

BAASTA: Battery for the Assessment of Auditory Sensorimotor and Timing Abilities

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Abstract The Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA) is a new tool for the systematic assessment of perceptual and sensorimotor timing skills. It spans a broad range of timing skills aimed at differentiating individual timing profiles. BAASTA consists of sensitive time perception and production tasks. Perceptual tasks include duration discrimination, anisochrony detection (with tones and music), and a version of the Beat Alignment Task. Perceptual thresholds for duration discrimination and anisochrony detection are estimated with a maximum

likelihood procedure (MLP) algorithm. Production tasks use finger tapping and include unpaced and paced tapping (with tones and music), synchronization-continuation, and adaptive tapping to a sequence with a tempo change. BAASTA was tested in a proof-of-concept study with 20 non-musicians (Experiment 1). To validate the results of the MLP procedure, less widespread than standard staircase methods, three perceptual tasks of the battery (duration discrimination, anisochrony detection with tones, and with music) were further tested in a second group of non-musicians using 2 down / 1 up and 3 down / 1 up staircase paradigms ($n = 24$) (Experiment 2). The results show that the timing profiles provided by BAASTA allow to detect cases of timing/rhythm disorders. In addition, perceptual thresholds yielded by the MLP algorithm, although generally comparable to the results provided by standard staircase, tend to be slightly lower. In sum, BAASTA provides a comprehensive battery to test perceptual and sensorimotor timing skills, and to detect timing/rhythm deficits.

Keywords Timing · Rhythm perception · Rhythm performance · Sensorimotor synchronization · Beat deafness · Music cognition

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Introduction

Humans encounter regular events in the environment that are defined by different time scales, spanning from the millisecond to the minute range. The timing of such regularly occurring events is critical when predicting the correct time for action, for example, to decide when to cross a crowded street, or to perform movements at the right time while dancing with a partner. Capturing the timing of events is also critical for adapting to changes in the environment. People are generally highly skilled at processing the duration of events (Grondin

2008). This is apparent in their fine-grained beat perception in music, in processing the regular ticking of a clock, and in their ability to move along with it (e.g., in dance or synchronized sports). These skills are common to musicians and non-musicians alike, and are widespread in the general population (Repp, 2010; Sowiński & Dalla Bella, 2013). A large body of research has focused on the timing mechanisms underlying the perception and production of durations over the past few decades. This research has led to a variety of influential theories and models (for reviews, see Buhusi & Meck, 2005; Grondin 2008; Merchant & de Lafuente, 2014), such as the Scalar Expectancy Theory (Gibbon, Church, & Meck, 1984), or computational models such as the Wing and Kristofferson model (Taatgen, van Rijn, & Anderson, 2007; Vorberg & Wing, 1996; Wing & Kristofferson, 1973a; Wing & Kristofferson, 1973b).

The empirical research inspired by these and other approaches employs a multitude of paradigms and tasks. Perceptual timing has been studied in a number of tasks ranging from duration discrimination, estimation, production and reproduction, temporal bisection (i.e., classifying durations as comparable 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) (e.g., Dalla Bella & Sowiński, 2015; Ehrlé & Samson, 2005; Fujii & Schlaug, 2013; Grahn & Brett, 2009; Hyde & Peretz, 2004; Iversen & Patel 2008; Sowiński & Dalla Bella, 2013; for recent extensive reviews, in both healthy and patient populations, see Grondin 2008; Grondin, 2010; Merchant & de Lafuente, 2014). Some of these tasks, typical in the study of interval timing (or duration-based timing; Grube, Cooper, Chinnery, & Griffiths, 2010; Teki, Grube, Kumar, & Griffiths, 2011), make use of isolated durations. Examples are temporal bisection with temporal scales ranging from the millisecond to several seconds (Penney, Gibbon, & Meck, 2000) or temporal generalization, in which a standard repeated interval is compared with subsequent shorter or longer intervals (Wearden, Denovan, Fakhri, & Haworth, 1997). Other tasks make use of sequences of durations, which require the extraction of an underlying beat, thus tapping beat-based timing mechanisms (Grahn & Brett, 2009; Watson & Grahn, 2013). Material varies in these tasks from simple sequences of durations, as in the anisochrony detection task (Ehrlé & Samson, 2005; Hyde & Peretz, 2004) to complex auditory material such as metrical sequences, including different durations or intervals, or music, thus requiring memory and more complex beat extraction processes (Fujii & Schlaug, 2013; Grahn & Brett, 2009; Iversen & Patel 2008; Müllensiefen, Gingras, Musil, & Stewart, 2014; Sowiński & Dalla Bella, 2013). Sensorimotor timing skills have mostly been examined with the finger tapping paradigm, which has been in use for more than a century (Dunlap, 1910). In this task, participants tap

their index finger in synchrony with a pacing stimulus, such as a sequence of tones equally spaced in time, or a musical beat (synchronized or paced tapping task; for thorough reviews, see Repp, 2005; Repp & Su, 2013). Another paradigm, which has generated considerable modelling efforts (e.g., Ivry & Hazeltine, 1995; Vorberg & Wing, 1996; Wing & Kristofferson, 1973a; Wing & Kristofferson, 1973b), is the synchronization-continuation paradigm. Here a participant continues tapping at the rate provided by a metronome after a sound has stopped, and the performance in the continuation phase is analyzed. Different variations of these paradigms have been proposed; for example, introducing time shifts in the sequences (Repp, 2005, for a review), using time sequences that vary in real time as a function of the participant's response (Repp & Keller, 2008), or testing the effect of a tempo change in the continuation phase (adaptive tapping task; Repp & Keller, 2008; Schwartze, Keller, Patel, & Kotz, 2011). Note that an assessment of internal timing mechanisms in the absence of a pacing stimulus can be made via unpaced tapping (e.g., Drake, Jones, & Baruch, 2000).

In sum, a large number of tasks has been used in the study of timing skills. The current state of affairs reflects the richness of the domain and its many methods. It also underlines the complexity of the cognitive and brain mechanisms involved in perceptual and sensorimotor timing (Buhusi & Meck, 2005; Coull, Cheng, & Meck, 2011; Ivry & Spencer, 2004; Kotz & Schwartze, 2011; Merchant, Harrington, & Meck, 2013; Schwartze & Kotz, 2013, 2016; Wing, 2002). Tasks are likely to involve different processes such as duration-based vs. beat-based timing, or perceptual vs. sensorimotor timing. Hence, they are likely to inform us about the functioning of dissociable (or only partly overlapping) components of the timing system(s) and their associated neuronal circuitry. Notably, most studies have focused on time perception, beat production or sensorimotor timing, which were tested in isolation. Entire research lines have been built on behavioral evidence coming from a single task (e.g., duration bisection or paced tapping) or a very restricted subset of tasks, depending on the theory or phenomenon of interest (e.g., duration-based vs. beat-based timing, perceptual vs. sensorimotor timing). This approach has the advantage that it focuses on the same timing component by submitting its functioning to the test of systematic variations of the same paradigm. However, its drawback is that it makes comparisons across paradigms, studied using different tasks, and group samples rather arduous. In addition, regarding clinical applications, confining testing to a limited set of tasks may be particularly problematic when assessing the performance of patient populations (e.g., patients with Parkinson's disease, schizophrenia, or attention deficit hyperactivity disorder; Allman & Meck, 2011; Noreika, Falter, & Rubia, 2014) or beat deafness (e.g., Palmer, Lidji, & Peretz, 2014; Phillips-Silver et al., 2011; Sowiński & Dalla Bella, 2013). As deficits are sometimes limited to specific timing

processes (e.g., Grahn & Brett, 2009; Merchant, Luciana, Hooper, Majestic, & Tuite, 2008; Sowiński & Dalla Bella, 2013; Spencer & Ivry, 2005), an approach based on a restricted set of tasks may indeed fail to pinpoint and circumscribe such impairment. In addition, by providing a limited assessment of the timing system, it may be incapable of capturing subtle individual differences among patients (e.g., Merchant, Luciana et al., 2008).

These issues can be circumvented by using a comprehensive test battery that assesses both perceptual and sensorimotor timing abilities. A few test batteries have been proposed in the past. For example, Kidd and coworkers (Kidd, Watson, & Gygi, 2007) performed a wide screening of auditory abilities with 19 tests (Test of Basic Auditory Capabilities – TBAC-E) administered to 300 participants, with the goal of detecting individual differences. The tests did not exclusively focus on timing, but also targeted pitch and loudness perception, as well as auditory recognition. The tests of perceptual timing included duration discrimination, temporal order judgments, and gap duration discrimination. Using factor analysis and structural equation modeling, they uncovered the tested auditory abilities that most account for individual differences (e.g., loudness/duration discrimination, and spectral/temporal pattern discrimination). However, the screening selectively addressed auditory perception, and excluded production tasks. Other examples of perceptual tasks, which may have the status of a “battery” can be found for duration-based timing (Wearden et al., 2008) and for both duration-based and beat-based timing (Grube et al., 2010). To our knowledge, tasks focusing on both perceptual and sensorimotor timing have been combined in only three recent test batteries. Iversen and Patel (2008) proposed the Beat Alignment Test (BAT), a set of tasks for assessing sensorimotor synchronization with a paced tapping task (with isochronous sequences and music) and beat perception abilities (with music only). In the BAT, participants are asked to detect whether or not beeps superimposed onto musical excerpts are on the beat in a perception task and to synchronize with the beat of the same excerpts in a production task. Preliminary data obtained from 30 participants showed that larger tapping variability was associated with lower beat perception. An extended version of the BAT (the Harvard Beat Alignment Task – H-BAT; Fujii & Schlaug, 2013) was recently put forward, in which paced tapping to music (Music Tapping test – MTT) is complemented by three tests focusing on the perception/production of simple meters (duple vs. triple), sequences of tones with a tempo change, and detecting/tapping to the beat of patterns of time intervals. Two important advantages of the H-BAT are that the same nonmusical material is used to test perceptual and sensorimotor timing; moreover, the same adaptive staircase procedure is adopted to compute thresholds in all perceptual and motor tasks. The results obtained in a group of 30 participants with variable musical expertise generally confirmed the

results of Iversen and Patel (2008), who observed that better performance in a synchronization task (i.e., higher consistency) is associated with lower perceptual and motor thresholds. The battery is assumed to be appropriate for testing individual perceptual and sensorimotor timing abilities. Finally, note that both the BAT and the H-BAT focus on testing beat-based timing, with auditory sequences of variable complexity. A multi-task approach to test interval-timing abilities was adopted by Merchant and coworkers (Merchant, Zarco, Bartolo, & Prado, 2008), who used categorization and discrimination of durations, duration reproduction, synchronization-continuation, and synchronization by circle drawing (relying more on implicit or emergent timing mechanisms) with non-musical material. With hierarchical clustering techniques, they showed that tasks group along the dimension of explicit vs. implicit interval timing. Interestingly, these tasks showed sensitivity to individual differences and different profiles of timing impairments in Parkinson’s disease (Merchant, Luciana et al., 2008).

In sum, previous evidence suggests that a number of tasks is likely to reveal multiple facets of human timing abilities, thereby differentiating individual profiles in both healthy and patient populations. In order to obtain a complete picture of these abilities, a unified set of tasks is needed to test a broad range of timing skills while being sensitive enough to study individual differences and impairments in specific populations. Building on these prior studies and test batteries, we propose the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA), a new tool for assessing timing abilities in the general population. BAASTA includes eight tasks, four testing perceptual timing and five sensorimotor timing. BAASTA has a few advantages compared to previous batteries. It tests both perception and action timing using the same stimulus material, while including both beat-based and interval-timing tasks. Moreover, both simple and complex stimulus material (a single repeated tone vs. music) is used in the tests. Previous studies have shown that rhythm deficits are easier to detect with more complex auditory material (Sowiński & Dalla Bella, 2013; Falk et al., 2015). Therefore, we expect that the battery will be particularly sensitive to individual differences. This may be particularly useful for detecting rhythm deficits (e.g., beat deafness) in the general population, and for capturing dissociations between perception and sensorimotor timing. To test perceptual timing, thresholds for duration discrimination (Grondin 2008) and anisochrony detection with music and nonmusical stimuli (Ehrlé & Samson, 2005; Hyde & Peretz, 2004; Sowiński & Dalla Bella, 2013), are computed using an adaptive maximum-likelihood procedure (MLP; Green, 1993, 1995). Moreover, BAASTA implements an adapted version of the perceptual task of the BAT (Iversen & Patel 2008).

Motor tasks include both unpaced and paced tapping with both musical and nonmusical stimuli (Repp, 2005; Repp & Su, 2013), synchronization-continuation (Wing & Kristofferson, 1973a; Wing & Kristofferson, 1973b), and an adaptive-tapping task (Repp & Keller, 2004; Schwartze et al., 2011). In the following, we describe BAASTA and provide a proof-of-concept of the battery by presenting representative results obtained in a group of 20 non-musicians. The focus will be on the capacity of the battery to detect cases of timing/rhythm deficits in the general population.

Experiment 1

Methods

Participants

Twenty right-handed adults (12 females; mean age = 23.9 years, $SD = 4.1$) participated in a first validation of BAASTA. Participants were non-musicians according to self-reports (musical training, $M = 1.05$ years, $SD = 1.56$).

Tests and procedure

BAASTA consists of a series of perceptual and production timing tasks as illustrated in Table 1

Table 1 BAASTA, test battery description

| Tests | Duration (min.) | Outcome measures |
|--|-----------------|---|
| Perceptual tasks | ~ 60 | |
| Duration discrimination | 6 | Duration discrimination threshold |
| Anisochrony detection with tones | 20 | Anisochrony detection threshold |
| Anisochrony detection with music | 8 | Anisochrony detection threshold |
| Beat Alignment Test (BAT) | 15 | Performance in detection of aligned beats |
| Production tasks | ~ 60 | |
| Unpaced tapping | 5 | Spontaneous tapping rate and variability |
| Paced tapping with metronome and music | 8 | Synchronization accuracy and variability/consistency |
| Synchronization-continuation | 6 | Tapping rate and variability in the continuation phase |
| Adaptive tapping | 25 | Measures of adaptation of tapping performance, and accuracy in the detection of tempo changes |
| Total | ~ 120 | |

Perceptual tasks Perceptual thresholds were estimated in three tasks, namely, *Duration discrimination*, *Anisochrony detection with tones*, and *Anisochrony detection with music*, using a maximum-likelihood adaptive procedure (MLP) (Green, 1993) implemented in the MLP toolbox (Grassi & Soranzo, 2009) in Matlab. In the Duration discrimination task the threshold for discriminating the duration of two tones was estimated; in the anisochrony detection tasks, the threshold to detect a time shift in an isochronous sequence of tones or in a musical excerpt was computed. In each task, participants performed three blocks of 16 trials. In addition, 20 % of the trials across the three blocks were catch trials, in which there was no change in the duration of the two tones or no time shift in a sequence. The stimulus difference in each trial was changed adaptively depending on the participants' response. Thresholds corresponded to the midpoint of the psychometric curve defined as a probability of 63.1 % of correct detection (Grassi & Soranzo, 2009). Stimuli were delivered via headphones (Sennheiser HD201) at a comfortable sound pressure level. A response was provided verbally by participants and entered by the experimenter via a computer keyboard. The tasks were preceded by 4 practice trials with feedback.

1) Duration discrimination

To measure the ability to discriminate two subsequent durations, the participants were presented with pairs of pure tones (frequency = 1 kHz; interval between tones = 600 ms). The standard tone (duration = 600 ms) was presented first, followed by a comparison tone, whose duration varied between 600 and 1000 ms. The duration of the second tone was adaptively controlled by the MLP algorithm. Participants judged whether the second tone lasted “longer” than the first or whether the two tones had the “same” duration.

2) Anisochrony detection with tones

In this task the ability to perceive a temporal irregularity (i.e., a time shift) in an isochronous sequence of tones (i.e., a metronome) was assessed (Hyde & Peretz, 2004; Sowiński & Dalla Bella, 2013). Sequences of 5 tones (tone frequency = 1047 Hz, duration = 150 ms) were presented. Isochronous sequences had a constant inter-onset-interval (IOI) while in non-isochronous sequences the 4th tone occurred earlier than expected based on the IOI of the preceding tones. This displacement resulted in reciprocal time shifts between tones 3–4 (shortened) and 4–5 (lengthened). The standard IOI was 600 ms. The magnitude of the local shift, up to 30 % of the IOI (180 ms), was controlled by the

MLP algorithm. Participants judged whether each sequence was “regular” or “irregular”.

3) Anisochrony detection with music

This task is similar to the previous one, but with musical material. Its purpose is to assess the ability to detect a deviant beat in a short musical excerpt (Sowiński & Dalla Bella, 2013). A musical excerpt was presented in each trial. The music was a computer-generated 2-bar fragment (8 quarter notes) taken from Bach’s “Badinerie” orchestral suite for flute BWV 1067, played with a piano timbre at a tempo of 100 beats/minute (IOI = 600 ms; beat = quarter note). In a stimulus with regular beat (i.e., isochronous) the IOI between musical beats was not manipulated. In an irregular stimulus a local time shift was introduced at the onset of the fifth beat, as done in the previous task. The standard IOI between musical beats was 600 ms. The magnitude of the time shift, up to 30 % (180 ms) of the IOI between musical beats, was controlled by the MLP algorithm. Participants judged whether each sequence was “regular” or “irregular”.

4) Beat Alignment Test (BAT)

To assess beat perception inherent in a musical stimulus, a version of the perceptual task of the BAT reported in previous studies (Fujii & Schlaug, 2013; Iversen & Patel 2008) was devised. The musical material consists of four computer-generated musical excerpts with a salient beat structure. Two fragments were taken from Bach’s “Badinerie” and two from Rossini’s “William Tell Overture”. Each excerpt included 20 beats (beat = quarter note). An isochronous sequence with a triangle timbre was superimposed on the music starting from the 7th beat. The isochronous sequence was either aligned to the musical beat or non-aligned. In the latter case either relative phase was changed (the tones preceded or followed the beats by 33 % of the inter-beat-interval, while keeping the same tempo of the musical stimulus), or period (the tones were presented at a tempo, which was 10 % slower or faster relative to the quarter note duration). The four musical excerpts were presented at 3 different tempos (inter-beat intervals, IBIs, of 450, 600 and 750 ms, respectively), for a total of 24 beat-aligned trials and 48 beat-non-aligned trials (72 trials overall). Participants were asked whether the triangle sounds were aligned to the perceived musical beat.

Production tasks Motor abilities were assessed using finger tapping (Aschersleben, 2002; Repp, 2005). Participants were asked to tap as regularly as possible with their right hand either in the absence of a pacing stimulus (unpaced tapping) or to

synchronize to a rhythmic auditory stimulus (paced tapping). Tapping was recorded via a Roland SPD-6 MIDI percussion pad controlled by MAX-MSP software (version 6.0). Stimuli were delivered over headphones (Sennheiser HD201) at a comfortable sound pressure level. No auditory feedback was provided during tapping. The tasks were preceded by practice trials.

1) Unpaced tapping

To assess the tapping rate and motor variability without a pacing stimulus participants were asked to tap regularly at a comfortable rate for 60 seconds, with the instruction to maintain the tapping rate as constant as possible. In two additional conditions, the participants were instructed to tap as fast and as slowly as possible, for 30 and 60 seconds, respectively. Unpaced tapping tasks were repeated once more at the end of all the motor timing tasks of BAASTA.

2) Paced tapping to an isochronous sequence

The ability to synchronize to a metronome was tested by asking the participants to tap to an isochronous sequence of 60 piano tones (tone frequency: 1319 Hz). There were three sequences, in which the IOIs between tones are 600, 450, and 750 ms. Each trial at a given tempo was repeated twice.

3) Paced tapping to music

To test the synchronization to the beat of music, participants were asked to tap to the beat of a well-formed musical excerpt from Bach’s “Badinerie” and from Rossini’s “William Tell Overture” (quarter note IOI = 600 ms), each including 64 beats. Each trial was repeated twice.

4) Synchronization-continuation

The classical synchronization-continuation paradigm (O’Boyle, Freeman, & Cody, 1996; Wing & Kristofferson, 1973a; Wing & Kristofferson, 1973b) was implemented in BAASTA. In this paradigm, the participants tapped to a series of 10 piano tones presented isochronously at 3 tempos (600, 450 or 750 ms). After the last tone they were asked to continue tapping at the same rate (continuation phase) for a duration corresponding to 30 IOIs in the absence of the pacing stimulus. The trial ended with a low-pitch tone signalling that the participant could stop tapping. Each trial at a given tempo was repeated twice.

5) Adaptive tapping

In order to assess participants’ flexibility in adapting to a changing pacing stimulus, a simplified version of an adaptive

tapping task (Schwartz et al., 2011) was implemented. This task is a variation of the synchronization-continuation paradigm. Sequences of 10 tones were presented. The first 6 tones of a sequence had an IOI of 600 ms, while the remaining 4 tones either maintained the same IOI or, in 67 % of the trials, were presented at a slower tempo (with a final IOI of 630 or 670 ms) or at a faster tempo (with a final IOI of 570 or 525 ms). Participants were asked to synchronize to the initial tempo, to adapt to the tempo change, and to continue tapping at the new tempo after the presentation of the last tone for a duration corresponding to 10 IOIs. At the end of each trial, participants were asked whether they perceived an acceleration, a deceleration, or no tempo change in the sequence. There were 10 blocks, each including 6 trials (4 with tempo change, 2 without), presented in random order.

Analyses

Perceptual tasks

The thresholds in the duration discrimination and anisochrony detection tasks were obtained by averaging the values obtained in the three blocks, expressed in percentage of IOI (Weber ratio). Blocks with more than 30 % of false alarms (FAs, when a difference for a catch trial is reported) were discarded. Moreover, blocks leading to aberrant threshold estimations due to persistent local minima in the maximum-likelihood procedure, or due to a lack of convergence of the estimation function at the end of a block, were rejected. In the latter case, the convergence of the estimated threshold was assessed by calculating the slope of local threshold values across the last eight trials of a block. Lack of convergence was indicated by a slope exceeding 10 % relative to the mean threshold of the preceding trials. In the BAT, the sensitivity index (d') was calculated, as an unbiased measure of detection performance. The computation was based on the number of Hits (i.e., when a misaligned metronome was correctly detected) and False alarms (i.e., when a misalignment was erroneously reported). In addition, d' was calculated separately for each of the three tempos (450, 600, and 750 ms).

Production tasks

In all tapping tasks, tapping data were pre-processed as follows before conducting the main analysis. For paced and unpaced tapping, the first ten taps were discarded. For synchronization-continuation, a minimum of ten continuous taps was necessary to analyze a trial with a maximum of 30 taps in the continuation phase corresponding to the length of the trial. Last, tapping sequences obtained in the adaptive tapping task were rejected when participants were not able to synchronize with the metronome (i.e., with fewer than four taps produced in the second half of the synchronization phase corresponding

to the pacing stimuli). A trial was treated as valid when it included eight taps without outliers in the continuation phase. In addition, for all tasks taps leading to inter-tap intervals (ITIs) smaller than 100 ms (artifacts) were rejected and outlier taps were discarded. An outlier was defined as a tap for which the ITI between the actual tap and the preceding tap was smaller than $Q1 - 3 \cdot \text{Interquartile range (IQR)}$ or greater than $Q3 + 3 \cdot \text{IQR}$, where $Q1$ is the first quartile and $Q3$ is the third quartile.

The mean ITI was computed for tapping sequences yielded by the unpaced tapping task, the continuation phase of the synchronization-continuation task, and the adaptive tapping task. Tapping *motor variability* was obtained by calculating the coefficient of variation of the ITI (CV of the ITI, namely, the ratio of the SD of the ITIs over the mean ITI). Tapping sequences in the paced tapping tasks were submitted to the following analyses. For the purpose of this study we implemented two classes of analyses of synchronization performance, one based on linear statistics, the other on circular statistics. Metrics of synchronization issued from linear statistics are very common, but present some drawbacks. Data can be analyzed with linear statistics under the constraint that taps are in a one-to-one relation with the pacing stimulus (i.e., when only one tap occurs before or after a pacing tone or musical beat, within a time window of ± 50 % of the IOI). Circular statistics are not conditional on this constraint. This has the advantage that data from individuals showing poor synchronization can still be analyzed (e.g., Falk, Müller, & Dalla Bella, 2015; Kirschner & Tomasello, 2009; Pecenka & Keller, 2011; Sowiński & Dalla Bella, 2013), thus making circular statistics particularly well-suited to detect poor synchronization and to capture individual differences (Dalla Bella & Sowiński, 2015; Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014).

When using linear statistics, *synchronization accuracy* was obtained by calculating the mean absolute asynchrony (i.e., not signed) between the taps and the pacing stimuli/beats. Small asynchrony indicated high accuracy. *Synchronization variability* is the SE of asynchrony between taps and pacing stimuli. Both synchronization accuracy and variability are indicated in percentage of the IOI. When synchronization data were submitted to circular statistics (Fisher, 1995), the Circular statistics Toolbox for Matlab (Berens, 2009) was used. Taps are represented by angles on a 360-degree polar scale, where 0 degrees indicate stimulus/beat onsets. Angles indicate taps' relative phase, with respect to the pacing stimuli (i.e., tone onsets or beats). For example, a tap occurring 100 ms after a tone in an isochronous sequence with an IOI of 800 ms is indicated by an angle of 45° on the circle. Angles on the circle are treated as unit vectors and used to calculate the mean resultant vector R (Berens, 2009; Fisher, 1995; Mardia & Jupp, 1999). The vector R served

to calculate *synchronization consistency* (i.e., the reciprocal of variability) and *synchronization accuracy* (Sowiński & Dalla Bella, 2013). *R* vector length (from 0 to 1) indicates synchronization consistency. It reflects the variability of the time differences between the taps and the pacing stimuli. A vector length of 1 means that all the taps occur exactly the same time interval before or after the pacing stimulus (i.e., maximum consistency); 0 means lack of synchronization (i.e., the taps are randomly distributed between the beats). The angle of vector *R* (θ or relative phase, in degrees) indicates synchronization accuracy, namely whether participants tapped before (negative angle) or after (positive angle) the pacing event. Accuracy was calculated only if participants' synchronization performance was above chance (null hypothesis = random distribution of data points around the circle), as assessed with the Rayleigh test for circular uniformity (Fisher, 1995; Wilkie, 1983). The null hypothesis is rejected when *R* vector length is sufficiently large according to this test. Vector length data was submitted to a logit transformation (e.g., Falk et al., 2015) before conducting further analyses. In both paced tapping and synchronization-continuation tasks, the results in the two trials were averaged and submitted to further analyses.

Finally, in the adaptive tapping task, adaptation of tapping to the tempo change was measured by calculating the Adaptation index during the continuation phase, as done in Schwartze et al. (2011). Mean ITIs were considered as a function of the final sequence tempo, and regression lines were fitted to the slopes of these ITI functions. The slopes were used as adaptation indices. An Adaptation index of 1 indicates perfect adaptation; values lower than 1 indicates undercorrection and values greater than 1 overcorrection. This index was calculated separately for tempo acceleration (i.e., faster tempos with final sequence IOIs < 600 ms) and tempo deceleration (slower tempos with final sequence IOIs > 600 ms). The sensitivity index (d') for detecting tempo changes was also calculated. The computation was based on the number of Hits (when a tempo acceleration or deceleration was correctly detected) and False alarms (when a tempo acceleration or deceleration was reported while there was no change or the opposite change).

Results

The data were first screened for outliers, as defined above. In the perceptual tasks, 3.8 % of the trials were rejected and in the production tasks less than 1 % of taps were discarded. Since the data were not normally distributed in more than 50 % of the cases as assessed by the Kolmogorov-Smirnov test, conditions were compared using Friedman non-parametric ANOVAs and two-tailed

Wilcoxon matched-pairs tests with Bonferroni correction for the number of comparisons.

Perceptual tasks

The results obtained in the perceptual tasks are presented in Fig. 1. Duration discrimination thresholds were generally higher (about 10 %) compared with the thresholds obtained in anisochrony detection ($W = 155, p < .001$; Fig. 1a). In addition, detecting a deviation from isochrony in a musical sequence was easier than in an isochronous sequence of tones ($W = 138, p < .01$). The results from the BAT showed that, in general, non-musicians could easily detect when a metronome was not aligned with the beat of the music (Fig. 1b). This performance did not vary as a function of the beat rate ($\chi^2(2) = 1.56, p = .46$)

Production tasks

The results obtained in unpaced and paced tapping tasks are presented in Figs. 2, 3 and 4, respectively. Participants showed a spontaneous tapping rate in the vicinity of 600 ms (Fig. 2a), with lower and higher rates for the Slowest and Quickest conditions ($\chi^2(2) = 40.0, p < .001$; Slowest vs. Spontaneous, $W = 210, p < .001$; Quickest vs. Spontaneous, $W = -210, p < .001$). In contrast, motor variability, did not vary as a function of the condition ($\chi^2(2) = 0.10, p = .95$; Fig. 2b). The results yielded by the paced tapping tasks revealed no differences in synchronization accuracy ($\chi^2(4) = 4.76, p = .31$), depending on the pacing stimulus (metronome vs. music) and the rate of the pacing stimulus (IOI). With linear statistics, it was found that participants were as accurate when they synchronized to the beats of music as to the sounds of a metronome ($W = 32, p = .56$; Fig. 3a). Although a slight tendency towards increased variability was observed when participants synchronized with music as opposed to a metronome, this effect did not reach significance ($W = -16, p = .78$; Fig. 3b). No significant differences were found between the three metronome rates for both accuracy ($\chi^2(2) = 1.30, p = .52$) and variability ($\chi^2(2) = 0.90, p = .64$). In general, data analyzed with circular statistics showed similar results. However, participants were clearly more accurate with music than with a metronome, a difference which reached significance when data were averaged for the IOI and the musical stimulus (Watson-Williams circular ANOVA, $F(1,39) = 9.03, p < .01$; Fig. 4a). No differences between metronome rates and musical stimuli were found in terms of both accuracy and consistency (Fig. 4a and b).

Non-musicians' average performance in the synchronization-continuation and adaptive tapping tasks are presented in Figs. 5, 6, and 7, respectively. As can be seen from the tapping rate (Fig. 5a), the participants successfully continued tapping at the rate indicated by the metronome; accordingly, tapping rates differed at the three tempos ($\chi^2(2) = 40.00, p < .001$). Motor

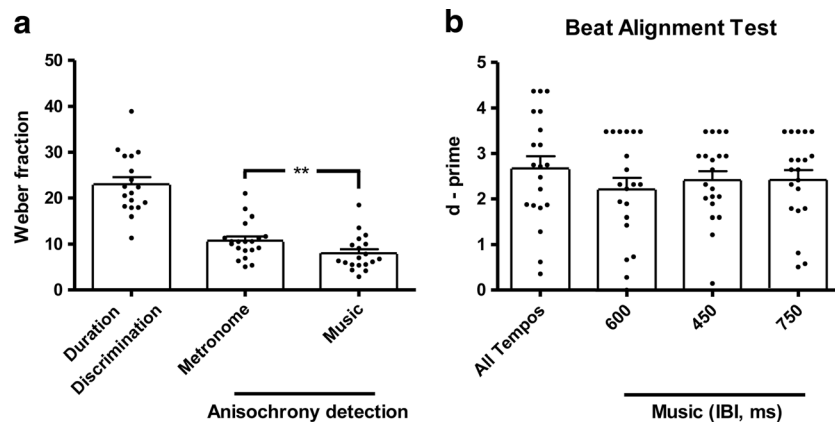


Fig. 1 Performance in the perceptual tasks of BAASTA. Error bars indicate the Standard Error of the mean. $**p < .01$

variability in the continuation phase (Fig. 5b) differed as function of tempo ($\chi^2(2) = 11.70, p < .01$) and was the largest at the fastest tempo (450 ms vs. 600 ms; $W = -158, p = .01$). Similarly, in the adaptive tapping task, it can be seen that participants were able to adapt to slower and faster stimulus rates as shown by the tapping rates in the continuation phase (Fig. 6a) ($\chi^2(4) = 79.24, p < .001$). Participants similarly adapted to faster ($W = -210, p < .001$) and to slower tempos ($W = -210, p < .001$). The adaptation index generally showed values above 1 (Fig. 7a) indicating a tendency to overcorrect the interval between the taps, when the sequence tempo was slower or faster. Last, participants mostly detected the largest tempo changes (525 ms vs. 570 ms; $W = 190, p < .001$, 630 vs. 675 ms; $W = -171, p < .001$).

Relations between perceptual and production tasks

In order to examine whether the different perceptual and production tasks of BAASTA probe similar underlying processes, correlations between all the tasks were computed. A subset of measures obtained from these tasks, selected as representative of individual performances, was used. For perceptual tasks, the

thresholds obtained in the Duration discrimination task (*Per1*), Anisochrony detection with tones (*Per2*), Anisochrony detection with music (*Per3*), and the overall d-prime in the BAT (*Per4*) were entered in the analysis. For production tasks, motor variability was considered for Unpaced tapping (*Prod1*). Moreover, accuracy and variability (based on linear statistics) were submitted to the analysis of Paced tapping to an isochronous sequence (*Prod2a*, *Prod2b*, respectively), averaged across the three tempos, and of Paced tapping to music (*Prod3a*, *Prod3b*, respectively), averaged across the two excerpts. Finally, for the Synchronization-continuation task, motor variability averaged across the three tempos (*Prod4*) was analyzed, and for Adaptive tapping, the adaptation index for slower and faster tempo changes (*Prod5a*, *Prod5b*, respectively), and the average d-prime (*Prod5c*) were considered. The correlation matrix between all the tasks of BAASTA is reported in Fig. 8. As can be seen, some tasks or measures are significantly correlated with others. For example, the performance in the Anisochrony detection task with tones (*Per2*) and in the BAT (*Per4*) is highly correlated with accuracy and variability in Paced tapping (*Prod2* and *Prod3*). Similarly, the detection of tempo changes in

Unpaced tapping

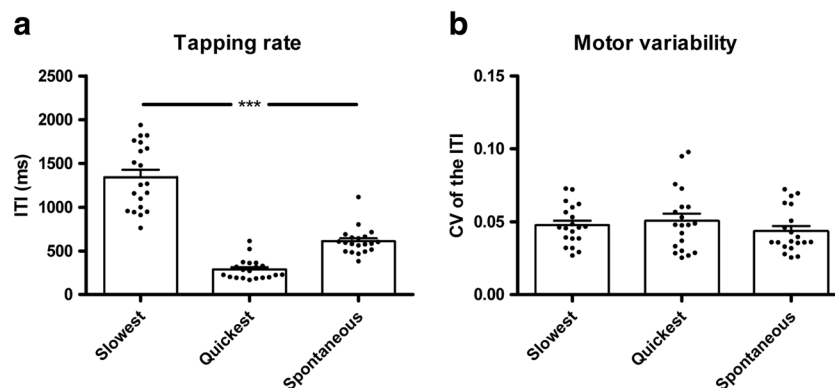


Fig. 2 Performance in the unpaced tapping task of BAASTA. $***p < .001$

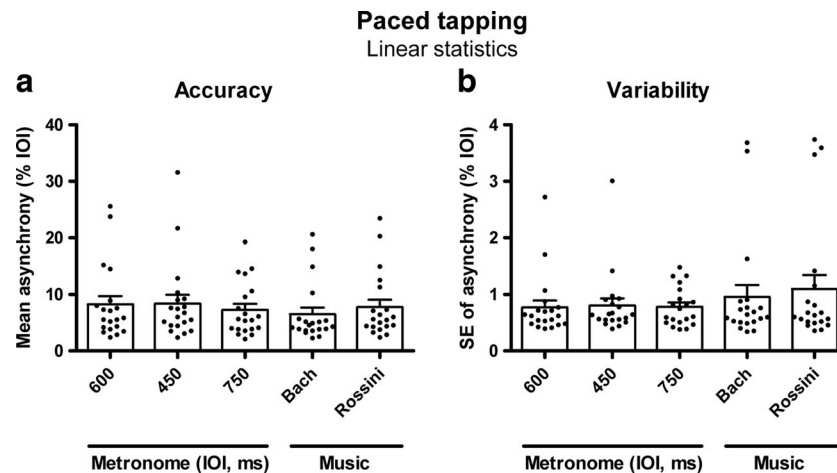


Fig. 3 Performance in the paced tapping task of BAASTA using linear statistics

the Adaptive tapping task (Prod5c) correlates with various perceptual and production tasks of BAASTA. This suggests that these tasks may tap shared beat-based mechanisms (e.g., beat extraction, needed in both perceptual and tapping tasks), or common latent processes (e.g., similar attentional or memory processes). In contrast, some tasks such as Duration discrimination, Anisochrony detection with music, and the Adaptive tapping task (motor performance only) are not correlated with other tasks, thus pointing to potentially independent components of the timing system(s).

Individual differences

The results obtained with BAASTA also revealed important individual differences among non-musicians in both perceptual and sensorimotor skills. The primary objective of the present study was not to focus on a thorough analysis of individual differences using BAASTA. However, further data collection in support of such an analysis is currently under way.

Nevertheless, one aim of the test battery is to capture individual differences, which will allow identifying participants with rhythm deficits (e.g., beat deaf or poor synchronizers; e.g., Palmer et al., 2014; Sowiński & Dalla Bella, 2013). Variable performance in each task was determined by pinpointing those participants who deviated from the group average by at least 2 *SD* (cutoff score). This method has been applied successfully in the past to identify individuals suffering from congenital amusia or tone-deafness (e.g., Berkowska & Dalla Bella, 2013; Dalla Bella, Giguère, & Peretz, 2009; Peretz, Champod, & Hyde, 2003; for a discussion of the use of a relative criterion for detecting music disorders, see also Dalla Bella et al., 2015). Cutoffs and the number of participants showing extreme values for the major outcome variables of BAASTA are presented in Table 2. For simplicity, only data from linear measures of synchronization in paced tapping are considered here, as analyses with linear and circular statistics provided similar results. As can be seen, some participants showed values beyond the cutoffs indicating poor perceptual timing skills, poor sensorimotor synchronization, or both. Sensorimotor tasks

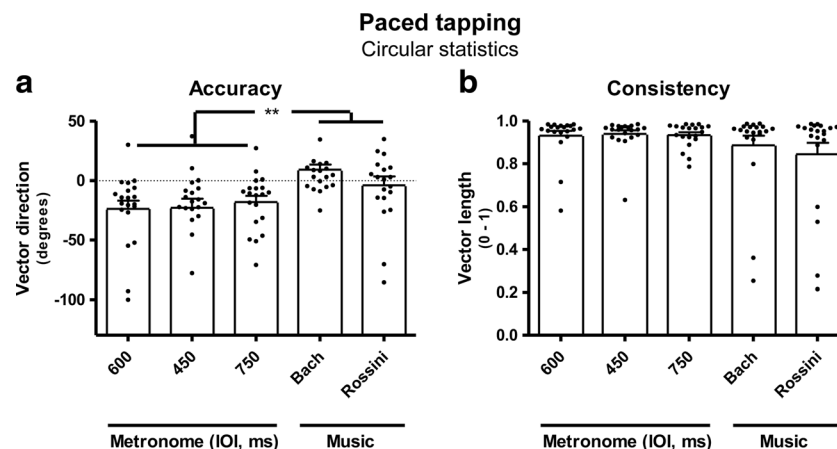


Fig. 4 Performance in the paced tapping task of BAASTA using circular statistics. $**p < .01$

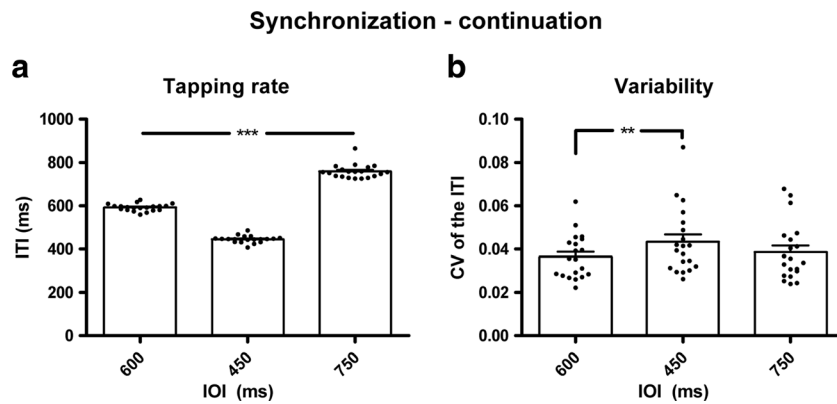


Fig. 5 Performance in the synchronization-continuation task of BAASTA. Results from the continuation phase are reported. $**p = .01$; $***p < .001$

(i.e. paced tapping more than perceptual tasks) were particularly sensitive to increased variability in rhythm production/perception.

Discussion

In this proof-of-concept study of BAASTA, data from this battery for the assessment of perceptual and sensorimotor timing skills was obtained from a group of 20 non-musicians. The results are consistent with previous studies using the same or similar tasks, and show that the MLP adaptive algorithm can provide valuable measures of thresholds in perceptual timing skills. The battery, thanks to the testing of a variety of rhythmic skills, shows sensitivity to poor perceptual and sensorimotor timing skills. Indeed, based on the data obtained in a relatively small sample of non-musicians, the battery can sensitively identify individual differences in perceptual and sensorimotor timing skills. Hence, BAASTA can serve to uncover individuals with spared or impaired rhythmic skills in healthy participants without musical training and in clinical populations (e.g., Benoit et al., 2014; Falk, Müller & Dalla Bella, 2015).

In the perceptual timing tasks the thresholds provided by the MLP adaptive algorithm was within the range of the results previously reported for individuals without musical training on anisochrony detection tasks with tones (Ehrle & Samson, 2005; Hyde & Peretz, 2004; Sowiński & Dalla Bella, 2013) or with a musical sequence (Sowiński & Dalla Bella, 2013). Detecting a time shift was easier when it was embedded in musical stimuli than in simpler isochronous sequences. This result is at odds with previous findings that the task is more difficult with music material (Sowiński & Dalla Bella, 2013). This discrepancy may be driven by the musical excerpts in BAASTA compared to previous testing, as BAASTA uses musical sequences with a particularly salient beat structure. Another possibility may pertain to the psychophysical procedure to determine the threshold. BAASTA used an adaptive procedure, which limits the deleterious effects of long testing sessions while in previous studies thresholds were obtained using the method of constant stimuli (Sowiński & Dalla Bella, 2013). With regards to duration discrimination, the results obtained in BAASTA yielded thresholds that were higher than those typically found in other studies (e.g., Grondin et al., 2001, using the same IOI). These higher thresholds may have resulted from

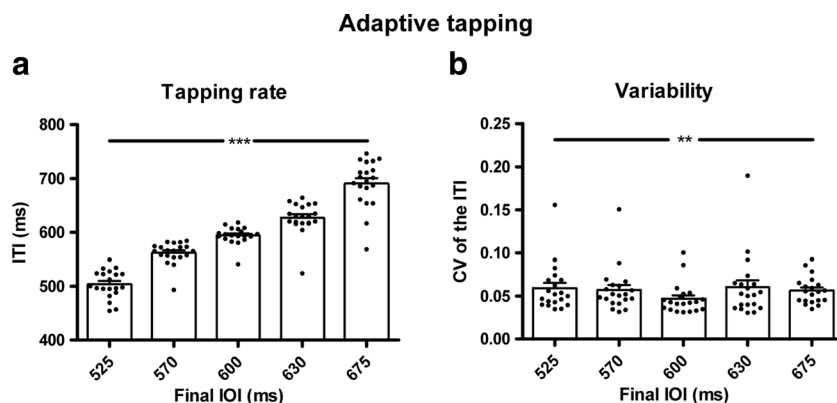


Fig. 6 Performance in the adaptive task of BAASTA. Results from the continuation phase are reported. $**p < .01$; $***p < .001$

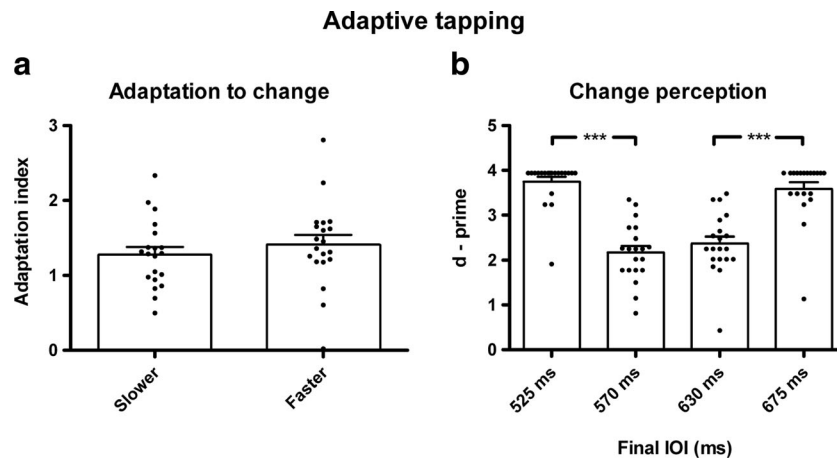


Fig. 7 Performance in the adaptive tapping task of BAASTA. *** $p < .001$

some of the choices adopted in devising this task. Unlike Grondin et al. (2001), the task version implemented in BAASTA did not provide any feedback after participants' responses, probably making it more challenging. Another factor that may have played a role is the use of the MLP algorithm, which can estimate a threshold with a very limited number of trials (Grassi & Soranzo, 2009; Soranzo & Grassi, 2014). Last, the results obtained in the BAT are generally consistent with the range of values reported in previous studies and the observed variability in a non-musician population (Iversen & Patel 2008).

In the production tasks, the unpaced tapping tasks implemented in BAASTA confirm the classic results in the tapping

literature. The preferred tapping rate around 600 ms with low variability and the mean fastest rate (ITI around 250 ms) is comparable to that of previous studies, whereas the slowest rate (ITI around 1400 ms) is a bit faster than reported elsewhere (e.g., Drake et al., 2000; McAuley, Jones, Holub, Johnston, & Miller, 2006). Synchronization accuracy and variability/consistency in the paced tapping tasks with both simple and complex sequences are within the range of values obtained in previous studies (Repp, 2010; Sowiński & Dalla Bella, 2013). Non-musicians were more accurate (and not more variable) when they tapped to the beat of music than to the sounds of an isochronous sequence. This finding reflects the observation that participants typically anticipate the pacing stimulus (mean negative asynchrony; Aschersleben, 2002) when tapping to a metronome, but not when tapping to a musical beat. Note, however, that there is contradicting evidence that tapping to a musical beat may be rather more difficult than synchronizing to a metronome (Repp, 2010; Sowiński & Dalla Bella, 2013). This discrepancy may result from the choice of music material in BAASTA, with a particularly salient beat structure. The same reasoning was provided above to account for stimulus differences in anisochrony detection. Performance in the synchronization-continuation task showed that the non-musicians were able to continue tapping at the target tempo; their variability was slightly lower than that observed in previous studies (McAuley et al., 2006), at least for comfortable and slower tempos (with IOIs of 600 and 750 ms). Last, the results obtained in the adaptive tapping task of BAASTA generally confirm the results from a population of participants experienced in tapping tasks (Repp & Keller, 2004), with slightly higher values for the adaptation index, revealing a greater tendency of the tested group to overcorrect the interval between the taps.

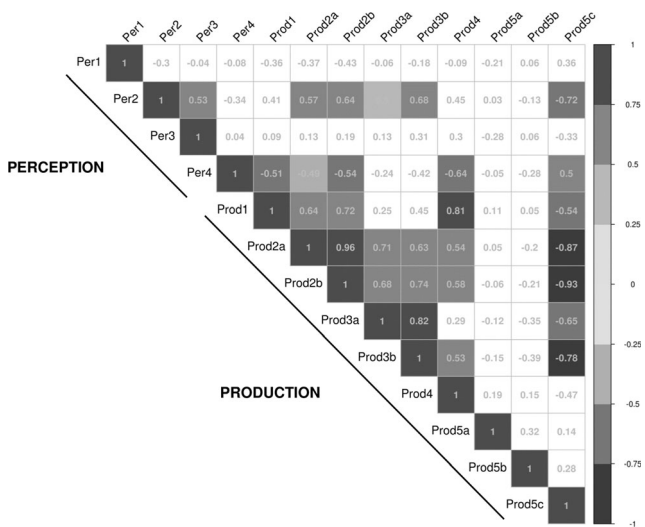


Fig. 8 Correlation matrix between the Perceptual tasks (Per1, Per2, Per3, Per4) and the Production tasks (Prod1, Prod2a-b, Prod3a-b, Prod4, Prod5a-b-c) in BAASTA. Pearson correlation coefficients are reported. Significant correlations ($p < .05$) are highlighted in gray. Per1, Duration discrimination; Per2, Anisochrony detection with tones; Per3, Anisochrony detection with music; Per4, BAT; Prod1, Unpaced tapping; Prod2a-b, Paced tapping to an isochronous sequence; Prod3a-b, Paced tapping to music; Prod4, Synchronization-continuation; Prod5a-b-c, Adaptive tapping

An evaluation of the correlations between the different tasks of BAASTA revealed that the results from different tasks are not systematically correlated. Some tasks, such as the BAT and paced tapping, show high correlation, thus

Table 2 Extreme performances obtained with BAASTA in a group of 20 healthy nonmusician adults

| Task | Variable | Cutoff | Extremes (participant number) |
|--|---------------------------------------|-------------------------|----------------------------------|
| Perceptual tasks | | | |
| Duration discrimination | Threshold | > 36.2 | 18 |
| Anisochrony detection with tones | Threshold | > 18.8 | 15 |
| Anisochrony detection with music | Threshold | > 15.6 | 9 |
| Beat alignment test | d' | > 5.1 | None |
| Production tasks | | | |
| Unpaced tapping | CV ITI | Spontaneous: > 0.07 | None |
| | | Slowest: > 0.08 | None |
| | | Quickest: > 0.09 | 1 |
| Paced tapping with metronome and music | Mean asynchrony / SE of asynchrony | 600 ms: > 21.4 / > 1.9 | 7, 15 |
| | | 450 ms: > 22.3 / > 1.9 | 15 |
| | | 750 ms: > 16.9 / > 1.5 | 15 |
| | | Bach: > 17.0 / > 2.9 | 8, 15 |
| | | Rossini: > 19.4 / > 3.3 | 1, 15, 16 |
| Synchronization – continuation | CV ITI | 600 ms: > 0.05 | 4 |
| | | 450 ms: > 0.08 | 8 |
| | | 750 ms: > 0.09 | 9, 15 |
| Adaptive tapping | CV ITI | 525 ms: > 0.11 | 15 |
| | | 570 ms: > 0.11 | 15 |
| | | 600 ms: > 0.08 | 4, 15 |
| | | 630 ms: > 0.13 | 7 |
| | | 675 ms: > 0.09 | 4 |

Note. CV ITI (coefficient of variation of the ITI) = motor variability; Mean asynchrony = synchronization accuracy; SE asynchrony = synchronization variability

suggesting that they may engage common beat-based processes. In contrast, other tasks (e.g., duration discrimination and motor performance in adaptive tapping) are not correlated with the others. Altogether, these are indications that BAASTA is testing a variety of timing skills (e.g., interval timing vs. beat-based timing, perceptual vs. motor timing, synchronization accuracy vs. consistency, etc.), and that it is capable of shedding light on different facets of timing skills. At the same time, the aforementioned relations and differences between the tasks may lead to choose a subset of tasks to test a particular component of the timing system, or to reduce the number of tasks to those tapping truly independent mechanisms.

In sum, the current results show that BAASTA provides a valuable set of tasks for a thorough and multifaceted testing of perceptual and sensorimotor timing skills in the general population. However, one concern is that the results obtained in the perceptual tasks, apart from the BAT, rely on the implementation of an adaptive maximum-likelihood procedure (Green, 1993, 1995) by Grassi and Soranzo (2009). This method is not very widespread, as compared to the more common adaptive staircase methods (Levitt, 1971; Soranzo &

Grassi, 2014; Taylor & Creelman, 1967). To our knowledge the MLP algorithm has not been validated so far against standard adaptive psychophysics methods in the perceptual tasks used in BAASTA. Therefore, we conducted a second Experiment, in which a second group of non-musicians was tested on the three tasks of BAASTA that use MLP, namely Duration discrimination, Anisochrony detection with tones, and Anisochrony detection with music. We analyzed the data using MLP as well as two examples of standard staircase methods.

Experiment 2

Methods

Participants

Twenty-four right-handed healthy adults (13 females; mean age: 26.5 years, $SD = 4.0$) participated in the Experiment. Fifteen participants were recruited from the MPI data base of the Max-Planck-Institute for Human Cognitive and Brain

Sciences, in Leipzig, Germany and the others were students from the University of Montpellier, France. They were non-musicians according to self-reports (musical training, $M = 2.0$ years, $SD = 2.02$).

Tasks and procedure

Participants were submitted to Duration discrimination, Anisochrony detection with tones, and Anisochrony detection with music tasks. Each task was repeated in three conditions using an adaptive two-alternative forced-choice paradigm. In the first condition, the threshold was estimated using the adaptive MLP procedure (Green, 1993) implemented in the MLP toolbox (Grassi & Soranzo, 2009). In the second and third conditions, the threshold was obtained using a staircase procedure (Levitt, 1971). In the three conditions, the same starting difference between standard and comparison stimuli (i.e., change in duration or inter-beat interval) and the same auditory stimuli as in Experiment 1 were used. In the first condition, the stimulus difference, conditional to the participant's response, was controlled by the MLP algorithm. In the second and third conditions, we implemented a 2 down / 1 up and a 3 down / 1 up staircase paradigm. In the first case, two consecutive positive responses to a difference are needed to reduce it in the following trial; in the second case, three positive responses are required. In both cases, the difference was

halved. A negative response led to a reverse in the change, and the difference was multiplied by a factor of 1.5. Every time the direction of a difference change reversed from up to down or from down to up the value of the difference at which this occurred was recorded as a turnaround point. The trial ended after eight turnaround points and the threshold was calculated by averaging the last four.

Thresholds with MLP corresponded to the midpoint of the psychometric curve defined as a probability of 63.1 % of correct detection (Grassi & Soranzo, 2009). With the staircase paradigms, thresholds corresponded to a probability of 70.7 % for the 2 down / 1 up and of 79.3 % for the 3 down / 1 up of the psychometric curve (Levitt, 1971). The tasks were carried out in Matlab. Stimuli were delivered via headphones (Sennheiser HD201) at a comfortable sound pressure level. A response was provided verbally by participants and entered by the experimenter via a computer keyboard. The tasks were preceded by 4 practice trials with feedback. The order of conditions was randomized across participants.

Results and discussion

As the data were normally distributed as assessed with the Kolmogorov-Smirnov test, conditions were compared using repeated-measure 1-way ANOVAs and two-tailed

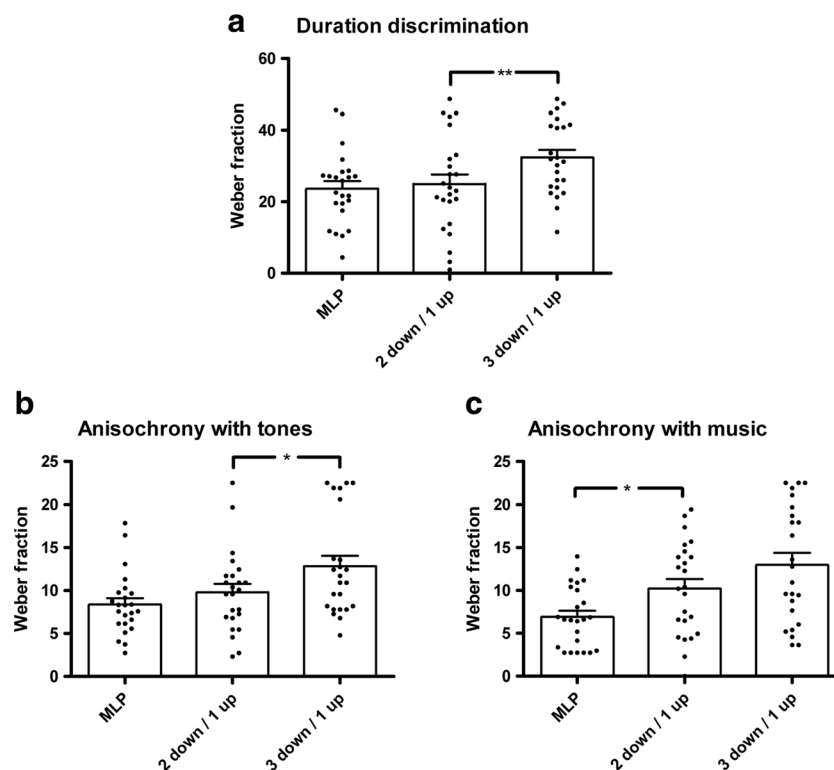


Fig. 9 Performance in the perceptual tasks of BAASTA using different adaptive methods for threshold estimation. $*p < .05$; $**p < .01$

paired *t*-tests, Bonferroni-corrected for the number of comparisons.

The number of trials needed for threshold estimation varied as a function of the condition. This number was set to 16 for MLP across all tasks. The 2 down / 1 up method required a lower number of trials (23.6; Duration discrimination, $M = 23.0$, $SE = 1.4$; Anisochrony detection with tones, $M = 21.0$, $SE = .8$; Anisochrony detection with music, $M = 26.9$, $SE = 1.4$) than the 3 down / 1 up method (29.0; Duration discrimination, $M = 28.4$, $SE = 1.1$; Anisochrony detection with tones, $M = 28.3$, $SE = .7$; Anisochrony detection with music, $M = 30.5$, $SE = 1.4$) ($t(23) = 8.91$, $p < .001$).

The results obtained in the three perceptual tasks in the three conditions are presented in Fig. 9. In all tasks, average thresholds differed as a function of the condition (Fig. 9a, Duration discrimination, $F(2,46) = 9.49$, $p < .001$; Fig. 9b, Anisochrony detection with tones, $F(2,46) = 12.21$, $p < .001$; Fig. 9c, Anisochrony detection with music, $F(2,46) = 14.12$, $p < .001$). In the Duration discrimination task, the 3 down / 1 up threshold was higher than both MLP ($t(23) = 4.27$, $p < .001$) and 2 down / 1 up thresholds ($t(23) = 3.42$, $p < .01$). In Anisochrony detection with tones, the 3 down / 1 up threshold was higher than both MLP ($t(23) = 4.78$, $p < .001$) and 2 down / 1 up thresholds ($t(23) = 2.94$, $p < .05$). The 2 down / 1 up threshold was also higher than MLP but only marginally significant ($t(23) = 1.82$, $p = .08$). A similar pattern was also observed in Anisochrony detection with music. The 3 down / 1 up threshold was higher than both the MLP ($t(23) = 4.94$, $p < .001$) and 2 down / 1 up ($t(23) = 2.54$, $p < .06$, marginally significant) thresholds while the 2 down / 1 up threshold was also higher than MLP ($t(23) = 3.0$, $p < .05$). In spite of these differences, the thresholds were significantly correlated across the three estimation methods, in the Duration discrimination task (average $r = .55$, $p < .01$, one-tailed), Anisochrony detection with tones (average $r = .62$, $p < .001$, one-tailed), and Anisochrony detection with music (average $r = .39$, $p < .05$, one-tailed). However, the correlation between MLP and 2 down / 1 up in the Anisochrony detection task with music just failed to reach significance ($p = .06$).

In sum, the results obtained with standard staircase methods are qualitatively comparable to the estimations of the threshold provided by MLP. In general, the obtained thresholds are lower with MLP as compared to staircase procedures. This finding is consistent with the fact that MLP estimates a threshold corresponding to a lower percent of the psychometric function (63.1 %) than staircase methods (75.0 %, on average).

Conclusion

The goal of the current study was to present a new test battery, BAASTA, for the assessment of perceptual and sensorimotor

timing in the general population (i.e., individuals without musical training). A set of tasks and analysis methods are proposed to characterize timing and rhythm abilities. A proof-of-concept of the battery was carried out in a group of 20 non-musicians. The obtained results align with previous findings that used the same or similar tasks tested in independent studies, and show that BAASTA can capture individual differences, in particular by identifying cases of poor timing/rhythm performance. The aforementioned discrepancies, relative to duration discrimination and paced tapping, are likely to stem from the choice of the music material, or from the characteristics of the chosen tests. Slightly lower thresholds were found using the MLP algorithm as compared to standard staircase methods, due to differences in threshold estimation. Thus, these findings show that MLP can be used successfully and reliably for threshold estimation in the perceptual tasks of BAASTA.

BAASTA has a few strengths as compared to previous batteries. For example, a quite direct comparison can be done with the H-BAT (Fujii & Schlaug, 2013), given that this battery focuses on beat-based timing in both perception and production. The tasks of the H-BAT include paced tapping to musical stimuli (real recordings with variable IBI), as well as tasks, in which participants detected/tapped along with duple/triple meters, and stimuli with decelerating/accelerating tempos. Although most of the tasks of BAASTA visibly require beat-based timing (e.g., paced tapping to music or a metronome, the BAT) the scope of BAASTA is wider than testing this class of timing skills. BAASTA also includes a typical interval timing task (duration discrimination), two tasks using a widespread paradigm in the timing literature (synchronization-continuation in a standard and in an adaptive version), and unpaced tapping. These tasks cannot be directly ascribed to beat-based processing. Thus, one strength of the battery is to provide a more general assessment of timing skills, which goes beyond beat-based timing while capitalizing on well-known paradigms in the timing literature. This may prove particularly useful for detecting timing disorders, which may not be confined to beat-based processing. Note that, as can be seen from the correlation matrix reported in Fig. 8, typical beat-based tasks (BAT and paced tapping) are usually correlated; however, the performance in these tasks is not related to other tasks such as duration discrimination or adaptive tapping (motor performance). This suggests that some of the tests of BAASTA tap different timing mechanisms, which need to be probed by dedicated tasks.

Due to its wider scope and to its extensive set of sensitive and well-established perceptual and sensorimotor timing tasks, BAASTA is well-suited to characterize specific profiles of timing abilities. Thus, the battery is an invaluable tool to uncover cases of timing/rhythm disorders. The likelihood for the battery to detect these disorders is enhanced by using a variety of sensitive conditions (e.g., different tasks, different

stimulus rates, simple and complex stimuli, etc.), and a rich array of measures of timing skills (e.g., linear and circular measures of synchronization accuracy and variability/consistency, motor variability, adaptation indexes, perceptual thresholds, etc.). To our knowledge, these characteristics are unique to BAASTA. A simple analysis of individual differences in a group of non-musicians reveals that BAASTA can be used successfully to identify performance variability in the general population regarding perceptual timing, sensorimotor timing, or both. In addition, by combining a set of both perceptual and sensorimotor tasks using the same auditory stimuli, BAASTA clearly allows to uncover potential dissociations between perception and action in the timing domain. There are indications that perception and action in duration and rhythm processing may dissociate in patients with brain damage (e.g., Fries & Swihart, 1990) or beat deafness (Sowiński & Dalla Bella, 2013), as previously observed for pitch processing (Dalla Bella & Berkowska, 2009; Dalla Bella, Berkowska, & Sowiński, 2011; Dalla Bella, Giguère, & Peretz, 2007; Loui, Guenther, Mathys, & Schlaug, 2008). In addition, the synchronization and perception tasks were performed with both simple and more complex auditory material (i.e., an isochronous sequence vs. music). The complexity of auditory stimuli provides an optimal condition for detecting impaired timing/rhythm processing, which may be confined to metrical processing and beat extraction when processing complex rhythmic stimuli such as music (e.g., Sowiński & Dalla Bella, 2013) and speech (Kotz & Gunter, 2015). Recent studies revealed that some of the tasks included in BAASTA, in particular paced tapping, are sensitive to peculiar disorders of beat-based timing in different populations. For example, synchronization consistency is particularly low in adult beat-deaf participants (Sowiński & Dalla Bella, 2013), in children suffering from developmental stuttering (Falk et al., 2015) and in preschoolers who score poorly in early language tests (e.g., phonological awareness and naming tasks; Woodruff Carr, Tierney, White-Schwoch, & Kraus, 2016; Woodruff Carr et al., 2014). Synchronization accuracy (i.e., whether participants anticipate or not the beat) is also impaired in children with developmental stuttering, who tend to anticipate the beat more than controls do. This finding is indicative of a greater predictive motor timing error in this condition (Falk et al., 2015). A recent study documented a similar bias toward anticipating the beat in poor-pitch singers (Dalla Bella, Berkowska, & Sowiński, 2015). This finding is in keeping with theories pointing to differences in auditory-motor translation to account for individual differences in singing proficiency (e.g., in imitation tasks; Hutchins & Peretz, 2012; Pfordresher & Brown, 2007; Pfordresher & Mantell, 2014). In sum, there is preliminary evidence that the results obtained with BAASTA, in particular in paced tapping, may act as indicators of particular timing/rhythm deficits,

which may span across different disorders. This possibility is currently being investigated in our laboratories in different populations.

In summary, BAASTA shows promise in providing an in-depth characterization of an individual's timing/rhythmic skills. However, this comes at a cost, namely the duration of the overall assessment, which is longer than other batteries (e.g., the H-BAT, Fujii & Schlaug, 2013). This may obviously represent an issue, in particular for using the battery in clinical populations. However, the problem can be circumvented. Given that BAASTA is likely to probe the functioning of different components of the timing system(s) in different tasks (e.g., beat-based vs. interval timing, perception vs. production, etc.), a subset of tasks, or even a single task, can be used to address a specific question or to test a given hypothesis. Another possibility is that because some of the tasks of BAASTA are correlated, the number of tasks testing independent timing components may be reduced in the future. To this aim, the testing of a larger sample than the aforementioned group will be needed to extract the common dimensions across tasks (e.g., using PCA or cluster analysis), and to develop more efficient testing strategies.

In conclusion, perceptual and sensorimotor timing tasks of BAASTA are sensitive to individual differences and can uncover individuals with timing/rhythm deficits. We expect that the use of these tasks and analysis methods will lead to the systematic assessment of these skills in other populations, such as patients with brain damage (e.g., Stewart, von Kriegstein, Dalla Bella, Warren, & Griffiths, 2009), neurodegenerative diseases (e.g., Parkinson's disease; Allman & Meck, 2011; Benoit et al., 2014), or developmental disorders (e.g., attention deficit hyperactivity disorder or dyslexia; Noreika et al., 2014). A systematic assessment of perceptual and sensorimotor timing skills in these patient populations may lead to identify those profiles that are most likely to benefit from rehabilitation strategies based on timing and sensorimotor synchronization (e.g., gait rehabilitation for patients with Parkinson's disease via auditory cueing; Dalla Bella, Benoit, Farrugia, Schwartze, & Kotz, 2015; Lim et al., 2005; Spaulding et al., 2013).

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