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Uncovering beat deafness: Detecting rhythm disorders with synchronized finger tapping and perceptual timing tasks

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Abstract:	A set of behavioral tasks for assessing perceptual and sensorimotor timing abilities in the general population (i.e., non-musicians) is presented here with the goal of uncovering rhythm disorders, such as beat deafness. Beat deafness is characterized by poor performance in perceiving durations in auditory rhythmic patterns or poor synchronization of movement with auditory rhythms (e.g., with musical beats). These tasks include the synchronization of finger tapping to the beat of simple and complex auditory stimuli and the detection of rhythmic irregularities (anisochrony detection task) embedded in the same stimuli. These tests, which are easy to administer, include an assessment of both perceptual and sensorimotor timing abilities under different conditions (e.g., beat rates and types of auditory material) and are based on the same auditory stimuli, ranging from a simple metronome to a complex musical excerpt. The analysis of synchronized tapping data is performed with circular statistics, which provide reliable measures of synchronization accuracy (e.g., the difference between the timing of the taps and the timing of the pacing stimuli) and consistency. Circular statistics on tapping data are particularly well-suited for detecting individual differences in the general population. Synchronized tapping and anisochrony detection are sensitive measures for identifying profiles of rhythm disorders and have been used with success to uncover cases of poor synchronization with spared perceptual timing. This systematic assessment of perceptual and sensorimotor timing can be extended to populations of patients with brain damage, neurodegenerative diseases (e.g., Parkinson's disease), and developmental disorders (e.g., Attention Deficit Hyperactivity Disorder).
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Dear Dr. Upponi:

Please find enclosed the revised manuscript submitted to *JoVE* (JoVE51761R2) entitled "Uncovering beat deafness: Detecting rhythm disorders with synchronized finger tapping and perceptual timing tasks". In the revised manuscript, Editorial and Reviewers' comments were carefully addressed, as indicated in the rebuttal letter. We are grateful to the Editor and to the Reviewers for the thorough review of the manuscript. We are confident that the revisions contributed to improve the quality of the manuscript.

Thank you for your attention, and we look forward to hearing from you.

Sincerely,

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TITLE: Uncovering beat deafness: Detecting rhythm disorders with synchronized finger tapping and perceptual timing tasks

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SHORT ABSTRACT:
Behavioral tasks that allow for the assessment of perceptual and sensorimotor timing abilities in the general population (i.e., non-musicians) are presented. Synchronization of finger tapping to the beat of an auditory stimuli and detecting rhythmic irregularities provides a means of uncovering rhythm disorders.

LONG ABSTRACT:
A set of behavioral tasks for assessing perceptual and sensorimotor timing abilities in the general population (i.e., non-musicians) is presented here with the goal of uncovering rhythm disorders, such as beat deafness. Beat deafness is characterized by poor performance in perceiving durations in auditory rhythmic patterns or poor synchronization of movement with auditory rhythms (e.g., with musical beats). These tasks include the synchronization of finger tapping to the beat of simple and complex auditory stimuli and the detection of rhythmic irregularities (anisochrony detection task) embedded in the same stimuli. These tests, which are easy to administer, include an

assessment of both perceptual and sensorimotor timing abilities under different conditions (e.g., beat rates and types of auditory material) and are based on the same auditory stimuli, ranging from a simple metronome to a complex musical excerpt. The analysis of synchronized tapping data is performed with circular statistics, which provide reliable measures of synchronization accuracy (e.g., the difference between the timing of the taps and the timing of the pacing stimuli) and consistency. Circular statistics on tapping data are particularly well-suited for detecting individual differences in the general population. Synchronized tapping and anisochrony detection are sensitive measures for identifying profiles of rhythm disorders and have been used with success to uncover cases of poor synchronization with spared perceptual timing. This systematic assessment of perceptual and sensorimotor timing can be extended to populations of patients with brain damage, neurodegenerative diseases (e.g., Parkinson's disease), and developmental disorders (e.g., Attention Deficit Hyperactivity Disorder).

INTRODUCTION:

Humans are particularly efficient at processing the duration of events occurring in their environment[1]. In particular, the ability to perceive the beat of music or the regular ticking of a clock and the ability to move along with it (e.g., in dance or synchronized sports) is widespread in the general population (i.e., in individuals who have not received musical training)[2,3]. These abilities are underpinned by a complex neuronal network involving cortical brain regions (e.g., the premotor cortex and the supplementary motor area) and subcortical structures, such as the basal ganglia and the cerebellum[4,5,6,7].

Disruption of this network and consequent poor temporal processing can result from brain damage[8,9,10] or neuronal degeneration, as observed in patients with Parkinson's disease[11]. However, poor perception of duration and poor synchronization to the beat of music can also manifest in healthy individuals in the absence of brain damage. In spite of the fact that the majority can perceive auditory rhythms and synchronize their movement to the beat (e.g., in music), there are notable exceptions. Some individuals have major difficulties in synchronizing their body movements or finger tapping to the beat of music and can exhibit poor beat perception, showing difficulties in discriminating melodies with notes of different duration. This condition has been referred to as "beat deafness" or "dysrhythmia." [2,12,13,14] For example, beat deafness was described in a recent study[13], in which the case of a patient named Mathieu was reported. Mathieu was particularly inaccurate at bouncing to the beat of rhythmical songs (e.g., a Merengue song). Synchronization was still possible, but only to the sounds of a simple isochronous sequence (e.g., a metronome). Poor synchronization was associated with poor beat perception, as revealed by the Montreal Battery of Evaluation of Amusia (MBEA)[15]. In an additional task, Mathieu was asked to match the movements of a dancer to the music; interestingly, Mathieu exhibited unimpaired pitch perception.

Poor rhythm perception and poor synchronization, in beat-deaf individuals with spared pitch perception, were observed in further studies[2,12,14], thus providing compelling evidence that rhythm disorders can occur in isolation. Beat deafness is therefore distinct from the typical description of congenital amusia (i.e., tone deafness), a neurodevelopmental disorder affecting pitch perception and production[16,17,18,19].

Interestingly, poor rhythm perception and production can co-occur with poor pitch processing in congenital amusia[12,16,20]. Nevertheless, poor rhythm perception in this case depends on the ability of an individual to perceive pitch variation. When pitch variations in melodies are removed, congenital amusics can successfully discriminate rhythm differences[21].

Important individual differences have been observed in beat deafness; this fact deserves particular attention. In most cases, both rhythm perception and synchronization to the beat of music are deficient[2,12,13,14]; however, poor synchronization can also occur when rhythm perception is spared[2]. This dissociation between perception and action in the timing domain has been shown using synchronized tapping tasks with a variety of rhythmic auditory stimuli (e.g., a metronome and music) and using different rhythm perception tasks (e.g., the discrimination of melodies based on different note durations and the detection of deviations from isochrony in rhythmic sequences). This finding is particular relevant because it points to the possible separation of perception and action with regard to timing mechanisms, as previously observed in pitch processing[17,22,23,24,25]. Further dissociations were highlighted depending on the stimulus complexity[2]. Most poor synchronizers exhibited selective difficulties with complex stimuli (e.g., music or amplitude-modulated noise derived from music), while they still showed accurate and consistent synchronization with simple isochronous sequences; other poor synchronizers showed the opposite pattern. In summary, these results converge in indicating that there are a variety of phenotypes of timing disorders in the general population (as observed in other domains of musical processing such as pitch[25,26]), which require a sensitive set of tasks to be detected. Characterizing the patterns of rhythm disorders is particularly relevant to shed light on the specific mechanisms that are malfunctioning in the timing system.

The goal of the method illustrated here is to provide a set of tasks that can be used to uncover cases of beat deafness in the general population and detect different subtypes of timing disorders (e.g., affecting perceptual vs. sensorimotor timing or a particular class of rhythmic stimuli). Sensorimotor timing abilities have mostly been examined using finger tapping tasks with auditory material. Participants are asked to tap their index finger in synchrony with auditory stimuli, such as to a sequence of tones equally spaced in time or to music (i.e., in a *synchronized* or *paced* tapping task[27,28,29]). Another popular paradigm, which has been the source of considerable modeling efforts[29,30,31,32], is the synchronization-continuation paradigm, in which the participant continues tapping at the rate provided by a metronome after the sound has stopped. Rhythm perception is studied with a variety of tasks ranging from duration discrimination, estimation, bisection (i.e., comparing durations to "short" and "long" standards), and detection of anisochrony (i.e., determining whether there is a deviant interval within an isochronous sequence) to the beat alignment task (i.e., detecting whether a metronome superimposed onto music is aligned with the beat)[1,2,20,33,34]. Most studies have focused on time perception, beat production or sensorimotor timing, which were tested in isolation. However, it is likely that such different tasks refer to somewhat different abilities (e.g., interval timing vs. beat-based timing, perceptual vs. sensorimotor timing) and do not reflect the functioning of the same timing mechanisms and the associated neuronal circuitry. This issue can be circumvented by using recently proposed batteries of tasks that assess both perceptual and sensorimotor timing abilities. These batteries allow researchers to obtain an exhaustive profile of an individual's timing abilities. Examples of such batteries are the beat alignment test (BAT) [34], the Battery for the Assessment of Auditory Sensorimotor Timing Abilities (BAASTA) [35], and the Harvard Beat Assessment test (H-BAT) [36]. These batteries consist of tapping tasks with a variety of rhythmic auditory stimuli ranging from music to isochronous sequences as well as perceptual tasks (e.g., duration discrimination, detection of the alignment of a metronome to the beat of music, and anisochrony detection). In all cases, the same set of musical excerpts was used in perceptual and sensorimotor tasks.

In this paper, we illustrate a set of tasks that are particularly efficient at revealing patterns of rhythm disorders in beat-deaf individuals and poor synchronizers, as shown in previous studies[2]. These tasks are part of a larger battery of tests, the BAASTA[35]. Sensorimotor timing abilities are tested by asking participants to tap their finger to the beat of simple and complex auditory stimuli (e.g., isochronous sequences, music, and rhythmic noise derived from musical stimuli)[27,28]. Perceptual timing is tested with an anisochrony detection task[2,20,33,37]. A set of isochronous tones is presented. In some cases, one of the tones (e.g., the penultimate) is presented sooner or later than expected based on the isochronous structure of the auditory sequence. Participants are asked to detect deviations from isochrony. The advantage of these sensorimotor and rhythm perception tasks is that they both involve sequences of stimuli (instead of single durations) and stimuli of different complexity. Thus, based on previous evidence, these tasks provide the optimal conditions to uncover different phenotypes of beat deafness and poor synchronization. Particular attention is paid to the technique adopted in the analysis of synchronization data. This technique is based on circular statistics, an approach that is particularly well-suited for examining inaccurate and inconsistent synchronization to the beat.

PROTOCOL:

1. Synchronization tasks

1.1) Preparation of instruments

1.1.1) Connect a standard MIDI percussion instrument to the computer via a conventional MIDI interface.

Note: Data acquisition is realized via a MIDI electronic percussion instrument. The device captures the exact timing of the finger taps during the motor synchronization tasks.

1.1.2) Open the dedicated software for stimulus presentation and response recording.

Note: The synchronization task is implemented using standard software for the presentation of audio material and recording of data from a digital MIDI musical instrument (with 1-ms precision).

1.2) Sound material and procedure

1.2.1) From the software interface, select the pacing stimulus to be used in the synchronization task from among three choices (isochronous sequence, music, and amplitude-modulated noise obtained from the wave envelope of the musical stimulus).

Note: The isochronous sequence is composed of 96 isochronously presented tones (duration = 30 ms). The musical stimulus is a computer-generated piano version of a fragment of the Radetzky March (Opus 228) by Johann Strauss that includes 96 beats (beat = quarter note). Excerpts of the three stimuli are provided as Additional Materials to this manuscript.

1.2.2) Select the appropriate tempo for the selected pacing stimulus (450, 600, or 750-ms Inter-onset-interval (IOI) / Inter-beat-interval (IBI)) as indicated in the software interface. Ensure that the stimuli are delivered at a comfortable volume level over the headphones.

1.2.3) Ask the participant to sit in a quiet room in front of the computer monitor.

1.2.4) Ask the participant to tap on the MIDI percussion instrument using the index finger of her or his dominant hand in synchrony with the tones of the isochronous sequence or with the musical beats for more complex stimuli (music or noise). Instruct the participant to tap as regularly as possible, without changing the tapping rate, while synchronizing with the pacing stimulus.

1.2.5) Start the stimulus presentation and recording of taps.

1.2.6) End recording of taps after presenting the last tone or musical beat.

1.3) Data analysis

Analyze the data from the synchronized tapping tasks using circular statistics[38,39]. This method is particularly well-suited for the analysis of synchronization data[40,41]; moreover, circular statistics are sensitive to individual differences in timing abilities and are therefore able to uncover cases of poor synchronization[2,40]. The analysis procedure outlined below is implemented using Matlab software (using the CircStat toolbox[39]).

1.3.1) Transform the time of the taps relative to the pacing stimuli into angles on the unit circle (from 0 to 360°) following the procedure indicated by Berens[39]. Zero degrees (which is equal to 360°) correspond to the time of the occurrence of the pacing stimulus (i.e., the sounds or musical beats). Use the following formula to obtain the angle for each tap time: [*angle (radians)* = 2*PI*(time of the tap / IOI)]. Convert radians into degrees with the *circ_rad2ang* function[39].

1.3.2) Plot the angles obtained in the tapping trial as a distribution of dots on the unit circle. Do this using the *circ_plot* function[39]. Provide angles in radians as the argument for the function to display the plot (see example in Figure 1).

1.3.3) For each tapping trial, use the angles (dots on the circle) to compute the mean resultant vector *R*[38,39,42] (see Figure 1). Use the *circ_mean*[39] and *circ_r* [39] functions, which allow for the computation of *synchronization accuracy* and *consistency*, respectively.

1.3.4) Compute the synchronization accuracy (i.e., on average, how far from the pacing stimulus the participant taps in a synchronized tapping trial), which corresponds to the angle θ of vector *R*. Use the *circ_mean* function [39]. Provide angles in radians as the argument for the function.

1.3.5) Submit the tapping data to the Rayleigh test[43] to assess whether the distribution of the dots around the circle is random, using the *circ_rtest* function [39]. Provide angles in radians as the argument for the function.

Note: In the Rayleigh test, reject the null hypothesis (i.e., circular uniformity, randomly distributed dots around the circle) if the *R* vector length is large enough (e.g., greater than 0.4), indicating that participants tapped at a given phase relationship with respect to the pacing stimulus above chance. Only when Rayleigh test is significant (i.e., when the distribution of dots around the circle is not random) synchronization accuracy can be properly interpreted.

1.3.6) Compute the synchronization consistency (i.e., the variability in the discrepancy between the time of the taps and the pacing stimuli), which corresponds to the length of the vector *R* (from 0 to 1). Use the *circ_r* function [39]. Provide angles in radians as the argument for the function.

Note: The consistency is 1 when all of the taps occur at exactly the same time interval before or after the pacing stimuli; the consistency is 0 when the taps are randomly distributed around the circle.

1.4) Evaluation of individual results

Compare the performance of a participant to a normative group or to a control group to uncover cases of poor synchronization accuracy or poor consistency. To perform this comparison, run a corrected *t*-test[44] implemented in the *singlims* computer program (http://homepages.abdn.ac.uk/j.crawford/pages/dept/SingleCaseMethodsComputerPrograms.htm).

1.4.1) Open the *singlims* computer program. Enter the mean and *SD* of the synchronization accuracy, and the sample size of the normative or control group. Provide the synchronization accuracy for the participant to be compared to the normative or control group. Click on the “Compute” button to obtain the results of the corrected *t*-test.

Note: The participant performed significantly poorer than the normative or control group when the two-tailed probability of the corrected *t*-test is below 0.05.

1.4.2) Enter the mean and *SD* of the synchronization consistency and sample size of the normative or control group. Provide the synchronization consistency for the participant who is to be compared to the normative or control group.

2. Rhythm perception tasks (anisochrony detection)

2.1) Preparation of instruments

2.1.1) Open the computer program used for implementing the anisochrony detection tasks. Ensure that the keys of the computer keyboard are properly set to record participants’ answers.

Note: The rhythm perception tasks are implemented using standard software for running behavioral experiments (i.e., stimulus presentation and behavioral responses recording).

2.2) *Sound material and procedure*

2.2.1) Select the stimulus (either isochronous stimulus or music) as indicated by the software interface. Choose the appropriate tempo (450, 600, or 750-ms IOI/IBI) of the selected stimulus. Ensure that the stimuli are delivered over the headphones at a comfortable volume level.

Note: Stimuli are based on the same auditory material used in the Synchronization tasks. Each stimulus includes only 8 isochronous presented tones or musical beats instead of 96. For each stimulus type, there is a “change” version (50% of the trials, n = 24) and a “no-change” version (50% of the trials, n = 24). In the change stimuli, the penultimate sound or musical beat occurs earlier or later than expected (by 8, 12, or 16% of the sequence IOI/IBI) based on the previous IOIs/IBIs. In the no-change stimulus, the IOIs/IBIs are completely isochronous.

2.2.2) Instruct the participant to sit in a quiet room in front of the computer monitor, listen to the stimulus and then judge, after its presentation, whether a change in the interval between the stimuli or beats (i.e., anisochrony) is present or not. Encourage the participant to pay attention to the entire sequence.

2.2.3) Start the stimulus presentation. Ask the participant to respond by pressing one of two keys on the computer keyboard (i.e., one key for “change” or the other key for “non-change” responses) after the presentation of the stimulus.

2.3) *Data analysis*

Analyze the data obtained from the rhythm perception task by calculating the discriminability index (*d'*) at each level of change (at 8, 12, 16% of the IOI/IBI) and for each IOI/IBI. The higher the *d'* value, the greater the sensitivity to anisochronies.

2.3.1) Consider the responses (n = 48) yielded by each participant for a given stimulus, recorded in the output file by the software used to run the behavioral experiment. Count the number of responses when the anisochrony present in the stimulus has been correctly detected. Compute the Hits rate (i.e., number of Hits / number of *change* stimuli).

2.3.2) Count the number of responses when the participant reported a change in the interval between stimuli or beats when there was no change. Compute the False-Alarm (FA) rate (i.e., number of FAs / number of *change* stimuli).

2.3.3) Calculate the *z*-score for the Hits rate and FA rate, using the *norminv* Matlab function (z-score = *norminv*(Hits rate or FA rate)). Subtract the *z*-score for the FA rate from the *z*-score for the Hits rate to obtain *d'*.

2.4) Evaluation of individual results

Compare the performance of a participant to a normative or control group to uncover cases of poor rhythm perception. Regarding the results of the synchronization tasks, perform a corrected *t*-test using the *singlims* computer program.

2.4.1) Open the *singlims* computer program. Enter the mean and *SD* of *d'* and the sample size of the normative or control group. Provide the *d'* value for the participant who is to be compared to the normative or control group.

Note: The participant performed significantly poorer than the normative or control group when the two-tailed probability of the corrected *t*-test is below 0.05.

REPRESENTATIVE RESULTS:

The tasks described above have been used with success to characterize the timing abilities of individuals without musical training[2,34,35,36]. In a recent representative study on beat-deafness[2], a group of 99 non-musicians (university students) were screened using two simple synchronization tasks. Participants synchronized their finger tapping with an isochronous sequence and a musical excerpt at a comfortable tempo (with an IOI/IBI of 600 ms). Ten of the participants showed particularly poor synchronization with at least one of the two stimuli and were referred to as “poor synchronizers”. These participants showed synchronization accuracy that deviated by more than 2 *SD* from the mean of the screened group; synchronization consistency was lower than 2 *SD* from the mean of the group. They were compared to a group of 23 participants (controls) who were randomly selected among those students who did not exhibit poor synchronization on the screening tasks. Poor synchronizers and controls were submitted to thorough testing with the synchronization and rhythm perception tasks described here. The order of the tasks and stimuli was counterbalanced across participants.

Sequences of tapping times collected in the synchronization tasks served to compute the synchronization accuracy and consistency for poor synchronizers and controls with different pacing stimuli and at the different IOI/IBIs. Mean results for their accuracy and consistency are illustrated in Figure 2 and Figure 3, respectively. These data show that both poor synchronizers and controls significantly anticipate the pacing stimuli when tapping along with an isochronous sequence. This phenomenon, which is referred to as "mean negative asynchrony," is well known in tapping studies[27,45]. Mean negative asynchrony tends to reduce or disappear with stimuli (e.g., music and noise) that are more complex than isochronously presented tones, an effect also reported in previous studies[45]. Note that poor synchronizers do not differ from controls in terms of accuracy. Thus, accuracy does not appear to be a measure that is sensitive enough to detect beat deafness or poor synchronization. The results were more revealing when considering synchronization consistency. Poor synchronizers were significantly less consistent than controls across all stimuli and IOIs/IBIs. This difference was more significant when participants tapped along with isochronous sequences and music compared with noise (across tempos). Therefore, synchronization consistency is very sensitive to synchronization deficits and thereby represents an ideal measure for uncovering and characterizing individual differences. Representative results from the same study obtained in the rhythm perception tasks are displayed in Figure 4. As seen, both poor synchronizers and controls were affected by the amount of change in the auditory sequence (i.e., greater discrepancies in the sequence are easier to detect) in both isochronous stimuli and music. The effect of the change was statistically significant and is more visible at faster tempos. However, on a group level, poor synchronizers did not perform worse than controls in the perceptual task.

The results obtained in these sensorimotor tasks (synchronization consistency) and in the rhythm perception tasks were used to uncover cases of poor synchronization. To illustrate the procedure used to identify these conditions, the data taken from the representative study were further analyzed to perform the evaluation of individual differences. In Table 1, data are presented for the 10 poor synchronizers who were identified in the screening tests. When participants performed significantly worse than controls on one of the tasks, as determined with corrected *t*-tests[44], the values of their performance are presented in the Table. The cut-off scores to identify a participant as a poor synchronizer in terms of synchronization consistency were 0.92, 0.51, and 0.51 for isochronous sequences, music, and noise, respectively. The results obtained by the poor synchronizers in the rhythm perception tasks were also compared to controls' performance. In the rhythm perception task with a metronome, the cut-off scores (*d')* were 0.33, 1.38, and 1.84, for a 8%, 12%, and 16% change in duration (relative to the sequence IOI), respectively. With music, the cut-off scores were 1.52, 1.98, and 2.10 for the three changes.

This simple method used to analyze individual differences in the timing domain allows us to uncover the profiles of timing disorders (beat deafness or poor synchronization).

Indeed, poor synchronization may or may not be accompanied by deficient rhythm perception. Moreover, individuals showing difficulties in synchronizing to the beat can perform more poorly with an auditory stimulus (e.g., music) than with the other stimuli (e.g., an isochronous sequence). The representative study reveals different profiles of impairment. For example, participants S2, S3, S8 and S9 showed poor synchronization across most of the pacing stimuli, as well as impaired rhythm perception. Impairments in both perceptual and sensorimotor timing was previously observed in studies on congenital amusia[12,16]. Participants S1 and S5 showed a different pattern. They performed similarly to controls in the rhythm perception task, with *d′* values below the cutoff. Unimpaired perception in these two participants was confirmed in additional tasks, such as the MBEA[2,15]. However, S1 and S5 were poor synchronizers, particularly when tapping with complex stimuli such as music and amplitude-modulated noise. For example, S5′s performance was at chance when synchronizing taps to noise (i.e., the Rayleigh's test was not significant) and just above chance with music (at chance with 750-ms IBI). Similar results were found for participants S6 and S10. Note that this dissociation between perceptual and sensorimotor timing cannot be accounted for by impaired motor control because the participants, in spite of their poor synchronization, were still able to tap at a spontaneous tempo, similar to controls. Finally, for some participants (e.g., S2, S5, and S6), poor synchronization, relative to the control group, can selectively concern only one type of stimuli (e.g., complex stimuli such as music or noise, as opposed to a metronome). In summary, different profiles of timing disorders can be uncovered with the aforementioned tasks. This is particularly relevant to shed light on the mechanisms behind different timing tasks, as well as to examine the interdependence of these mechanisms.

Figure Legends:

Figure 1: Example of the distribution of taps in a synchronization trial. The resultant vector *R* and its direction (angle theta, θ) are indicated. In the example, vector length = 0.95 and θ = -25°. (Adapted from Sowiński & Dalla Bella, 2013, with permission.)[2]

Figure 2: Synchronization accuracy for a group of poor synchronizers (*n* = 10) and controls (*n* = 23) with different pacing stimuli at different IOI/IBIs[2]. The occurrence of the pacing stimuli (e.g., tones or musical beats) corresponds to 0 degrees. Negative angles indicate that, on average, participants' taps precede the pacing stimuli (leading), whereas positive angles show that these taps occur after the stimuli (lagging). Error bars indicate the Standard Errors of the Mean (*SEM*).

Figure 3: Synchronization consistency obtained in a previous study for a group of poor synchronizers (*n* = 10) and controls (*n* = 23) with different pacing stimuli at different IOI/IBIs[2]. Consistency ranges from 0 (no synchronization with a completely random distribution of their taps) to 1 (perfect consistency with taps that occur at exactly the same time interval before or after the pacing stimuli). Error bars indicate the *SEM*.

Figure 4: Results from the rhythm perception task (values of *d'*) obtained in a previous study for a group of poor synchronizers (*n* = 10) and controls (*n* = 23) with the

isochronous sequence and with music at different IOI/IBIs. Error bars indicate the *SEM*. (Adapted from Sowiński & Dalla Bella, 2013, with permission.)[2]

Table 1: Summary of the individual results obtained in the synchronization and rhythm perception tasks by a group of 10 poor synchronizers. Values on the different tests are reported only when participants performed significantly worse than controls. Participants who correctly perceived deviations from anisochrony in spite of their poor synchronization are indicated in bold. (Adapted from Sowiński & Dalla Bella, 2013, with permission.)[2]

DISCUSSION:

The goal of the described method is to provide a set of tasks and analysis strategies to characterize the timing abilities of the majority of individuals and detect cases of beat deafness or poor synchronization. The critical steps of the protocol involve 1) the setup of the instruments used for stimulus presentation and collection of finger tapping data and subjects' responses, 2) data collection using two sets of tasks (synchronization and rhythm perception), 3) analysis of synchronization data with circular statistics and rhythm perception data, and 4) evaluation of individual results. These steps can be easily carried out by trained experimenters. Data analysis is performed with Matlab software by implementing the steps described in our Protocol. A basic knowledge of circular statistics is required for the correct interpretation of the synchronization results.

The method has a few advantages compared to those in the existing literature[1,27,46]. First, timing is tested in tasks involving both perception and action as well as with comparable stimulus material. In most of the previous studies, sensorimotor synchronization and duration perception are typically studied independently using a variety of tasks[1,27]. However, there are indications that perception and action in time processing may dissociate in patients with brain damage[8] or beat deafness[2], as previously observed in pitch processing[17,22,23,24,25]. It is important to utilize a set of tasks capable of uncovering these dissociations without being biased by the choice of auditory materials. The tasks proposed in the methods illustrated here are successful in showing the dissociations between perception and action in time processing. However, we are aware of the fact that further confirmation of this dissociation would require the testing of perceptual and sensorimotor timing with a wider range of tasks, evaluating a variety of timing abilities. This objective can be achieved by using a battery of tests, such as the BAASTA[35], as well as by including paced tapping and anisochrony detection tasks (using a maximum-likelihood procedure for computing detection thresholds) and the H-BAT[36]. Second, synchronization and perception tasks are performed with both simple and more complex auditory material; the latter includes either all of the elements of a musical piece (e.g., pitch and rhythmic structure) or solely its rhythmic features (i.e., amplitude-modulated noise). Variety in musical material can provide the optimal conditions for detecting impaired timing, which may be confined to metrical processing and beat extraction when processing complex rhythmic stimuli such as music. Finally, we illustrated that circular statistics are a valuable and relatively easy method that can be used for analyzing synchronization performance, as has been shown in previous studies[2,40,41]. This method has a few advantages, making it particularly well-suited to uncover and characterize individual differences in sensorimotor synchronization[2,40]. Circular statistics do not require a one-to-one correspondence between taps and pacing stimuli, a condition that is rarely met in participants showing poor synchronization. For example, beat-deaf individuals, children, and poor synchronizers tend to omit taps or produce more than one tap corresponding to the same pacing stimulus[40]. This makes the computation of synchronization accuracy impossible in many cases. By not requiring a one-to-one correspondence between taps and pacing stimuli, circular statistics overcome this difficulty so that all taps can be analyzed.

The representative results highlighted in this paper show that a set of behavioral tasks focusing on both sensorimotor synchronization with finger tapping and detecting the irregularity (anisochrony) in rhythmic sequences are sensitive enough to individual differences in perceptual and sensorimotor timing. These tasks and measures allow cases in which perceptual timing dissociates from sensorimotor timing to be discovered, as shown in a recent study from our laboratory[2]. We expect that the use of these tasks and methods (e.g., within extensive batteries of tests) for examining systematic perceptual and sensorimotor timing abilities can be successfully extended to populations of patients with brain damage[47], neurodegenerative diseases (e.g., Parkinson's disease)[11,35], or developmental disorders (e.g., Attention Deficit Hyperactivity Disorder)[48]. A thorough assessment of perceptual and sensorimotor timing in these patient populations has the potential to pave the way for rehabilitation strategies when timing abilities seem to play a critical role (e.g., in the rehabilitation of gait in patients with Parkinson's disease via auditory cueing) [49,50].

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The authors have nothing to disclose.

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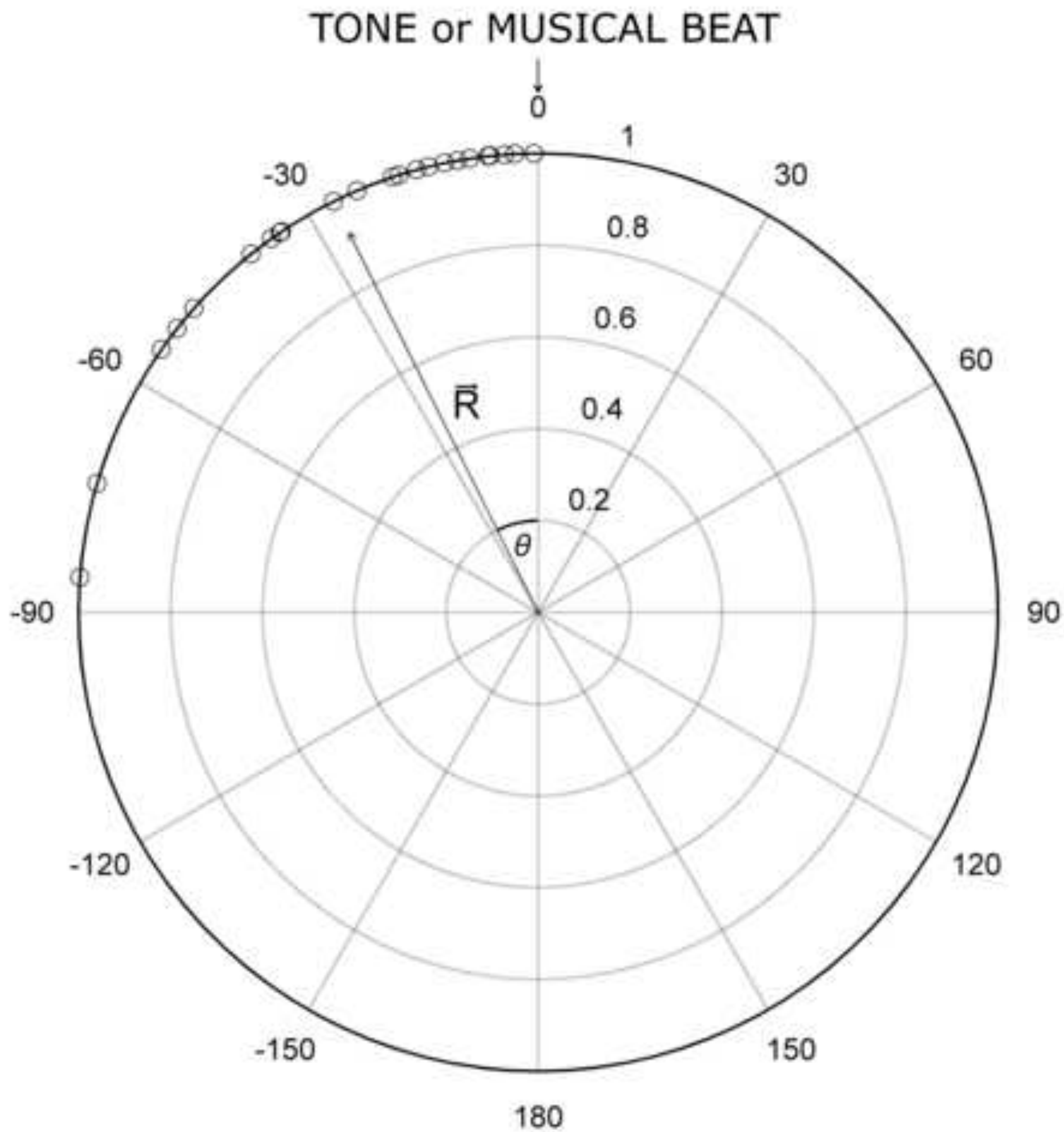

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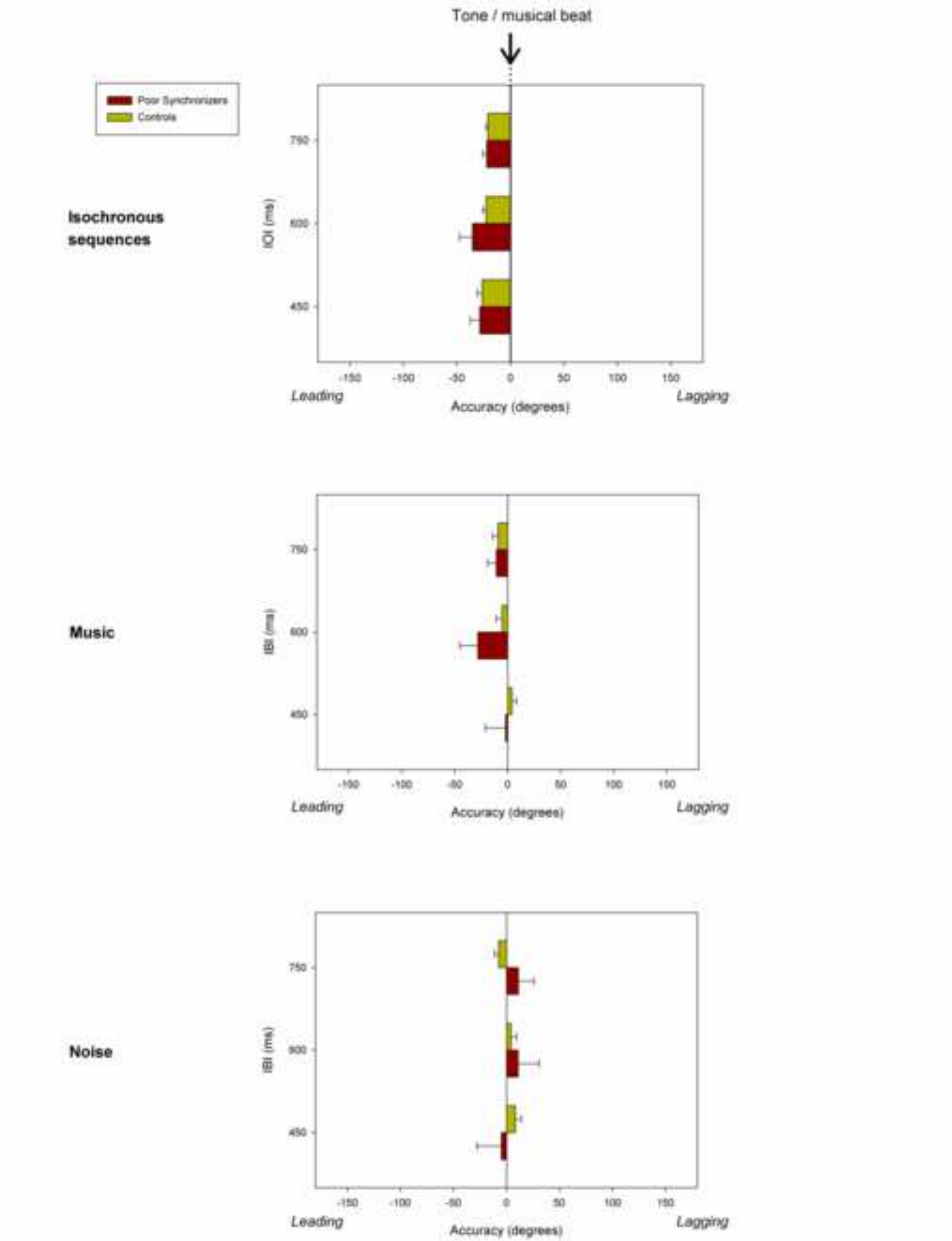

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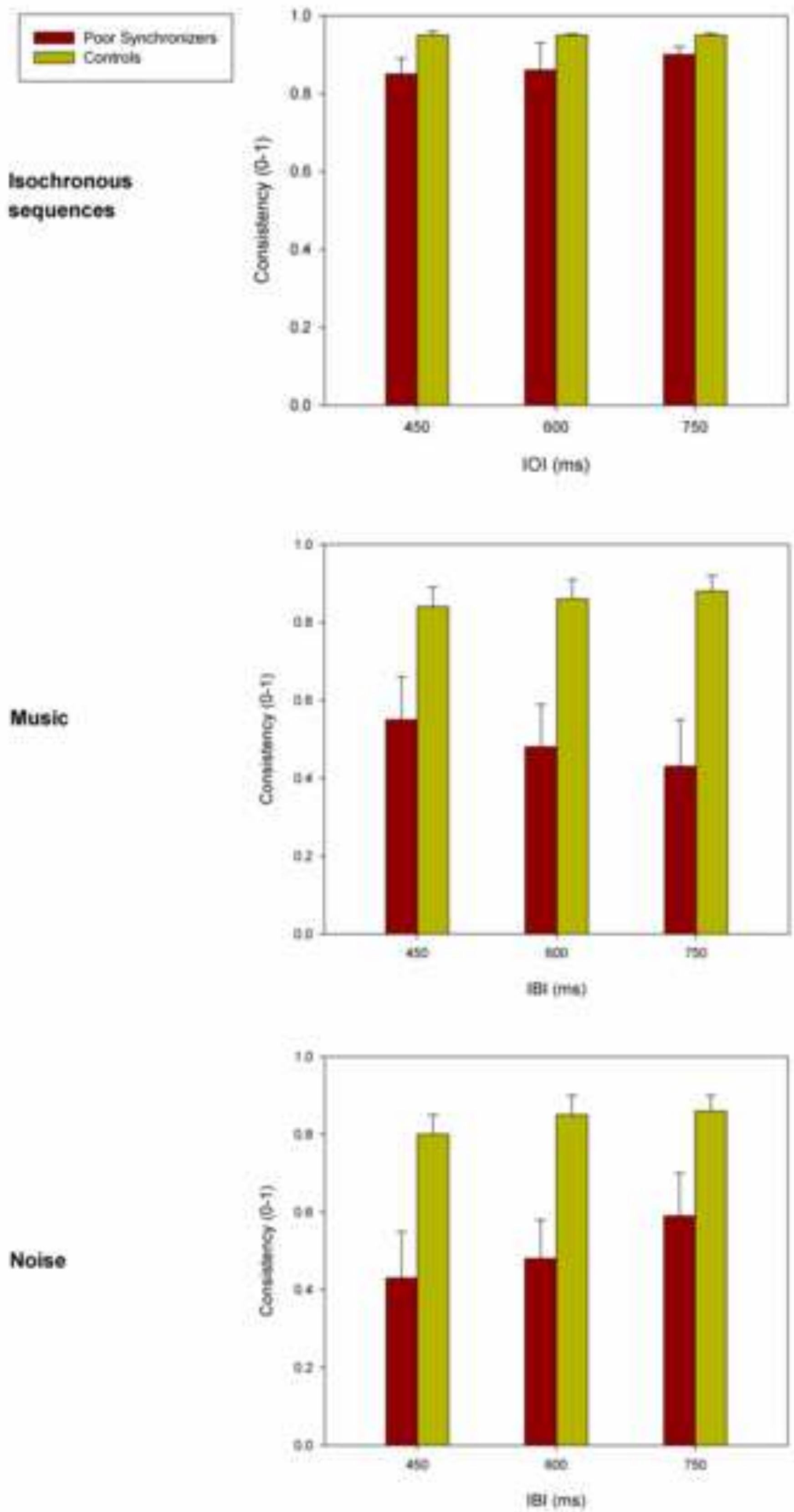

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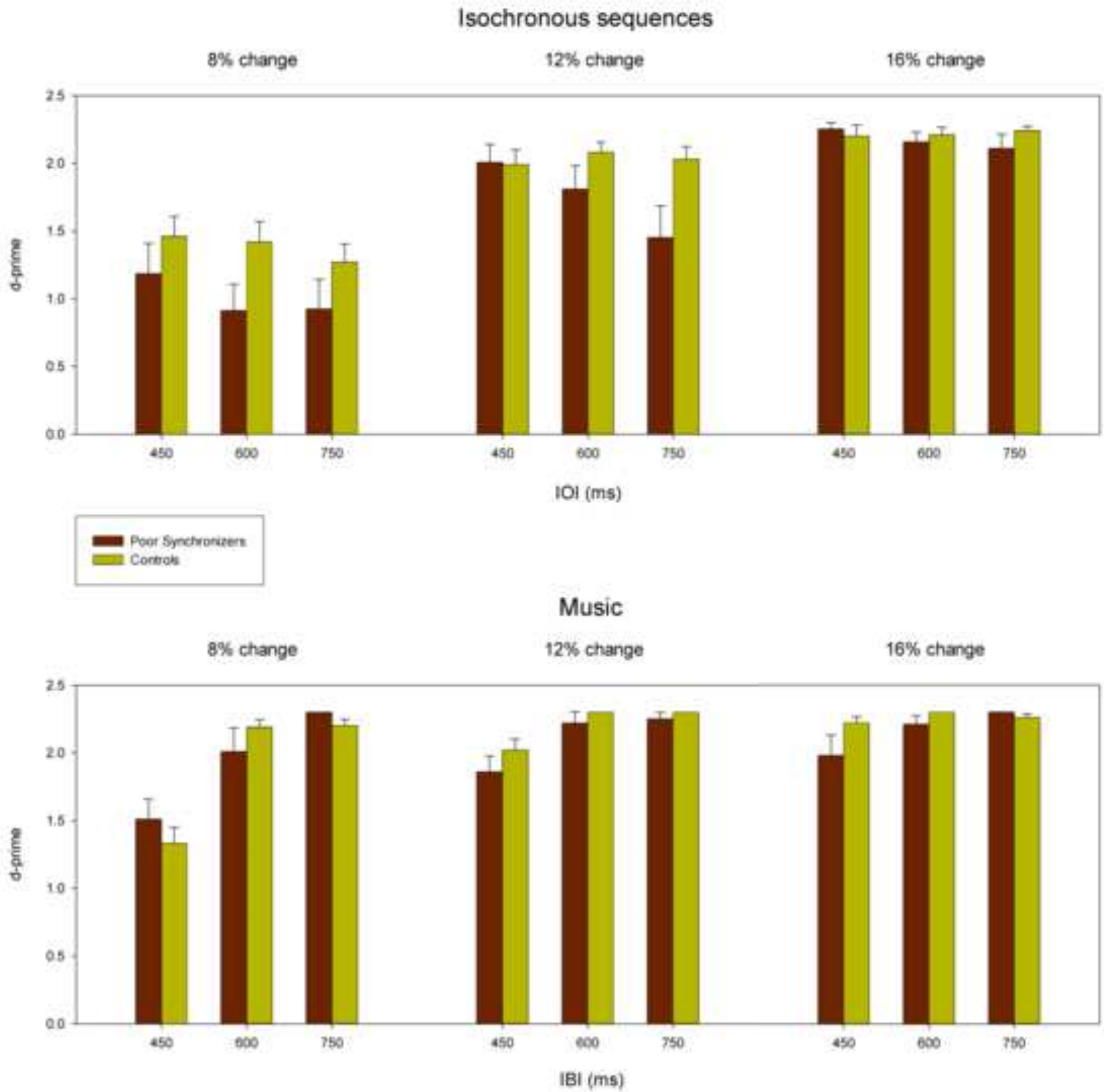

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	SYNCHRONIZATION (*consistency*)			**RHYTHM PERCEPTION** (*d'*) (change %)	
Poor synchronizer	Isochr. sequence	Music	Noise	Isochr. sequence	Music
S1	**.75**	**.30**	**.37**		
S2		.28	.40	.22 (8)	1.92 (16)
S3	.63	.16	.33		1.71 (12) 1.98 (16)
S4					
S5		**.24**	**.09**		
S6		**.24**	**.31**		
S7					
S8	.90		.42	.24 (8) 1.20 (12) 1.67 (16)	
S9	.89	.13	.24		1.38 (8) 1.92 (12) 1.92 (16)
S10	**.83**				

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RESPONSE TO COMMENTS FOR THE MANUSCRIPT TITLED "Uncovering beat deafness: Detecting rhythm disorders with synchronized finger tapping and perceptual timing tasks" SUBMITTED TO JoVE (submission n. 51761R2)

Editorial comments:
Please address the following as well:
1) The protocol steps describing the tasks themselves do not say when the experimenter begins and ends the recording of data. It would be useful to add step indicating the start and end of the trials (i.e. "Click start..." or "End recording when...").

This information has been added.

2) The Materials table currently lists only Matlab. Will the other software and functions used be mentioned? Can the availability of the script used to detect anisocrony in 2.1.1 be mentioned as well?

The Materials table has updated, including all the material and software used. The program needed to run the anisochrony detection task (i.e., Presentation) is now mentioned in the table. Since some of the procedures used to implement the anisochrony detection tasks are making the object of a patent request, they cannot be made available at the present stage. Nevertheless, the description of the materials and of the procedure, as well as the reference to previous articles using the anisochrony detection tasks is in our opinion sufficient to reproduce the task.

3) The False Alarm rate and Hits rate in steps 2.3.1 and 2.3.2 are defined rather than telling how to calculate them. Please detail how to calculate these.

FA and Hits rate are simply calculated by counting the occurrence of FAs and Hits in the output log file provided by the software used to run the experiment (Presentation). This has been specified, without referring to the specific software.

4) How is the z-score calculated in 2.3.3?

This is now indicated.

5) Minor grammar note, Short Abstract: "Synchronized finger tapping to the beat of simple and complex auditory stimuli, and detecting rhythmic irregularities allow to uncover rhythm disorders."

The error has been corrected.

6) Often reviewers request the addition of a large amount of details or explanations. We realize that, especially in the protocol section, brevity and clarity are important for a JoVE publication and expect the focus to be on providing a framework for the method presented rather than a comprehensive review of the research field. Please address each comment in your rebuttal and note if you choose not to include the requested information in the text and the reasoning behind this decision.
For example: Reviewer 2

Although we agree with most of the comments and requests from the Reviewers, a few of them cannot be properly addressed given the constraints of the JoVE publication format. In addition, they go beyond the focus of the protocol description, which is different from a standard experimental report. Details are provided below for each comment.

7) Please take this opportunity to thoroughly proofread your manuscript to ensure that there are no spelling or grammar issues. Your JoVE editor will not copy-edit your manuscript and any errors in your submitted revision may be present in the published version.

The manuscript has been proofread by a native English speaker.

Reviewers' comments:

Reviewer #1:
Manuscript Summary:
This is a nice description of a method for testing perceptual and motor timing abilities in the general population with the goal of identifying individuals with temporal processing difficulties of one sort or another. The approach is well described and it will be a useful contribution to the field.

Major Concerns:
No major concerns

Minor Concerns:
I have some wording suggestions to make things clearer in a few places and have included these in an annotated file. See attachment.

We wish to thanks the Reviewer for the useful suggestions, most of which have been integrated in the revised version.

I was a bit confused about whether the authors would intend to make available the actual stimuli and scripts required to perform this data collection and analyses or not. In places, it sounds like they are (eg 'Select the stimulus as indicated in the software interface'. But unless I missed something, there are no links to these materials...

Snippets of the three stimulus types (with a 600-ms IOI) are now uploaded as additional material. This is now indicated in 2.1.2. However, for the reasons mentioned above, the scripts cannot be made available at this time. However, details regarding the steps implemented in the scripts are indicated in the text and allow their reproduction on a given software platform. To eliminate ambiguities, references to specific scripts were removed from the text and only the software for stimulus presentation, response recording, and data analysis were generally mentioned.

Additional Comments to Authors:
N/A

Reviewer #2:

Major Concerns:

1. Making a case for the task set:
The authors need to make a stronger and more detailed argument for the need and the advantages for their set of tasks in the context of existing literature. In the present version, I find the praising of the presented set of tasks in terms of their usefulness a little repetitive and not very well backed up. In my mind, even details like the choice of stimuli and response method should be justified - if the authors are aiming to make this battery "the" future choice and standard test battery. I am sure the arguments are there -just not spelled out- and make a few suggestions here.

What strikes me the most is a general lack of elaborate description and comparison with existing work on: the nature of previously reported rhythm-related deficits; tapping and perception studies in normal subjects that *may be taken as a departure point -for exploring deficits and to describe the advantages of the present tasks in this exploration; evidence for and against common neural substrates underlying perception and action timing, rhythm and melodic processing, and related dissociative deficits -which are only mentioned by citing one of the authors' previous papers; finally and most importantly, existing sets of tasks of beat perception and synchronization with similar aims would deserve mentioning, although some have only been presented at conference proceedings.*

Most specifically, I would suggest a more elaborate description in the introduction and to fleshing the discussion of disorders to be addressed, in particular that of "beat deafness". This is currently very limited and in clear contrast with the title. Two particular instances to this point: a) Introduction (line 70): mentioning "beat deafness" in brackets only; which is then followed by an explicit description of synchronization impairment in the presence of intact perception only (i.e. the opposite profile in terms of dissociation). b) Discussion (line 374): "detect individuals with beat deafness / poor synchronization" -without much discussion of beat deafness, rhythm deficits or dysrhythmia (see literature recommendations below).

Some useful/relevant literature:
Assessment:
Fujii, S. & Schlaug, G. The Harvard Beat Assessment Test (H-BAT): a battery for assessing beat perception and production and their dissociation. Frontiers in human neuroscience 7, 771, (2013).

Farrugia, N., Benoit, C.-E. & Harding, E. BAASTA: Battery for the Assessment of Auditory Sensorimotor and Timing Abilities in International Conference on Music Perception and Cognition. (eds E. Cambouropuoulos, C. Tsougras, P. Mavromatis, & K. Pastiadis) 292-299.

Iversen, J.R, & Patel, A.D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. In: Proceedings of the 10th International Conference on Music Perception & Cognition (ICMPC10), August 2008, Sapporo, Japan. K. Miyazaki et al. (Eds.), Adelaide: Causal Productions

Beat deafness/ dysrhythmia:
Launay, J., Grube, M. & Stewart, L. Dysrhythmia: a specific congenital rhythm perception deficit. Frontiers in psychology 5, (2014).

Dissociated deficits in rhythm and melody:
Foxton, J. M., Nandy, R. K. & Griffiths, T. D. Rhythm deficits in 'tone deafness'. Brain and cognition 62, 24-29, (2006).

The standard battery for musical disorders, mostly pitch-based but also including rhythm and meter:
Peretz, I., Champod, A. S. & Hyde, K. Varieties of musical disorders. The Montreal Battery of Evaluation of Amusia. Annals of the New York Academy of Sciences 999, 58-75, (2003).

Synchronization with increasing complexity:
Madison, G. Sensori-motor synchronisation variability decreases as the number of metrical levels in the stimulus signal increases. Acta psychologica, (2013).

[I refrained from recommending a list of tapping and perception studies from normal population and on the distinction of motor and perceptual timing.]

We are grateful to the Reviewer for raising these important points, which we are of course aware of. The lack of information provided in the introduction was mostly driven by the requirements of JoVE to provide a simple context for presenting the method and providing a “user guide” in support to the video recording of the method. However, a more detailed introduction has now been provided, following the suggestion of the Reviewer, thus focussing on rhythmic disorders and beat deafness in particular, as announced in the title.

2. Confusion between content of present vs. previous study:
My other main concern may either be easily alleviated, as I may just be mistaken - or else be a major issue. It did not become clear to me, when reading the manuscript, which data and procedures are actually new and which were taken from the "representative" study by the same authors that most of the figures come from (Sowinski & Dalla Bella, 2013). Double checking the previous paper, it appears to me that most of the content of the present paper has been reported in the previous one already, but I may just have missed or misread something.

Similarly, it is a bit difficult to follow in the introduction which research is done here and has been done before. This might in part simply be a problem of the use of English tenses (see also minor comments below). One specific instance is the use of "is" in line 105, which seems to refer to previous work but this can only be inferred from the content of the sentence - after the preceding back and forth between previous work in past tense and the present study in present tense.

It is true that the representative study is one of the studied that we published in 2013, and obviously the reported data is taken from that study. However, please note that the goal of the publications in JoVE is to provide clear instructions to accompany a visual demonstration of existing and working protocols, not to present new experimental results. For this reason strict “rules” are applied to the preparation of the methodological section. Presenting previously published findings as representative results is thus compatible, and actually encouraged, but JoVE.

3. Evaluation procedure for individual results missing:
The instructions in the protocol are very clear and detailed, easy to follow and "idiot-proof" in the positive sense, starting with the instruction to open the software and finishing with the calculation of measures. However, the final and very important "step" that seems to be missing is the evaluation of individual results. This seems odd and I fear I may have overlooked something, as this is what this protocol is supposed to be about, i.e. the uncovering of individual disorders. I saw no mentioning of how significant deviations in the individual were analysed: maybe by z scores (?), based on mean and standard deviation (given the appropriate distribution?), or maybe based on Bayesian statistics following Crawford's methods (?). In addition to a written description, a formula for the evaluation would be useful -also for the calculation of d' (line 271).
One specific detail to this comment: it is unclear what "large enough" means (in the "Note: ..." following 1.3.5).

We thank the Reviewer for raising this important point. A new step has been added to the protocol to specify the operations to be followed to evaluate individual results against the performance of a normative group or a of a control group. The additional information requested was added.

4. Choice of tasks:
Interestingly, the perceptual tasks tests only 1 instance of deviation -as opposed to the sense of the beat across a sequence, which would be more akin to the synchronization tasks.
Furthermore, for the motor tasks, it might have been useful to include a synchronization continuation on top of a free-tapping task.

Finally, the perceptual tasks surprisingly have no noise condition. This takes some double checking -after several mentionings of the "same material" being used for motor and perceptual tasks and a semi-clear description at the end of the intro. (Minor formal detail that contributes to this point: The description at the end of intro includes some misleading grammar inconsistencies between the motor and perceptual tasks.)
As already mentioned in the context of comment 1, I recommend for the authors to discuss the choice of tasks more.

The choice of the tasks has been better justified in the Introduction of the revised manuscript. We agree with the Reviewer that additional tasks could be added to obtain a more detailed profile of participants' timing abilities. Note that this suggestion has already be implemented in a battery of perceptual and sensorimotor tasks we have developed (the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities - BAASTA; Benoit et al., in press), which includes a synchronization task. We have acknowledged in the Introduction that there are batteries including more than the tasks presented; at the same time, the purpose of this video article is to illustrate in detail two particular tasks (implemented in more extensive batteries, such as the BAASTA), as they have shown as particularly sensitive to individual differences and to beat deafness. The illustration of these two tasks is also compatible with the time constraints to show the various steps of the procedure in the visual article.

6. Under-presentation of the "individual differences":
I was a bit surprised to see Figures 1 to 4 present group plots, on top of that without any statistical evaluation of the group differences described. Solely Figure 5 shows individual data, for synchronization; no individual perception data are plotted at all. The table on individual results lists only the significant differences to controls, again like the protocol without any mentioning of how these are evaluated. A description of evaluating "disorders" ought to be included in the protocol -representing the main point that the paper is claiming to address. Editorial Note: Please mention any description in the Discussion rather than the Protocol.

As mentioned before, the text accompanying a JoVE visual article is supposed to include representative data, rather than a full-fledged "Results" section from a regular research article (from JoVE Author Instruction guidelines: "Please add a concise, written description of a "representative" outcome following the use of this protocol, so that a viewer will have a sense of what a "good" or "bad" result looks like."). Thus, as far as it can be seen in previously published JoVE visual articles, statistical tests are not included in the "Representative results" section of the JoVE manuscript accompanying the visual article. Yet, these analyses are included in the original manuscript where the results are reported in detail (Sowinski & Dalla Bella, 2013).

Following JoVE requirements, the goal of the reported figures is to show what are the general results which are typically obtained in the 2 sensorimotor and rhythm perception tasks presented. This goal is achieved by presenting Figure 1 through 4. In addition, Table 1 was aimed at showing the results of the analysis of individual differences, which has now been described more thoroughly in the text.

The main goal of Figure 5 was merely to show that participants are in general more variable in terms of consistency than in terms of accuracy, thereby leading to choose consistency as the main performance variable for detecting beat-deaf individuals. However, the analysis of individual differences was done in Table 1. More details are now provided which describe the various steps needed to characterize beat-deaf individuals in Table 1, in keeping with the goals of the method. Thus, Figure 5 became unnecessary to present the method, and eventually has been removed. Still, information about the choice of synchronization consistency in the paper for detecting beat-deafness has been underscored, with reference to Sowinski & Dalla Bella (2013).

5. Appropriate controls and cut-offs:
Such a task set/ test battery should in my mind, like the MBEA, ideally come with cut-offs and description of how they were derived, in the best case for different age-groups if needed (or the demonstration of age-independency).

In the revised version of the manuscript, the procedure used to identify sensorimotor or rhythm perception disorders relative to a normative or a control group is provided. In the representative study, beat-deaf individuals were defined relative to a control group of 23 participants. The cut-off scores relative to this group are now provided.

Minor Concerns:
1. I find the use of "general population" somewhat confusing. Would "special populations" or individuals with profiles of disorder be part of the general population or not? At some points it seems they are, e.g. its first mentioning in the short abstract, as well as at the end of second paragraph of introduction, but at other points, e.g. in the last paragraph of the discussion or the end of the abstract it seems they are not. In other work I seem to recall this term is often used exclusive of those with defined disorders but including those with certain "traits" (weaker than the disorder). The authors might want to be more explicit about this to save the reader wondering.

By “general population” we indicated here the majority, namely individuals who did not receive musical training. This is now indicated to avoid confusion.

2. Order of tests: Is this fixed and would the authors expect any order effects, especially with using the same stimuli for action and perception? Would they advise against carrying out perception first?

The order of the tests is typically counterbalanced across subjects. This is now specified in the representative results.

3. Synchronization data analysis: 1.3.4 and 1.3.5 seem to be two parts of computing one statistic and should be one sub-point.

The subdivision of the analysis into 2 sub-steps was requested by the Editor, to limit the number of operations included in each individual step.

4. The use of "for example" (line 276) when referring to the previous study seems inappropriate; the whole "representative results" section builds on that one study.

The expression was removed.

5. A few puzzling wordings in the results:
"less consistent" (line 292) - than what (controls or tones)?
"asynchrony smaller with more complex stimuli" (297) - does that refer to noise and music?
I note in fact in the related figure, that poor synchronizers do anticipate the beat in their tap in noise, which does not become clear in text.
"These tasks" (line 303) is unclear (motor and/or perceptual?), as is the content of the statement in this sentence, referring to "individual differences" after looking at group data only.
The "In spite of" (line 306) seems to suggest a contradiction - however if this is about individual differences it shouldn't be one. Same is true for use of "even" in following sentence.

The sentences have been corrected or reworded.

6. English: there are several instances of odd use of English language, e.g. participants being "submitted" (line 281). I will refrain from making a list of instances that stood out to me, but strongly suggest the manuscript be thoroughly proof-read by a native speaker.

The manuscript has been proofread by a native English speaker.

7. Minor formal details:
*- unclear use of "the same" in the stimulus description in line 245 - which seem to be "the same" *except 8 beats* in length rather than 90?*
- "Precision" = consistency? (in synchronization tasks protocol; Data analysis 1.3.3)
- "Representative Results", second paragraph: Consistency and accuracy would for (this) reader better be described in the same order as they are in the protocol and presented in the figures.
- Figure 5 could be better presented and labelled (lines etc like in corresponding group figure).
- Lim et al. 2005 reference: not formatted in text (and not appearing in reference list).
- Table 1 (caption): suggest to change to "correctly perceive a single deviation from the beat".
- Line 412 (Discussion): the authors might want to start the sentence with "successfully extended" with something like "We expect that ...".

The changes have been applied.

Additional Comments to Authors:
N/A

Reviewer #3:
Manuscript Summary:
This paper in an invited method paper describing how to administer tests for measuring both perceptual-motor timing using a synchronized finger tapping paradigm and perceptual timing using a perceptual judgement paradigm. The paper introduces reasons for why one would want to do these kind of experiments.
It then describes a specific methodology with representative results from a previous experiment. Finally there is a discussion highlighting advantages of this methodological approach and suggesting future applications.

The technical details of how to administer the tests using a digital MIDI percussion instrument and the instructions regarding use of circular statistics for the synchronization task (using CircStat toolbox in Matlab) are straightforward and very useful instructions to those experimenters who are new to this kind of work and who do not yet have technical or analytical abilities in this area of research. The calculation of a discriminability index for the judgement task is also explained and could perhaps be useful (see later comments). Although I have not used the MIDI instrument myself there is not reason to suspect that these instructions will not work.

Enthusiasm for the paper in general is tempered by the explanation for the rationale for doing this work, the representation of the results and following discussion. The following are more specific comments.

1. Line 49. The use of the term "perceptual and motor timing abilities" is not strictly true. While perceptual abilities can be assessed separately, motor abilities are never tested without perception involved. Even if one asked a person to self-generate their own isochronous tapping and withdrew vision and audition, they would still have proprioceptive input. Thus, the term perceptual-motor task is more appropriate than motor task for the synchronization task throughout the document.

We agree with the Reviewer, and therefore replaced “motor timing” with “sensorimotor timing” in the manuscript.

2. Line 51. Minor language issue is "allow to uncover". It should be either "allow one to uncover" or "allow the uncovering of".

The sentence has been rephrased.

3. Line 78-82. Is judging the duration of time to a colliding event (and sometimes including movement) the same as predicting a time period based on past memory and are either of these the same as perceiving the timing of a beat and is this the same as being able to time a movement to a beat. To me, these are all separate abilities and should not be presented as though they are all part of a similar problem.

We concur with the Reviewer that the mentioned abilities are likely to be underpinned by different processes and mechanisms. The reference to phenomena requiring temporal prediction may be misleading here and has been removed.

4. Line 82. It is not quite clear how the references apply to the statement here.

The references indicated well apply to the statement, by showing that the majority of individuals without musical training can move along to the beat, and have intact rhythm perception.

5. Line 85. Only the first reference refers to data that directly verify this statement. There are many better references e.g., Grahn JAW, S.L. Perspectives on rhythm processing on motor regions of the brain. Music Therapy Perspectives Special Issue: Music and Neuroscience Clinical Implications for Sensorimotor Functioning 2013;31:25-30.

We disagree with the Reviewer, since the three mentioned references indicate, at different degrees, the subcortical and cortical contributions to timing, and thus support the general statement we made. However, we thank the Reviewer for proposing an additional reference which we included.

6. Line 105. There is also the "continuation" paradigm, which is probably more popular than the synchronous paradigm with movement scientists including Wing whose model is based on this.

The synchronization-continuation paradigm, indeed very popular, is now also mentioned.

7. Line 105-107. It might be better to describe all of these tasks rather than just the one. Again, they refer to somewhat different abilities.

A description of the different tasks is beyond the scope of this Introduction. The Introduction has now been restructured so that we first mention the different sensorimotor and rhythm perception tasks, adding a few information (no thorough descriptions) so that the reader can have an idea of the specific tasks being used in the literature. We acknowledge that different tasks are likely to refer to different abilities, and the need to have a variety of tests to obtain a thorough timing profile. The anisochrony detection task is presented in detail later as part of the method described in the manuscript.

8. Line 108+. Is the anisochrony detection task run as a psychophysical forced choice staircase method? If not, then is it correct that one would not know the absolute error between isochronous tones that is detectable by a particular individual? The discrimination index gives a relative ability between the subjects I think. Is that correct? If my thinking is correct, then would it be more useful to adapt the detection task to the staircase method? It would be an easy fix presumably. In this way, you could control for the fact that some individuals might not be capable of "perceiving" a particular asynchronous phasing relationship between beats in the synchronous paradigm.

The anisochrony detection task as described here is not using a forced-choice staircase method. Thus, the measure of a psychophysical threshold cannot be obtained with this method, also considering the fact that only 3 levels of change (8, 12, and 16% of the IOIs were chosen here), which hardly allow to draw a full psychophysical function. Note, however, that the 3 levels of changes, based on previous literature with isochronous sequences, correspond to asynchronous phasing which is definitely perceived (16%), close or below threshold (8%), and in between (12%). We agree with the Reviewer that using an adaptive procedure to compute the anisochrony detection threshold (with the added value of reducing the duration of the task) would be fruitful. This is indeed what we already did by implementing threshold estimation via a maximum likelihood procedure in a recent battery of tests we developed (the BAASTA), and which includes anisochrony detections tasks. The fact that the anisochrony detection task can be implemented using an adaptive procedure, with reference to our own battery, is now mentioned in the discussion.

9. Line 280. Exactly how the 10 poor synchronizers were selected is not clear. For example, was this only on consistency or was it accuracy too? It might be better to state inconsistent synchronizers rather than poor synchronizers since the latter terminology implies that they could not exactly time their finger to the beat, which is incorrect according to figure 2. In addition to the negative asynchrony effect, we know from previous work by Thaut and Repp that non-disabled individuals will normally vary more (between themselves) with the accuracy of their timing to the actual beat (phasing relationship to beat) than the accuracy of their ability to keep to the frequency/period of the beat (what is called here synchronization consistency).

Potential poor synchronizers were selected based on consistency and accuracy. They were individuals with accuracy departing by more than 2 SD from the mean of the screened group, or showing consistency lower than 2 SD from the mean of the group. Thus the term poor synchronization still seems appropriate. This now has been clarified in the text.

After thorough analysis of the synchronization performance of those poor synchronizers as compared to controls, we realized that accuracy did not make a difference between the two groups, whereas consistency did. As mentioned by the Reviewer, indeed, poor synchronizers varied a lot in terms of accuracy; however, this is also true for controls and for this reason group differences were not significant. Hence we decided to use consistency as a measure which non-controversially, and significantly, allowed showin a difference between poor synchronizers and controls, in order to examine individual differences (see Table 1). This has now been clarified in the text.

Finally, we think that “poor synchronizers” is still a good term, and quite appealing for a multidisciplinary readerships, thus we prefer to keep the original terminology. In addition, note that low synchronization consistency is a good indicator of poor synchronization (relatively independent from accuracy). For example, a participant producing taps at times much earlier than the pacing stimuli and at other times significantly lagging after the stimulus in the same tapping sequence would have accuracy (relative phase) around 0. This may lead to the conclusion that s/he is a good synchronizer, which is obviously not the case. However, low consistency (high variability) in this case would point toward poor synchronization.

10. On a general note, it is not clear to whom this article is directed? Is it clinicians, physical/occupational therapists, music therapists, movement disorder scientists? The audience might influence how terms are used.

To our knowledge, the readership in JoVE is typically multidisciplinary, thus we preferred general terms, providing definitions when necessary to reach the non-expert in the field.

11. Lines 286-301. This paragraph would be more compelling with some specific discussion of where the groups do and do not differ statistically in the data presented. At the moment, there are only generalities.

As mentioned above, statistical tests are not included in the "Representative results" section of the JoVE manuscript accompanying the visual article, but reported in detail in Sowinski & Dalla Bella (2013). Nevertheless, it is now clearly indicated which results are statistically significant in the text.

12. Lines 303-313. It seems as though only the synchronization task is needed to uncover those who show inconsistent synchronization so the first sentence is misleading. Also it is the inconsistency that is common to all so that is all that is needed. However, it is true that some individuals seem far from the beat in addition. These may be the ones who are really "beat deaf". The others are just variable in the their motor response to a perceptual cue, a key characteristic of clumsy children by the way (children with developmental coordination disorder).

We agree with the Reviewer that the first sentence is misleading. The section has been totally rewritten. Please see above for the relevance of considering synchronization consistency instead of accuracy.

13. Lines 315-322. The idea of discovering profiles of timing disorders is appealing but this paragraph does not really give the reader any idea of how this might be useful.

The paragraph has been developed and extended, and it is made clearer why uncovering profiles of timing disorders is relevant.

14. Lines 383-389. I am not sure that this is a true advantage for two reasons. First I suspect that people were measuring different timing abilities and secondly you cannot separate action from perception anyway.

We are afraid, but we disagree with the Reviewer regarding the separability of perception and action. This is obviously possible in terms of the tasks. For example, whereas we agree that a paced tapping task engages both perception and action, an anisochrony detection task (or any other perceptual task) does not require movement to be performed. Secondly, there is a growing amount of data showing separability of perception and action in the pitch domain (in tone deafness/congenital amusia, as we mentioned in the Introduction), and more recently in the timing domain. This point is now made clearer in the Discussion. Yet, we concur with the Reviewer, that in order to have robust and compelling confirmation of the dissociation between perception and action in the timing domain, it would be preferable to have a variety of timing tasks tapping different sensorimotor and perceptual timing abilities. This is exactly the purpose of recent battery of tests (e.g., the BAASTA and the H-BAT). This important point has now been mentioned.

15. Lines 395-404. I agree that circular statistics are important for the reasons given but the way it is presented sounds like this is a new analysis never before applied to these kind of rhythmic perceptual-motor tasks. It might be better to merely emphasize that this is an easy way to incorporate this valuable statistical analysis.

We agree with Reviewer, and the text has been changed accordingly.

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