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

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ABSTRACT

In this paper we describe the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA), a new tool developed for assessing systematically rhythm perception and auditory-motor coupling. BAASTA includes perceptual tasks and sensorimotor synchronization (SMS) tasks. In the perceptual tasks, auditory thresholds in a duration discrimination task and anisochrony detection tasks (i.e., with an isochronous sequence and with music) are measured via the maximum likelihood procedure (MLP). In addition, a customized version of the Beat Alignment Task (BAT) is performed to assess participants' ability to perform beat-extraction with musical stimuli. Tapping tasks are used to assess participants' SMS abilities, including hand tapping along with isochronous sequences and music, and tapping to sequences presenting a tempo change. The battery is validated in groups of young expert musicians, young non-musicians, and aged non-musicians. In addition, the results from 3 cases of patients with Parkinson's disease are presented. BAASTA is sensitive to differences linked to musical training; moreover the battery can serve to characterize differences among individuals (e.g., patients with neurodegenerative disorders) in terms of sensorimotor and rhythm perception abilities.

I. INTRODUCTION

During the last decades a large body of research has been devoted to timing mechanisms that are involved in rhythm perception and production, and in sensorimotor synchronization. Many theories and models have surfaced to account for these phenomena; a small sample includes the Scalar Expectancy Theory (Gibbon, 1977), the Attentional Gate Model (Zakay, 2004), neural-integration based models (e.g. Simon et al., 2011), computational cognitive-based models (e.g. Taatgen, Rijn, & Anderson, 2007), and the Dynamic Attending Theory (Jones, 1976; Large & Jones, 1999). Empirical studies based on these and other theories and models often employ single tasks, spanning a multitude of paradigms and parameters. For example, in the timing-perception literature one finds classical interval timing tasks such as duration discrimination or temporal bisection (with scales ranging orders of milliseconds to several seconds) (e.g. Buhusi & Meck, 2005), anisochrony detection (Hyde & Peretz 2004), and other tasks related to metrical memory or beat perception (Grahn & Brett, 2009). Timing-production literature similarly includes a variety of tasks spanning from interval production, synchronization-continuation, and sensorimotor synchronization to diverse stimuli and under diverse task instructions using the finger tapping paradigm (Repp, 2005; 2006; 2010). Considering the varied approaches to empirical timing research, the 'big picture' with respect to timing abilities across populations becomes ever more elusive – results from different studies are difficult to compare across paradigms and various group samples. Moreover, from a clinical perspective, it is known that disorders such as Parkinson's disease or schizophrenia are associated with deficits in time perception and reproduction tasks (for a review, see Allman & Meck, 2012). However, without unified measures the potential to explore timing deficits with a comprehensive diagnostic tool remains unexplored. To address this issue, extensive test batteries have been proposed in the past. Kidd and coworkers (Kidd et al., 2007) performed a wide screening of auditory abilities with 20 tests administered to 300 participants. With a factor analysis and structural equations modeling, they successfully uncovered basic auditory abilities pertaining to spectral and temporal processing, pitch perception, speech, and familiar sound recognition. However, the study selectively addressed auditory perception excluding production tasks. Others reported results on multiple tasks focusing on both temporal perceptual and production aspects. Iversen and Patel proposed the BAT (Iversen & Patel, 2008), as a set of tasks for assessing SMS and beat perception abilities in the general population, which was able to show a positive correlation between variability of tapping and performance in perceptual judgment of beat perception. In the interval timing field, Merchant and coworkers (Merchant et al., 2008a), using interval categorization and discrimination tasks, and single and multiple interval tapping tasks could show that tasks group dependent on their reliance on explicit as opposed to implicit interval timing. In the same vein, these authors (Merchant et al., 2008b) also uncovered two subgroups of patients with Parkinson's disease exhibiting high and low variability when performing various interval timing tasks. Finally, to our knowledge, no study reported results from a test battery of timing abilities including both interval timing tasks and beat-based timing tasks, the latter having been relevant to study rhythm perception deficits in patient populations (e.g. Hyde & Peretz 2004, Grahn & Brett 2009). In sum, there is evidence that a variety of tasks is likely to reveal different facets of human timing abilities, capable to not only differentiate individual capacities in patients but also in healthy populations. In order to obtain an exhaustive picture of these abilities, there is a strong need for a unified set of tasks to test a broad range of timing and SMS abilities, while being sensitive enough to study individual differences and impairments in specific populations.

To fill this gap, we propose the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA), a new tool for assessing perceptual and sensorimotor abilities in the general population. The broad set of tasks covers a range of abilities in interval timing, beat-based timing, and beat perception, as well as spontaneous motor behavior (tapping) and SMS. We rely on previous work of psychophysical testing using adaptive procedures (Green et al., 1993), as well as on a customized version of the BAT (Iversen & Patel, 2008), classical SMS tasks, and an adaptive tapping paradigm (Repp & Keller, 2004). To validate BAASTA, we present data obtained from healthy participants (musicians and non-musicians) and from three Parkinson patients.

II. METHODS

A. Participants

1) *Group 1: Young adult musicians.* Participants in Group 1 (*n* = 15, 8 females), aged between 20 and 23 years (*M* = 21.1 years, *SD* = 0.88) were all musicians recruited from the University of Leipzig or the University of Music and Theatre Felix Mendelssohn Bartholdy in Leipzig, with an average of 13.5 years (*range* = 9-18 years) of musical training. All participants received formal musical training during childhood or adolescence. They gave informed consent for participating in the experiment and were remunerated.

2) *Group 2: Young adult non-musicians*. Group 2 (*n* = 15, 7 females) consisted of university students and professionals in the Leipzig area, who received little to no formal musical training beyond obligatory school courses (i.e., on average less than one year of training). One participant had 9 years of keyboard training, but had not practiced during the last 9 years before participating in the current experiment. They were aged between 22 and 31 years (*M* = 26.3 years, *SD* = 2.94). Participants gave informed consent for participating in the experiment and were remunerated.

3) *Group 3: Aged adult non-musicians***.** Healthy, aged non-musicians were recruited via the database of the Max-Planck Institute for Human Cognitive and Brain Sciences (*n* = 18, 9 females). Ages ranged from 50 to 77 years (*M* = 66.6 years, *SD* = 7.33). They had 14.4 years (*SD* = 3.2 years) of general education. Participants were not active musicians, and had little to no exposure to musical instruments in the past. They gave informed consent for participating in the experiment and were remunerated.

4) *Patients with Parkinson's disease (PD)*. Three patients with idiopathic Parkinson's disease were recruited via the database of the Max-Planck Institute for Human Cognitive and Brain Sciences: RW is a 65-year-old female, with 13 years of education; UK is a 57-year-old male, with 12 years of education; ML is a 58-year-old male, with 15 years of education. The Hoehn & Yahr (H&Y) rating scale was used to assess the progression of the disease (Hoehn & Yahr, 1967); each patient rated 2 on the H&Y scale, indicating that they had apparent motor symptoms and no impairment of balance. All patients received dopamine replacement therapy and were tested while on medication. None of the participants were active musicians and had little to no exposure to instruments in the past. They gave informed consent for participating in the experiment and were remunerated.

B. Tasks

As shown in Table 1, BAASTA includes perceptual and sensorimotor tasks. A thorough description of each task is provided below.

1) *Perceptual tasks.* A set of perceptual tasks was devised to assess participants' ability to discriminate durations and to detect temporal deviations in rhythmical sequences. An adaptive approach was adopted to estimate perceptual thresholds using the MLP (Grassi et al., 2009). The advantage of the MLP algorithm is that it allows quick and reliable estimation of psychophysical thresholds. All perceptual tasks except the BAT were implemented with the MLP algorithm.

Duration discrimination: In each trial, two 1 kHz pure tones (gated with 10-ms cosine ramps at the beginning and at the end of the tones) were presented. The duration of the first tone (standard duration) was 600 ms, and the duration of the second tone (comparison duration) was either 600 ms (like the standard tone) or longer (up to 1000 ms). The tones were separated by a 600-ms silent gap. Participants judged whether the second tone lasted longer than the first or had the same duration. The length of the second tone was set in real time using the MLP algorithm depending on the participants' responses. At the beginning of the experiment, participants were presented with examples of two standard pairs of tones and two comparison pairs (1000-ms comparison tones). In addition, four pairs of tones were used in a training phase, in which feedback about correctness was provided to the participants. The experiment included three blocks of 16 trials each. No feedback about correctness was given during the experiment.

Anisochrony detection with tones: Trials consisted of sequences of five 1047 Hz (C6) tones (duration = 150 ms). Participants were presented with isochronous sequences, which had a constant inter-stimulus-interval (ISI), and non-isochronous sequences, in which the fourth tone in the sequence was displaced to occur earlier (a similar procedure was used in Hyde and Peretz, 2004). Participants judged whether the sequence was regular or irregular. Note that this displacement resulted in a local shift were the two ISIs surrounding the displaced tone are respectively shortened and lengthened to the same degree; the amount of displacement was determined using the MLP algorithm. Three types of sequences with different ISI in the isochronous sequences were used: 600 ms, 450 ms, and 750 ms. A training phase including examples and practice was performed before each condition as previously described in the duration discrimination task. For each of the three experiments, there were three blocks of 16 trials.

Anisochrony detection with musical sequences: In this task, anisochrony detection was assessed with musical stimuli (instead of simple isochronous sequences). Each trial consisted of a computer-generated musical excerpt from Bach's "Badinerie," orchestral suite for flute BWV 1067, played with a piano timbre. The same excerpt of 2 bars (i.e. 8 quarter notes overall) was used in all stimuli and played at a tempo of 100 beats per minute (Inter Beat Interval, IBI = 600 ms). Participants were presented either with regular or irregular versions of the musical stimuli. The regular version was not manipulated (i.e., the beats were isochronous) and the irregular version included a local shift of the onset of the notes corresponding to the fifth quarter note of the excerpt. Participants judged whether the rhythm in the music seemed regular or irregular. The local shift anticipated the onset of the notes up to 30% (180 ms) of the IBI (i.e., 600 ms). The subsequent IBI was lengthened by the same amount. As in the previous task, the amount of local shift was calculated with the MLP algorithm. A training phase including examples and practice was performed. In the experiment there were 3 blocks of 16 trials each.

Beat Alignment Test: The last perceptual task is a version of the BAT (Iversen and Patel, 2008). In each trial a musical excerpt was presented. Four musical excerpts each including 20 quarter notes were selected: two from Bach's "Badinerie" and two from Rossini's "William Tell Overture." After the 7th quarter note through the 20th quarter note, an isochronous sequence with a triangle timbre was superimposed onto the music. The isochronous sequence either corresponded to the quarter note (beat-aligned stimuli) or was manipulated (beat-unaligned stimuli). There were four manipulations: two phase changes of plus or minus 33 % of the quarter note duration and two period change of plus or minus 10% of the quarter note duration. The stimuli were presented at three different tempi (slow, medium and fast, corresponding to 450-, 600- and 750-ms IBI). At each tempo, two beat-aligned stimuli were presented. The total number of presented stimuli was 72. Participants listened to all stimuli in pseudo-randomized order and were asked to judge after each stimulus if the isochronous sequence was aligned with the beat or not.

Setup for perceptual tasks: Two different setups were used in the perceptual tasks. All tasks were implemented in MATLAB using the MLP toolbox or customized scripts. In all tests with aged healthy participants and patients with PD, the participants, sitting in front of the experimenter, provided their answers verbally to the experimenter. Most of the participants in Group 1 and Group 2 performed the tests alone via a computer (three of them were assisted by the experimenter as described for the aged group). All participants received auditory stimuli via Sennheiser HD201 headphones.

2) *Sensorimotor tasks.* Sensorimotor tasks served to assess participants' production abilities in SMS. These tests were selected among the tasks adopted in classical SMS experiments (for reviews, see Repp 2005; 2006).

Unpaced tapping: In the first of three unpaced tapping tasks, participants were asked to tap regularly at a comfortable rate for 60 seconds in order to measure spontaneous motor tempo (similar to Drake, Jones, & Baruch, 2000; Fraisse, 1956). Tapping was measured for each of the two hands separately. In a second task, participants were asked to tap as slowly as possible for 60 seconds, while keeping the tapping as regular as possible. Finally, in a third task participants were instructed to tap at their maximum possible speed for 30 seconds. The first unpaced tapping task (spontaneous motor tempo) was carried out twice, that is, at the beginning and the end of the sensorimotor tasks.

Paced tapping with metronome and musical stimuli: In this task participants synchronized their taps to various auditory pacing stimuli. Three isochronous sequences and two musical stimuli were presented. The isochronous sequences consisted of 60 piano tones (E6) presented at three different interonset intervals (IOI): 600 ms, 450 ms and 750 ms. The musical stimuli were excerpts including 64 quarter notes taken from the same musical pieces used in the BAT test (IBI = 600 ms). The participants tapped along with the tones of the isochronous sequences and with the beats of musical excerpts. All stimuli were repeated twice. Before each new stimulus, a practice session was performed using a shorter version of the stimulus.

Table 1. BAASTA Test Battery.

TASK	DURATION	OUTCOME MEASURES
Perceptual Tasks	Between 60-80 min	
Duration discrimination	6 minutes	Duration discrimination threshold
Anisochrony detection with tones	20 minutes	Anisochrony threshold
Anisochrony detection with musical sequences	8 minutes	Anisochrony threshold in musical context
Beat Alignment Test	15 minutes	Performance in detection of aligned beat in musical context.
Sensorimotor Tasks	Between 70-90 min	
Unpaced tapping	5 minutes	Spontaneous tapping speed and variability
Paced tapping with metronome and musical stimuli	8 minutes	Synchronized tapping accuracy and variability
Synchronization-continuation	6 minutes.	Accuracy of tapping in the continuation phase
Adaptive tapping	25 minutes	Measures of accuracy in the detection of tempo changes and adaptation of tapping performance
TOTAL	Between 2 and 3 hours	

Synchronization-continuation: In the synchronization-continuation task (e.g., Wing & Kristofferson, 1973) participants synchronized with 10 piano tones presented isochronously. After this synchronization phase, they were asked to continue tapping (continuation phase) while keeping the same interval duration between the taps. A lower piano tone indicated the end of the trial. Three IOIs were used in the synchronization phase, respectively 600 ms, 450 ms, and 750 ms. The length of the continuation phase was 30 IOIs. All trials were repeated twice. A practice session was performed before each IOI, including a shorter continuation phase of 10 taps.

Adaptive tapping: In the adaptive tapping task (Repp & Keller, 2004; Schwartze et al., 2011), the synchronization-continuation paradigm was modified as follows: In 66% of the trials the last 4 tones of the synchronization phase included a tempo change; the first 6 tones of the sequence had an IOI of 600 ms, and the 4 last ones had a different IOI introducing either a faster tempo (570 or 525 ms), or a slower tempo (630 or 670 ms). Participants were asked to synchronize with the stimulus while following the tempo change, and had to maintain the speed of the new tempo during the continuation phase. At the end of each trial, the participants indicated if they had perceived an acceleration, a deceleration, or no tempo change. The experiment included 10 blocks; each block contained two non-manipulated sequences with no tempo change (all tones with an IOI of 600 ms) and four sequences with final IOIs of 570, 525, 630 and 670 ms.

Setup for sensorimotor tasks: In all of the sensorimotor tasks, tapping data were collected with a Roland SPD-6 MIDI tapping pad. The participants were asked to use their right hand for tapping on the pad (except during left hand tapping in the unpaced tasks). Before the beginning of the tasks, participants were familiarized with the setup and were encouraged to find the most comfortable way of using the tapping pad. Auditory stimuli were presented via Sennheiser HD201 headphones. No auditory feedback of the taps was provided.

C. Analyses

1) *Perceptual tasks.* Data from the perceptual tasks were analyzed using MATLAB Software. For each block in the tasks involving the MLP algorithm an estimate of the perceptual threshold was obtained and expressed in percent of the IOIs, to allow comparison across tasks. An estimate of the False Alarm (FA) rate was also computed for each block. Data from blocks with a FA rate higher than 30% (Green, 1993) were systematically rejected to avoid artificially low thresholds. Among the remaining blocks, the minimum threshold estimate was selected to obtain the final threshold value. In the BAT, we computed the number of errors in each of the 4 categories of stimuli (period plus or minus 10 %, phase plus or minus 33%) and at each tempo (slow, medium and fast).

2) *Sensorimotor tasks.* Data obtained in sensorimotor tasks were analyzed using tap onsets provided by MAX software. A constant midi delay of 4 ms between the tap and the MIDI “note on” signal was measured and subtracted from the measured note-onset time in the analyses. The first 7 taps (10 taps in the paced tapping tasks) were not analyzed. Raw data were preprocessed in order to eliminate artifacts and outliers. Rebound artifacts were eliminated using a 100-ms threshold. Moreover, inter-tap intervals (ITI) deviating by more than 3 standard deviations from the mean ITI (i.e., outliers) were removed.

In the unpaced tapping tasks, the mean ITI and the standard error of the ITI for each trial was calculated. Additionally, the Coefficient of Variation (*CV*) was computed as the ratio of the *SD* of the ITIs over the mean ITI. The same measures were used for the continuation phase in the synchronization-continuation task. These measures (*mean*, *SD* and *CV* of the ITI) were averaged for the two trials obtained at each IOI.

In paced tapping tasks, mean ITI and CV of the ITI were calculated as in the unpaced tapping. In addition, synchronization accuracy and variability with regard to the pacing stimuli was computed. Accuracy was measured by absolute mean asynchrony (i.e., the average absolute asynchrony of each tap with regard to the respective pacing stimulus) - large absolute asynchrony indicated low accuracy. Standard error of the mean (*SE*) of absolute asynchrony was calculated to obtain an estimate of participants’ variability. Only trials including more than 10 taps in a row with an absolute asynchrony inferior to 50% of the IBI were included, and measures from remaining trials of the same IBI were averaged. Note that participants can synchronize at different metrical levels of the musical stimulus (e.g., with the quarter note or with the half note). Thus, before computing measures of synchronization accuracy and variability, the metrical level targeted by the participant was determined. The targeted metrical level was the one associated with the highest number of synchronized taps (i.e. with absolute asynchrony inferior to 50% of the IBI) at one of three metrical references, corresponding to eighth notes, quarter notes, or half notes (i.e., with 300, 600, and 1200-ms IBI, respectively).

Finally, in the adaptive tapping task, only taps from the continuation phase were analyzed. All trials including outliers or missing taps were discarded and will be subsequently referred to as performance errors. On the remaining trials, the mean ITI was calculated and compared to the final IOI of the sequence, in order to analyze participants ’ adaptation to tempo changes. Additionally, participants’ answers were analyzed with respect to the magnitude of the tempo changes in order to uncover above-threshold and sub-threshold reaction to the stimuli.

3) *Impairment criteria for patient data.* In order to detect and to quantify impaired performance in patients with PD, the data obtained by Group 3 were used as a reference. PD patients departing from the average obtained by Group 3 by 2 or 3 *SD*, a common measure in neuropsychology (e.g., Hebben & Milberg, 2002), were considered as mildly impaired and severely impaired, respectively.

III. RESULTS

A. Group results

1) MLP tasks. The results of the duration discrimination and of the anisochrony detection tasks are reported in Table 2. The mean number of rejected blocks per participant, due to high false alarm rate, was less than 1, for all tasks and all groups. The results show that musicians (Group 1) outperformed young non-musicians (Group 2) on all tasks ($ps < .01$), as well as older non-musicians (Group 3) in all tasks ($ps < .05$) except for duration discrimination. Group 2 and Group 3 did not significantly differ; nevertheless, aged non-musicians performed slightly better than young non-musicians on the duration discrimination task ($t(29) = -2.5$, $p < .01$), anisochrony detection with 450-ms IOI ($t(30) = -2.0$, $p < .05$) and with 750-ms IOI ($t(30) = -1.9$, $p < .05$).

2) *BAT results.* The percentages of correct responses yielded by the BAT task for all types of stimuli are reported in Table 3. Musicians (Group 1) performed at ceiling in this task with 10 out of 15 participants achieving 100% correct responses. All participants in the three groups achieved 100% correct responses for the stimuli with the fastest tempo. Musicians' overall performance was superior to that observed in non-musicians of Groups 2 ($t(28)=3.3$, $p < .001$) and 3 ($t(30)=2.7$, $p < .01$), as well as when considering all other measures reported ($ps < 0.01$). Group 2 and Group 3 did not significantly differ either in overall performance or in the other measures.

Table 2. Thresholds obtained in the duration discrimination task and in the anisochrony detection tasks for the three groups. Values are indicated in % of interonset interval (IOI).

Perceptual Tasks		Group 1 (musicians) *M* (*SE*)	Group 2 (young non-musicians) *M (SE)*	Group 3 (aged non-musicians) *M* (*SE*)
Duration Discrimination		22.1 (2.1)	30.4 (2.4)	20.3 (2.3)
Anisochrony detection	450 ms	7.3 (0.5)	12.4 (1.1)	10.5 (0.9)
	600 ms	8.1 (0.7)	13.7 (1.4)	10.3 (0.9)
	750 ms	6.5 (0.5)	13.0 (1.3)	9.9 (1.0)
	Music	3.9 (0.5)	8.2 (0.7)	8.7 (1.4)

Table 3. Percent of correct responses obtained in the BAT task for the three groups.

BAT	Group 1 (musicians) *M (SE)*	Group 2 (young non-musicians) *M (SE)*	Group 3 (aged non-musicians) *M (SE)*
Overall performance (%)	98.1 (0.7)	87.4 (3.2)	89.2 (3.0)
Slow tempi (%)	98.9 (0.6)	88.9 (3.5)	94.1 (1.9)
Medium tempi (%)	97.8 (0.9)	86.4 (3.2)	89.9 (3.4)
Fast tempi (%)	100 (0)	100 (0)	100 (0)
Phase change (%)	98.6 (0.8)	85.0 (4.2)	89.7 (3.3)
Period change (%)	96.9 (1.5)	84.4 (3.8)	86.8 (4.1)

3) *Tapping tasks results.* Average ITIs and CV of the ITIs obtained in the tapping tasks by aged participants (Group 3) are reported in Table 4. The spontaneous motor tempo measured in the unpaced tapping task is in the vicinity of 600 ms. Variability of tapping was similar with both hands and across tasks as indicated by the CV of the ITIs, with the exception of one participant exhibiting higher variability in the unpaced slow condition (> 2 *SD* from the group mean). Variability in spontaneous tapping did not vary when tested after the other tapping tasks as shown by the CV of the ITIs of the Spontaneous "post" tapping conditions. Nevertheless, participants' spontaneous tapping tempo was faster when measured before the other tapping tasks, as compared to the measure at the end of the sensorimotor battery ($t(70) = 2.21$, $p < .05$). Furthermore, ITI values in the paced tapping tasks show that on average participants successfully reproduced the interval indicated by the metronome. In the synchronization-continuation task, participants could maintain an ITI of 450 ms on average but tapped slightly too fast with a metronome of 600 ms ($t(17) = -3.1$, $p < .01$) and 750 ms ($t(17) = -4.5$, $p < .001$).

In the paced tapping task, participants on average were able to synchronize with the isochronous stimuli, with on average 96.8% of taps occurring in the time window surrounding the pacing stimuli. With the musical stimuli, approximately 70% of all trials indicated synchronization with the quarter note on the strong beat, with the exception of one trial for one participant tapping in antiphase. In the remaining 30% of the trials, the taps occurred in correspondence of the eighth note. With music, in 92% of the cases participants tapped in the time window surrounding the pacing stimuli at the selected metrical level.

Accuracy and variability observed in the paced tapping tasks are reported in Table 5. Tapping variability was comparable across all conditions. When synchronizing with a metronome, the participants exhibited a mean absolute asynchrony between 4 and 6 % of the IOI. The participants tended to be less accurate when tapping with music (with 7 and 8 % of IOI in average absolute asynchrony) than with the metronome, though this difference was not statistically significant.

Finally, the results of the adaptive tapping task obtained by Group 3 are presented in Figure 1. The left panel represents participant's ability to match their tapping rate to the tempo change, by showing the mean ITI in the continuation phase (dashed line), versus the IOI of the sequence (x axis). Perfectly matched tapping would lie on the solid line. The right panel shows participants' perceptual ability in detecting the tempo changes; "no change" responses are expected for the 600 ms IOI, while "acceleration" responses are expected for the IOI smaller than 600 ms, and "deceleration" responses type for IOI values larger than 600 ms.

As can be seen in Figure 1 (left panel), participants in most of the cases were able to perform the task correctly by adapting their tapping behavior to the tempo changes. Only 6.7% of trials were discarded because of performance errors. The participants were successful in following all tempo changes, with the exception of the fastest tempo (525 ms), in which most tended to tap faster than the pacing stimulus (mean ITI = 505.4 ms, $t(19) = -2.9$, $p < .05$). The right panel in Figure 1 shows participants' performance in detecting the tempo changes. Participants accurately detected the changes with the largest magnitude (525 ms and 675 ms) with a percentage of correct responses larger than 98 %. The more subtle tempo changes (570 and 630 ms) were more difficult to detect, as indicated by correct responses rates under 40 %.

B. PD patients results

In Table 6, a summary of the results from three patients with PD are reported. The degree of impairment on the various tasks is indicated using a color coding scheme. All patients showed mild to severe impairments in some of the tasks with the exception of duration discrimination and anisochrony detection with tones. Patients RW and UK showed similar impairments in perceptual tasks, with higher anisochrony detection thresholds with musical stimuli as compared to Group 3. In addition, these two patients were less accurate in performing the BAT. RW obtained a percentage of good responses lower than 2 SD from the average of Group 3 on stimuli with period changes, while UK was impaired in detecting changes at the slowest tempi. Furthermore, these two patients could not detect subtle tempo variations in the adaptive tapping task.

In the tapping tasks, RW and ML were more variable than participants from Group 3 in most conditions of unpaced tapping, as measured by the CV of the ITI. Patient ML showed a severe impairment when tapping at his spontaneous rate with his left hand. Two patients, RW and ML, were more variable than controls when synchronizing with metronomes at the medium and fast tempi. Patient RW exhibited a severe impairment when tapping with musical stimuli, while patients ML and UK showed a mild impairment in the same task.

Table 4. Mean inter-tap interval (ITI) and Coefficient of variation (CV) of the ITI obtained in tapping tasks for aged non-musicians (Group 3). ITIs are expressed in ms. CV is in arbitrary units.

Task		Mean ITI (*SE*)	CV ITI (*SE*)
Unpaced Tapping	Spontaneous right hand	573.6 (37.4)	0.05 (0.001)
	Spontaneous left hand	566.4 (43.7)	0.05 (0.001)
	Fastest	266.8 (33.7)	0.05 (0.006)
	Slowest	1302.9 (142.9)	0.07 (0.01)
	Spontaneous right hand (Post)	514.4 (22.1)	0.04 (0.002)
	Spontaneous left hand (Post)	491.9 (21.7)	0.05 (0.002)
Paced tapping	Metronome 450 ms	451.9 (1.9)	0.04 (0.003)
	Metronome 600 ms	600.9 (1.1)	0.04 (0.002)
	Metronome 750 ms	749.7 (0.2)	0.04 (0.002)
Synchronization - Continuation	450 ms	451.2 (3.9)	0.04 (0.001)
	600 ms	582.4 (5.7)	0.04 (0.001)
	750 ms	727.9 (5.3)	0.04 (0.001)

Table 5. Mean accuracy (i.e., mean absolute asynchrony) and variability (i.e., SE of asynchronies) obtained in paced tapping tasks for aged non-musicians (Group 3). Accuracy and variability are expressed in percent of IOI.

Condition		Accuracy *M (SE)*	Variability *M (SE)*
Metronome	450 ms	5.5 (0.70)	0.8 (0.18)
	600 ms	6.6 (1.00)	0.6 (0.08)
	750 ms	4.3 (0.45)	0.6 (0.03)
Music	Extract 1	8.1 (0.96)	0.7 (0.13)
	Extract 2	7.2 (0.76)	0.8 (0.08)

Figure 1. Results obtained in the Adaptive tapping task from Group 3. Left panel: Mean ITI (in ms) of the continuation phase as a function of the final IOI of the sequence; 600 ms corresponds to the "no tempo change" condition. Right panel: Percentage of type of responses (" no change," " acceleration" or " deceleration") as a function of the final IOI of the sequence.

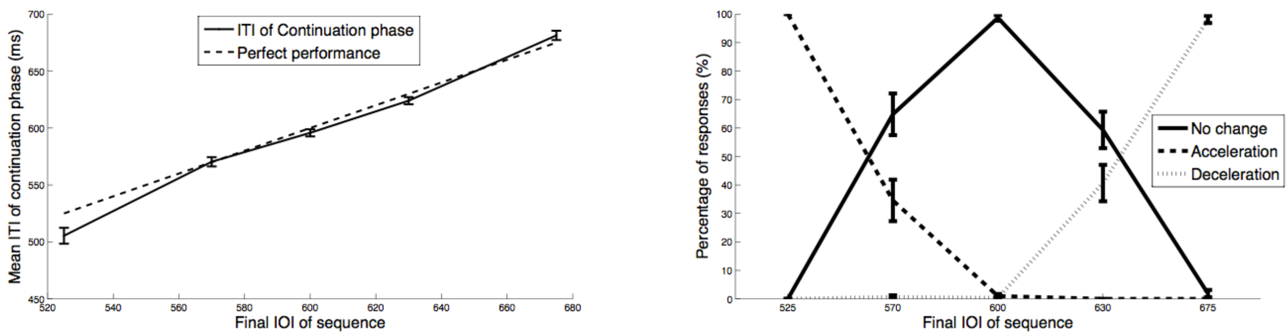

Table 6. Summary of the impairments shown by three patients with Parkinson's disease (PD) compared to aged non-musicians (Group 3). The light grey shade indicates a mild impairment. The dark grey shade refers to severe impairment.

	RW	UK	ML
Perceptual Tasks			
Duration discrimination			
Anisochrony detection with tones			
Anisochrony detection with musical sequences			
Beat Alignment Test			
Sensorimotor Tasks			
Unpaced tapping			
Paced tapping with metronome			
Paced tapping with musical stimuli			
Synchronization-continuation			
Adaptive tapping			

IV. DISCUSSION

The BAASTA, a new battery for testing systematically auditory timing and sensorimotor abilities, was administered to three groups of healthy participants (young musicians, young non-musicians, and aged non-musicians) and to three patients with PD.

A. Healthy groups

The results obtained with the BAASTA from the three groups are generally consistent with findings reported in previous studies. The thresholds yielded by the MLP procedure are within the range of anisochrony detection with tones (Hyde & Peretz, 2004), and musical sequences (Ehrlé & Samson, 2005). Nevertheless, the thresholds in the duration discrimination task are higher than previously reported for comparable durations (e.g., Grondin et al. 2001). Such discrepancy may stem from methodological differences. The duration discrimination task implemented in BAASTA may be more challenging as no feedback on participant's performance is provided (as compared to Grondin et al.'s study). In addition, inaccurate performances with a threshold above the 20% were retained in order to compute the average threshold, which may have boosted the average threshold value. This was not the case in Grondin et al.'s study. Finally, this overestimation of the threshold may be partly linked to the use of the MLP algorithm (e.g., when using short blocks; see Grassi et al., 2009, for a discussion).

In the BAT, musicians outperformed non-musicians overall, in spite of the fact that all groups were close to ceiling. However, in the original BAT (Iversen et al. 2008), reported correct responses percentage were lower, when taking all stimuli (*median* = 90 %), stimuli with tempo change (*median* = 80 %) and with phase change (*median* = 60 %), than the scores we report in table 3. Thus, our version of the BAT task is easier than the original one (Iversen et al. 2008), albeit still sensitive to musical expertise. As a consequence, a poor performance in this version of the task is likely to be caused by a deficit in beat perception rather than a lack of musical training.

Only aged non-musicians performed the sensorimotor tasks of the BAASTA. In the unpaced tapping tasks, the spontaneous motor tempo measured is comparable to the values obtained for this age group (McAuley et al., 2006). When synchronizing with a metronome, the participants exhibited accuracy comparable to previous studies (see Repp, 2005). Participants were less accurate when tapping with music than with an isochronous sequence, as shown by larger mean absolute asynchrony in the latter case. This phenomenon has been already described in the literature (Repp, 2005). Finally, in the adaptive tapping task, subtle tempo changes were more difficult to detect in our study than previously observed in healthy non-musicians (Schwartze et al. 2011). Nevertheless, this could stem from age differences, as in the study by Schwartze and coworkers participants were much younger (i.e., around 20 years) than in our study. Whether this discrepancy is merely resulting from age-related differences or from other factors should be examined in further studies.

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B. Patients with PD

It is noteworthy that BAASTA was sensitive enough to detect mild to severe impairments in three participants with PD, a neurodegenerative disorder. Altogether, patients were impaired in perceptual tasks involving musical stimuli as reported in previous studies targeting beat-based timing (e.g., Grahn et al., 2009). Yet, the patients were not impaired in tasks requiring interval-based timing (i.e., temporal discrimination in isochronous sequences or duration discrimination). The absence of deficits in these two tasks is likely an effect of dopaminergic replacement therapy that has been reported to partially restore these functions (Allman et al. 2012; Malapani et al. 2003). The inability of patients to synchronize properly could be due to their difficulty in performing beat-extraction while listening to complex musical stimuli (i.e., characterized by multiple metrical levels). This possibility is compatible with the idea that the basal ganglia play a relevant role in beat-based perception (Grahn et al. 2009). Finally, all patients had a more pronounced tendency to accelerate in the continuation phase of the synchronization-continuation and in the adaptive tapping tasks. Interestingly, one patient exhibited intact perceptual abilities but impaired sensorimotor skills. This type of dissociation between perception and action has previously been reported in vocal performance (Dalla Bella, Giguere, & Peretz, 2007; Dalla Bella et al., 2011; Pfordresher & Brown, 2007). Further studies are in order to examine whether a dissociation of perception and production extends to the timing domain.

V. CONCLUSION

The BAASTA is a new battery for testing systematically auditory timing and sensorimotor abilities. Our findings with musicians, non-musicians and aged non-musicians are generally consistent with the results obtained in previous studies using similar tasks; moreover we provided evidence that when compared to controls, BAASTA is sensitive to differences in musical training and neural impairment. BAASTA appears as a useful and sensitive tool in clinical research for assessing rhythm perception and performance abilities in patient populations with motor disorders. In particular, the battery would be particularly useful in the domain of motor rehabilitation, in order to assess the effect of the rehabilitation strategy on timing and sensorimotor processes. An example is provided by motor rehabilitation of gait via auditory cueing in PD. Cueing therapies, lauded for their effectiveness in initiation and continuation of movement via temporally predictable sensorimotor, visual, or auditory external stimuli (Lim, 2005; Nieuwboer, 2007), could perhaps be improved if a set of timing measures were available for individual patients (i.e. for choosing the correct parameters for motor rehabilitation tailored to the particular patients' deficits). BAASTA could potentially also be used as an objective 'before and after' measure to assess effectiveness of timing therapies. Finally, BAASTA may be particularly sensitive to detect early signs of sensorimotor impairment, an intriguing possibility, which should undergo further enquiry.

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