence and/or poor regularity in spontaneous movement production. Therefore, their deficit might not be specific to beat perception or synchronization, but rather might be due to internal timing or synchronization problems that are not specific to music. For now, they can't be considered as new beat cases. However, their profile is of remarkable interest for the validation of several cognitive models of tapping synchronization which have proposed that an internal timekeeper and correction mechanisms are involved in auditory-motor coupling (Repp, 2008; Repp, Keller, & Jacoby, 2012; Vorberg & Schulze, 2002). In these models, periodic beats are generated by an internal timekeeper and correction mechanisms make period and phase adjustments so that synchronization to the pacing stimulus can be achieved. The timekeeping mechanism has traditionally been explained by a pacemaker–accumulator model, but it has been recently proposed that timing would be dictated by coincidental activation detection of different neural populations (for a review see Buhusi & Meck, 2005). If we find that the synchronization deficit observed in some participants is due to impaired time generation mechanisms, this would provide further evidence of the crucial role of the timekeeper in sensory-motor synchronization models. More testing thus should be conducted with participants who were impaired in metronome synchronization and spontaneous beat production tasks to further assess the origin of their deficit.

The nine impaired profiles described above stand in sharp contrast with the precise synchronization observed in the general population. Interestingly, these cases share many similarities with behaviors associated with Parkinson's disease. Parkinson's disease is characterised by damage to the basal ganglia, which leads to problems with beat perception and the rhythmic production (Grahn & Brett, 2007, 2009). Moreover, we know that the dorsal premotor cortex plays a particularly important role in synchronization to an auditory beat on both the left and right side of the brain (Chen et al., 2009). Now that we have a group of several cases similar to Mathieu, the use of neuroimaging methods to study beat deafness is possible. Future work will assess the presence of anatomical and functional anomalies in brain regions previously associated with beat-finding in beat deaf individuals. This work will enable the further exploration of the role of these cerebral areas in beat-finding.

Interestingly, two of our new beat deaf cases were sisters. One previous family aggregation study has shown that the pitch deafness form of congenital amusia, a disorder of musical pitch, is hereditary (Peretz et al., 2002). Similar research with the families of beat deafs would enable us to search for a possible hereditary component for beat deafness.

In conclusion, beat deafness gives us a rare chance to examine the neurocognitive basis of synchronization behavior. The first step in this research enterprise was to identify individuals showing this deficit. Here we accomplished that goal by refining the metric perceptual test of the MBEA. Our priority for future research will be to further our ability to characterize the cognitive mechanisms of beat-finding through the study of beat deafness.

Table 1. Description of participant's musical training

	% of participants
No musical training	29
Self-learned (> 7 years of practice)	7
3 or less year of formal music classes	17
3 to 5 years of formal music classes	22
6 or more years of formal music classes	20
Professional or semi-professional musicians	6

Table 2. Description of stimuli

Tempo (BPM)	Beat frequency (Hz)	IBI (ms)	Marches	Waltzes	IsBI (ms)
100	1.67	600	5	0	1200
120	2	500	9	2	1000/1500
133	2.2	450	1	0	900
150	2.5	400	0	11	1200
180	3	333	0	1	1000
200	3.34	300	0	1	900

Table 3. Participants with extreme mean numbers of taps

Type of stimulus	Participants with a mean number of taps < *M*-1.5 *SD*		Participants with a mean number of taps > *M*+1.5 *SD*	
	Trial 1	Trial 2	Trial 1	Trial 2
Marches	3 18 31 35 46 53 74 77 78 93 97	18 24 31 53 93 97	6	6 77
Waltzes	18 31 35 46 68 93 97	18 31 53 70 93 97	6	6 90

Table 4. Individual SCC of participants below the cut-off on second trial (*M* = 2.83, *SD* = 0.83)

Participant	Synchronization Consistency Coefficient
6	0.63
18	0.55
31	1.32
37	1.41
53	1.04
54	1.33
80	0.66
93	0.69
97	1.56

Table 5. Synchronization with metronome: φ values of participants identified as 'Poor music synchronizers'

Participant	*Φ* value
6	16.55
18	-128.8
31	-59.11
37	-22.31
53	-86.46
54	-53.54
80	-39.44
93	-35.45
97	-19.69
Mean	-24.7

Table 6. Summary of Poor music synchronizers performances. Poor scores are indicated in bold.

Poor music synchronizers (participant's code)	Metronome (SCC: *M* = 3.2, *SD* = 0.82, cut-off : <1.97)	Spontaneous (CV : *M* = 0.042, *SD* = 0.015, cut-off : > 0.065)	MBEA metric test (score/30, cut-off: >22)	On-line 'off-beat' test (cut-off: >67%)
6	2.9	0.043	**13**	79
18	**1.83**	**0.109**	24	88
31	3.22	0.032	27	79
37	2.62	0.047	26	**54**
53	2.04	0.062	**22**	**63**
54	**1.44**	0.038	27	79
80	3.63	**0.09**	25	**63**
93	2.68	0.053	**20**	75
97	2.8	0.036	26	75

Figure 1. Waveforms and musical score of a waltz stimulus (top waveform is synchronization and bottom waveform is perception).

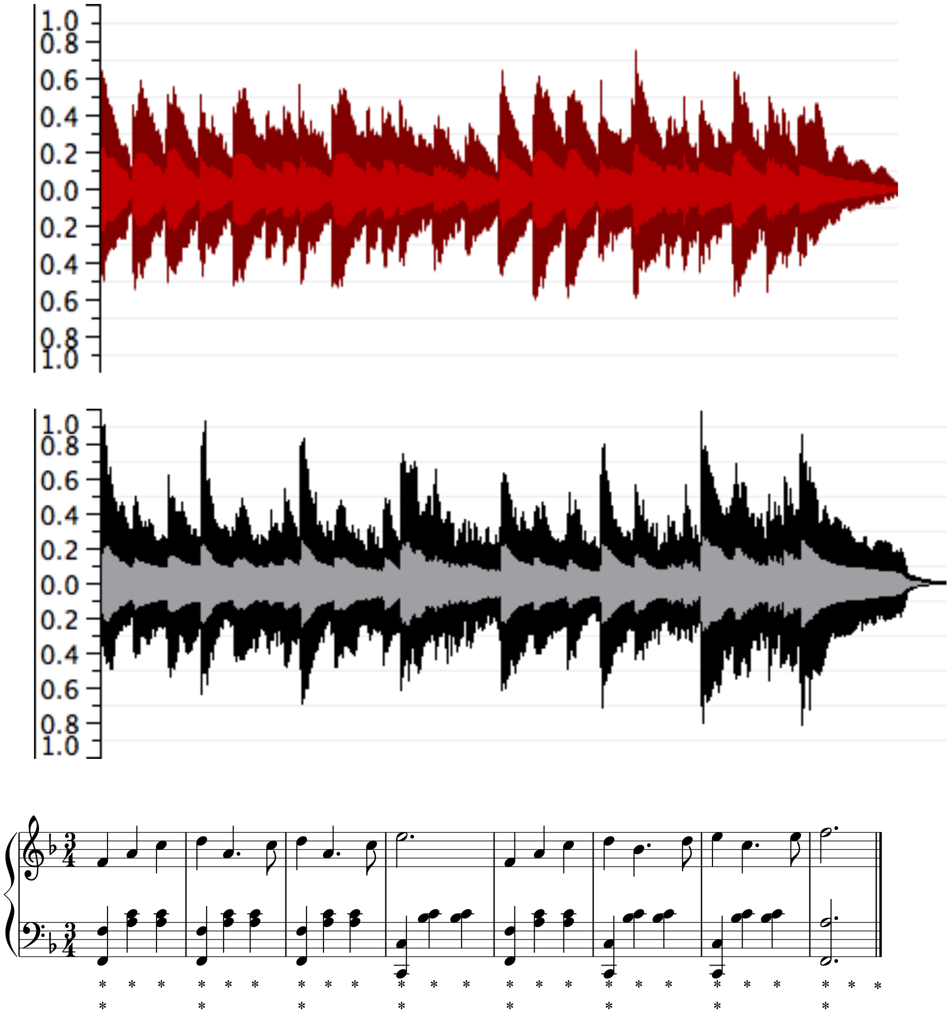


Figure 2. Distribution of scores on metric perceptual test for 100 participants A score of 15 represents chance

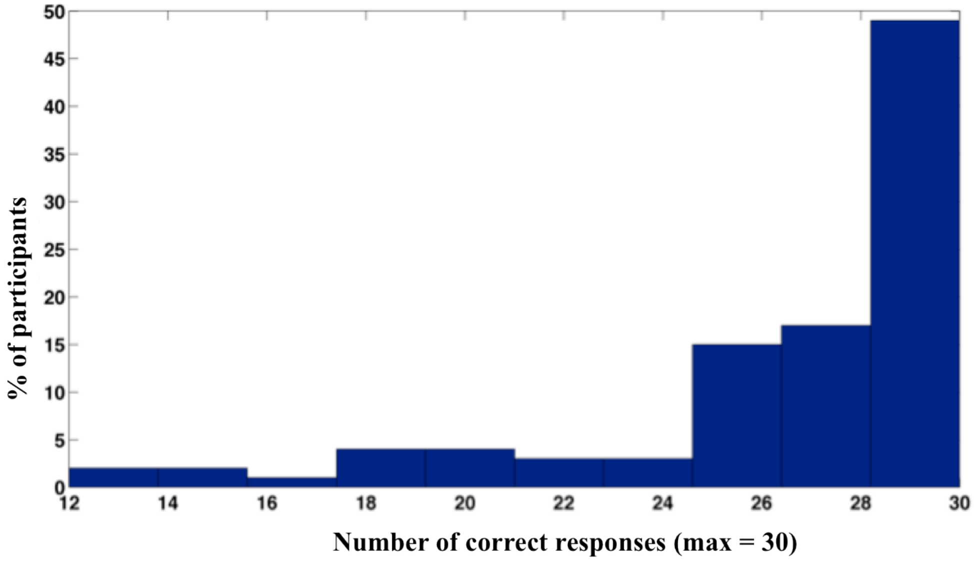


Figure 3. Distribution of averaged synchronization consistency coefficient.

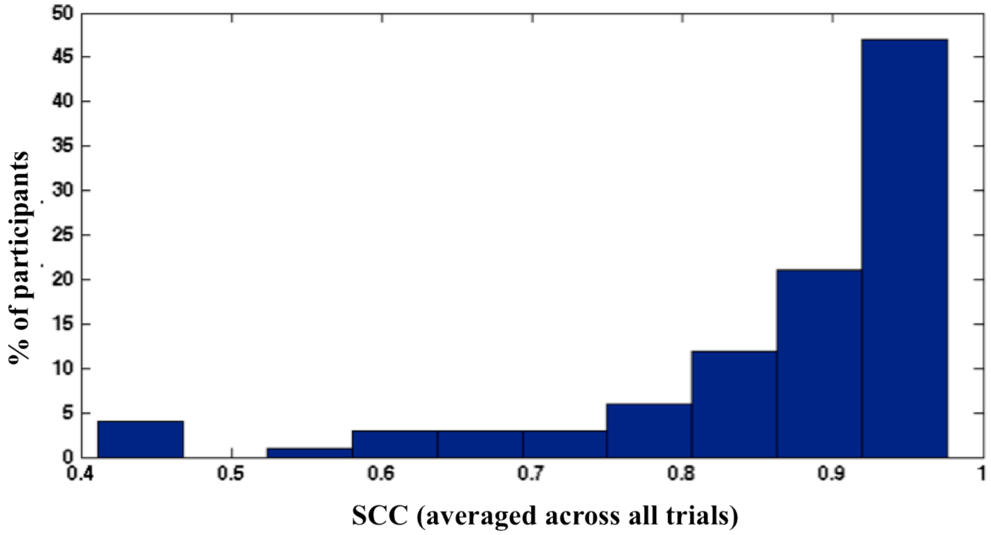


Figure 4. Synchronization consistency coefficients for each IsBI and metre, averaged across participants.

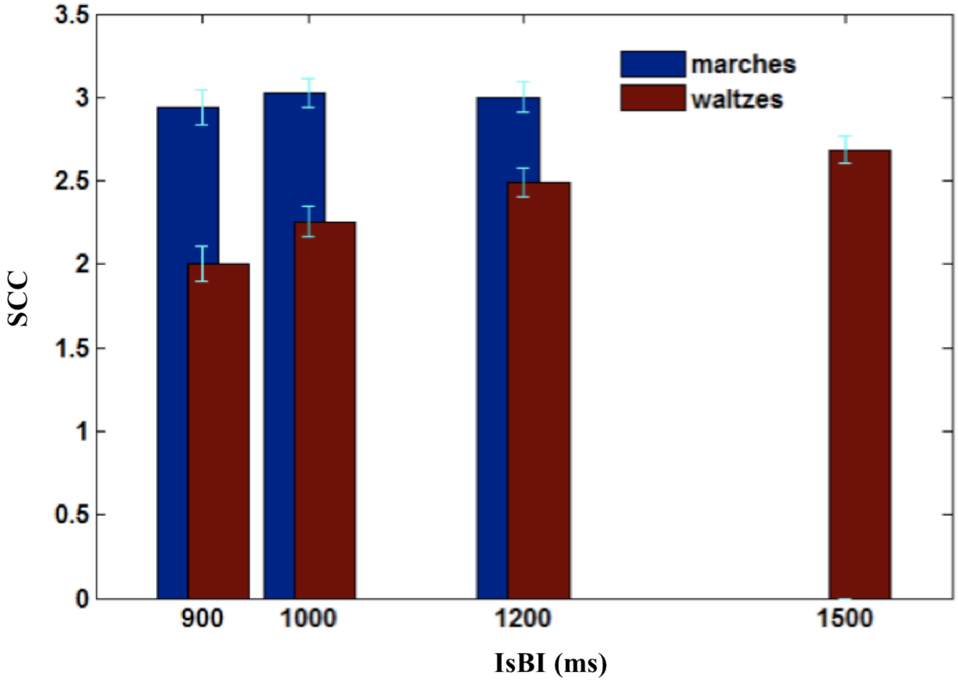


Figure 5. Distribution of global synchronization consistency coefficient for all participants.

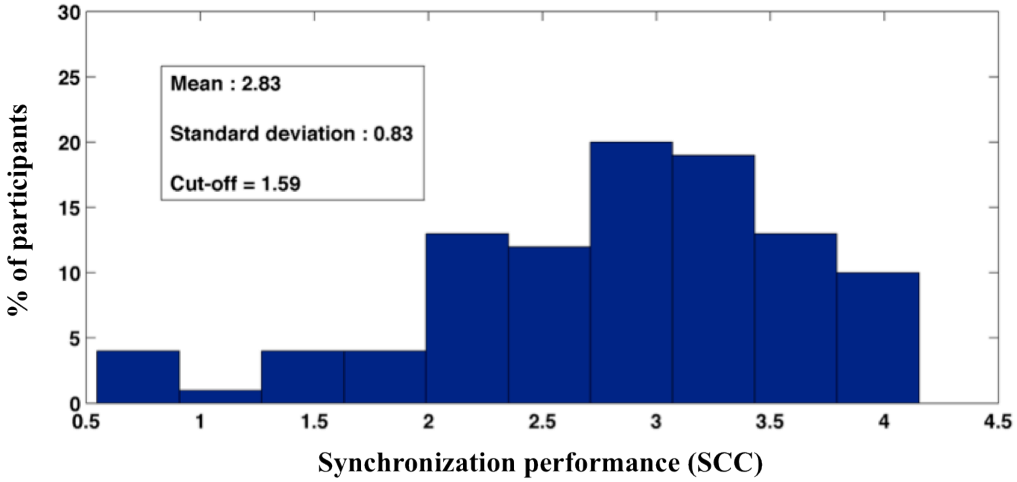


Figure 6. Variability across trials plotted against global SCC. Magenta lines represent the mean minus 1.5 standard deviations.

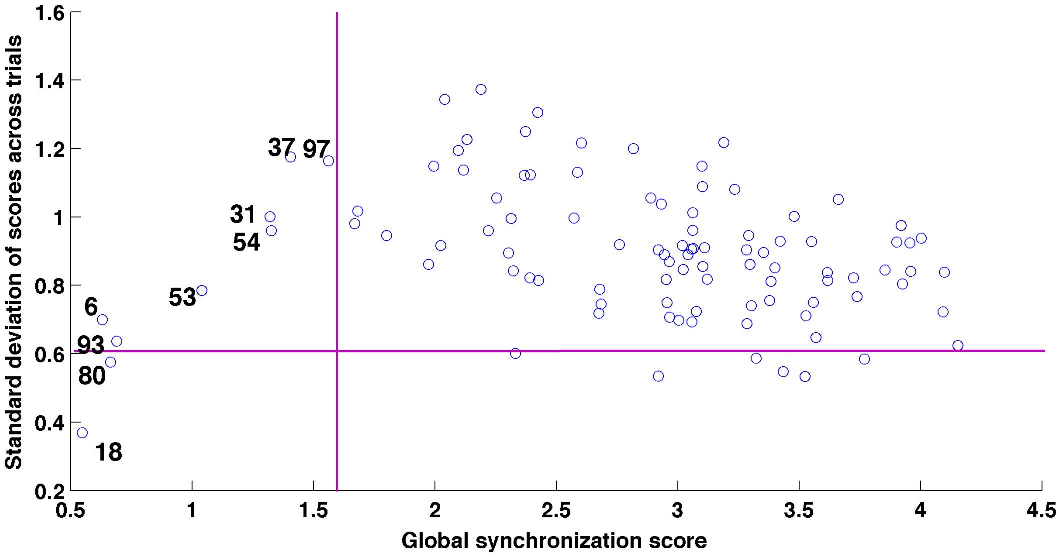
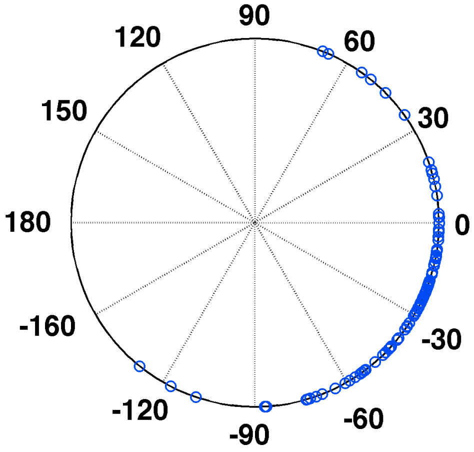


Figure 7. Distribution of φ values for all participants. A value of zero indicate perfectly synchronized taps.



Conclusion

Beaucoup reste à découvrir sur ce trouble particulier de la cognition musicale qu'est le *beat deafness*. Les résultats obtenus grâce à ce projet permettront de mieux comprendre les mécanismes qui sous-tendent la perception du *beat* musical et la synchronisation sur celui-ci dans la population normale. De plus, les nouveaux cas identifiés nous permettent à présent de conduire les études qui nous permettront mieux cerner le trouble et d'en caractériser les bases neurales et fonctionnelles. C'est donc avec beaucoup d'enthousiasme que j'y consacrerai les années à venir dans le cadre de ma recherche de doctorat.

Bibliographie

Buhusi, C. V., & Meck, W. H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews Neuroscience*, *6*(10), 755-765.

Cannam, Chris, Landone, Christian, & Sandler, Mark. (2010). *Sonic visualiser: An open source application for viewing, analysing, and annotating music audio files.* Paper presented at the Proceedings of the international conference on Multimedia.

Chen, Joyce L, Penhune, Virginia B, & Zatorre, Robert J. (2009). The role of auditory and premotor cortex in sensorimotor transformations. *Annals of the New York Academy of Sciences, 1169*(1), 15-34.

Epstein, David. (1995). *Shaping time: Music, the brain, and performance*: Schirmer Books New York.

Fisher, Nicholas I. (1995). *Statistical analysis of circular data*: Cambridge University Press.

Fries, Wolfgang, & Swihart, Andrew A. (1990). Disturbance of rhythm sense following right hemisphere damage. *Neuropsychologia, 28*(12), 1317-1323.

Kirschner, Sebastian, & Tomasello, Michael. (2010). Joint music making promotes prosocial behavior in 4-year-old children. *Evolution and Human Behavior, 31*(5), 354-364.

Large, Edward W. (2008). Resonating to musical rhythm: theory and experiment. *Psychology of time*, 189-232.

Lerdahl, FRED AUTOR, & Jackendoff, Ray S. (1983). *A generative theory of tonal music*: The MIT Press.

Liégeois-Chauvel, Catherine, Peretz, Isabelle, Babaï, Myriam, Laguitton, Virginie, & Chauvel, Patrick. (1998). Contribution of different cortical areas in the temporal lobes to music processing. *Brain, 121*(10), 1853-1867.

McCloskey, Michael. (2001). The future of cognitive neuropsychology. *The handbook of cognitive neuropsychology*, 593-610.

Meyer, Leonard, & Cooper, Grosvenor. (1960). The rhythmic structure of music: Chicago: The University of Chicago Press.

Nettl, Bruno. (2000). An ethnomusicologist contemplates universals in musical sound and musical culture. *The origins of music*, 463-472.

Nozaradan, Sylvie, Peretz, Isabelle, Missal, Marcus, & Mouraux, André. (2011). Tagging the neuronal entrainment to beat and meter. *The Journal of Neuroscience, 31*(28), 10234-10240.

Palmer, Caroline, & Krumhansl, Carol L. (1990). Mental representations for musical meter. *Journal of Experimental Psychology: Human Perception and Performance, 16*(4), 728.

Peretz, Isabelle. (1990). Processing of local and global musical information by unilateral brain-damaged patients. *Brain, 113*(4), 1185-1205.

Peretz, Isabelle. (2001). Brain specialization for music. *Annals of the New York Academy of Sciences, 930*(1), 153-165.

Peretz, Isabelle, Ayotte, Julie, Zatorre, Robert J, Mehler, Jacques, Ahad, Pierre, Penhune, Virginia B, & Jutras, Benoît. (2002). Congenital amusia: a disorder of fine-grained pitch discrimination. *Neuron, 33*(2), 185-191.

Peretz, Isabelle, Champod, Anne Sophie, & Hyde, Krista. (2003). Varieties of musical disorders. *Annals of the New York Academy of Sciences, 999*(1), 58-75.

Peretz, Isabelle, Gosselin, Nathalie, Tillmann, Barbara, Cuddy, Lola L, Gagnon, Benoît, Trimmer, Christopher G, . . . Bouchard, Bernard. (2008). On-line identification of congenital amusia. *Music Perception: An Interdisciplinary Journal, 25*(4), 331-343.

Phillips-Silver, J., Toiviainen, P., Gosselin, N., Piche, 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. doi: 10.1016/j.neuropsychologia.2011.02.002

Phillips-Silver, Jessica, & Trainor, Laurel J. (2005). Feeling the beat: Movement influences infant rhythm perception. *Science, 308*(5727), 1430-1430.

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

Phillips-Silver, Jessica, & Trainor, Laurel J. (2008). Vestibular influence on auditory metrical interpretation. *Brain and Cognition, 67*(1), 94-102.

Pinheiro, Jose, Bates, Douglas, DebRoy, Saikat, & Sarkar, Deepayan. (2007). Linear and nonlinear mixed effects models. *R package version, 3*, 57.

Polk, Marsha, & Kertesz, Andrew. (1993). Music and language in degenerative disease of the brain. *Brain and Cognition, 22*(1), 98-117.

Repp, Bruno H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review, 12*(6), 969-992.

Repp, Bruno H. (2008). Perfect phase correction in synchronization with slow auditory sequences. *Journal of Motor Behavior, 40*(5), 363-367.

Repp, Bruno H, Keller, Peter E, & Jacoby, Nori. (2012). Quantifying phase correction in sensorimotor synchronization: empirical comparison of three paradigms. *Acta psychologica, 139*(2), 281-290.

Repp, Bruno H, & Su, Yi-Huang. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic bulletin & review*, 1-50.

Sowiński, Jakub, & Dalla Bella, Simone. (2013). Poor synchronization to the beat may result from deficient auditory-motor mapping. *Neuropsychologia*.

Vorberg, Dirk, & Schulze, Hans-Henning. (2002). Linear phase-correction in synchronization: Predictions, parameter estimation, and simulations. *Journal of Mathematical Psychology, 46*(1), 56-87.

Wilkie, D. (1983). Rayleigh test for randomness of circular data. *Applied statistics, 32*(3), 311-312.