Evaluation and training of rhythmic skills via new technologies

Valentin Bégel

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THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE L'UNIVERSITÉ DE MONTPELLIER

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Evaluation and training of rhythmic skills via new technologies

Présentée par Valentin BÉGEL

Le 3 octobre 2017

Sous la direction de Simone DALLA BELLA

Devant le jury composé de

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UNIVERSITÉ DE MONTPELLIER

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Preface

The first time laypeople go to a classical music concert, they are tempted to tap their feet to the beat of the music as soon as the conductor initiates a piece with a highly salient beat. In spite of the rules of 'bon ton' so well known to classical concertgoers, for more than a century science has shown that this bodily reaction to musical groove is totally natural in humans. While listening to rhythmic music, most of us feel a compelling urge to move to its groove, a tendency particularly visible with certain musical genres such as popular music and dance music. This widespread tendency may be the result of thousands of years of evolution in which rhythmical behaviors have been beneficial to mankind.

Even if the capacity to perceive and synchronize to a beat is widespread in humans, it is important to note that individuals differ in their capacities to process rhythm. For instance, trained musicians are known to have great rhythmic abilities. In contrast, some individuals, referred to as 'beat deaf' or poor synchronizers, encounter particular difficulties in synchronizing and/or perceiving the beat.

Rhythmic skills are sustained by a complex neuronal network, including motor and sensorimotor regions such as the basal ganglia, the motor cortices, and the cerebellum, on top of auditory regions such as the superior temporal gyrus. In pathologies affecting these regions, rhythm skills can be disrupted. This is the case, for instance, in Parkinson's disease and in dyslexia. There is growing evidence that this disruption of rhythmic skills is associated to the deficits in motor and/or cognitive functions observed in these pathologies. Improving knowledge of rhythmic perception and production skills may serve to better understand the link between rhythmic processing and the associated cognitive and motor functions.

In this dissertation, I want to address two main questions. First, is it possible to extend our knowledge of inter-individual differences in rhythm processing in order to better understand the mechanisms underlying rhythmic skills and their link with other functions, such as cognition and movement, with a systematic tool? Second, can rhythmic skills be trained in order to improve rhythmic skills by means of a training protocol? These two questions are addressed in two separate experimental sections.

Accordingly, I pursued two goals in this dissertation. The first goal is to **study rhythm skills thoroughly with a systematic and reliable battery comprising a validated set of measures in order to further understand inter-individual differences in rhythm skills**. The second goal **is to create a rhythm training protocol implemented in a serious game on tactile tablet to test whether this kind of training can be used effectively to improve rhythmic skills in healthy adults**.

The theoretical section of the dissertation is divided into four chapters. In **Chapter 1**, I will introduce the neuroscience of rhythm and the different models, theories, and methods to study rhythm. Rhythmic disorders, which offer a window for the understanding of rhythm processing, will be presented in **Chapter 2**. **Chapter 3** will be devoted to the effect of rhythmic training and rhythm-based rehabilitation methods that were developed to stimulate rhythmic, cognitive, and movement skills. Finally, I will present a review of rhythm-based games available on the market and their limits in **Chapter 4**, in order to evaluate whether they would be well suited for rhythmic training.

In the experimental section, four empirical studies that aim at fulfilling the aforementioned goals are presented. Three studies are illustrated in **Chapter 5**. They concern the evaluation of rhythm skills with a new battery for the assessment of rhythm skills (Assessment of Auditory Sensorimotor and Timing Abilities—BAASTA) in different populations. First, healthy adults were tested in order to prove that BAASTA can provide a detailed characterization of rhythmic skills that is sensitive enough to detect individual differences such as beat deafness. Older adults were also tested to prove the reliability of the battery in a test-retest study. The last study, concerning the presentation of a new tool (*Rhythm Workers*) for the training of rhythm skills is presented in **Chapter 6**.

The discussion contains an overview of the results (**Chapter 7**), and the theoretical implications of these results are highlighted. Finally, the perspectives that result from the work of this dissertation are presented in **Chapter 8**.

Theoretical section

1. **Chapter 1**. The Neuroscience of Rhythm. Why studying rhythmic skills?

1.1. The origins of rhythmic skills in humans

The ability to perceive temporal regularities and to move along with rhythmic auditory stimuli is a widespread skill in humans. This capacity is visible in our tendency to clap our hands, tap our feet, or dance with music, deliberately or spontaneously. Synchronization of movement with music implies that the listeners can perceive a regular pulse, extracted from the musical structure, that mark equally spaced points in time. This feature is referred to as the *beat* (e.g., Grahn & Rowe, 2009; London, 2012). Most of us can accurately track the beat of rhythmic events and synchronize with it (Repp, 2005; Repp & Su, 2013; Sowiński & Dalla Bella, 2013). The question of the origins of human beat perception and synchronization to the beat has been debated over the last few decades. How can we explain that humans developed specific skills for processing rhythmic stimuli?

Reactions to regular event patterns in the environment are widespread in human and animal species, from autonomic nervous system regulation of circadian rhythms (Crystal, 2001) to the control of locomotion movements (Taga, Yamaguchi, & Shimizu, 1991), and the optimization of foraging activities (Brunner, Kacelnik, & Gibbon, 1992; Kacelnik & Brunner, 2002). These events occur at different timescales (Merchant & De Lafuente, 2014). For instance, echolocation requires timing at the level of the microsecond, music and speech timing precision is around the millisecond, while perceiving the alternation of days and nights (circadian rhythms) and the alternation of seasons involve much longer timescales. Thus, to adapt to the changes in the environment, stimulus durations and their temporal regularities must be processed by the nervous system.

The capacities humans possess for processing temporal information either voluntarily or involuntarily is related to the variety of timed events they encounter in their environment. In this regard, people are very efficient in processing the duration of events (Grondin, 2008). For instance, we rely on timing information to avoid collisions with other vehicles when driving (Gibson, 1979; Lee, 1976) or to estimate temporal durations or quantify the time elapsed between two events (Fraisse, 1984; Grondin, 2008; Ivry & Schlerf, 2008). Another example of temporal processing is provided by rhythmic skills, highly widespread in humans, in particular in fine-grained perception of—and synchronization to—a musical beat (Repp, 2005; Repp & Su, 2013; Sowiński & Dalla Bella, 2013) and in dance activities (Dean, Byron, & Bailes, 2009; Grammer, Oberzaucher, & Holzleitner, Atmaca 2011).

Rhythmic skills are mostly unique to humans and display flexibility that is not apparent in other species (Fitch, 2013; Hagen & Hammerstein, 2009; Honing et al., 2012).

Recently, studies reported evidence of synchronization of movement to the beat in other species (sea lion—Cook, Rouse, Wilson, & Reichmuth, 2013; birds—Patel, Iversen, Bregman, & Schulz, 2009; Schachner, Brady, Pepperberg, & Hauser, 2009). However, it remains unclear whether the rhythmic behavior observed in animals relies on key features of musical beat processing similar to those of humans, as originally stated by Darwin in *The Descent of Man,* or not (Fitch, 2012; Patel, 2014; Wilson & Cook, 2016).

Several hypotheses on the origins of rhythmic behavior have been proposed. Rhythm is one of the three main specific attributes of music, along with melody and harmony. The possibility that rhythm in a musical context is a cultural product, a human invention with no biological or adaptive functions, or a by-product of language evolution, raised by Steven Pinker (Pinker, 1997), is not totally ruled out (Patel, 2010; Trainor, 2015). However, during the last decades, the adaptive significance of rhythm in particular has been given much consideration (Wallin, Merker, & Brown, 1999; McDermott & Hauser, 2005; Mithen, 2006). For instance, it has been proposed that dance and music may have co-evolved because they supported rhythmic courtship displays and thus may have played a role in sexual selection (Dean, Byron, & Bailes, 2009). In addition, moving to a common beat in a group paves the way to cooperation between its members (Wallin, Merker, & Brown, 1999), for example, in motivating individuals to contribute toward the collective good in economic exercises (Wiltermuth & Heath, 2009), ultimately fostering social cohesion (Phillips-Silver, Aktipis, & Bryant, 2011).

It is therefore possible to consider rhythmic activities such as dance and music as pre-verbal communication tools (Richter & Ostovar, 2016). In this context, skills as beat tracking (the capacity to extract a beat from a stimulus; Honing, 2012) and synchronization may have conferred survival advantages in humans. For these reasons, the ability to process rhythmic information has been treated as a cornerstone of the evolution of musical skills (Hagen & Bryant, 2003; Hagen & Hammerstein, 2009; McDermott & Hauser, 2005).

One further argument supporting the prominence of rhythm skills in humans is that moving to a regular beat or at a spontaneous regular frequency, as well as perceiving rhythm, are skills that are likely to be hard-wired as they appear spontaneously and quite early during development (Drake, Jones, & Baruch, 2000; Hannon & Trehub, 2005; Phillips-Silver & Trainor, 2005). The emergence of an internal representation of the beat in humans is reflected by neuronal oscillations that are tuned to the beat frequency when passively listening to a rhythmic sequence (Fujioka, Trainor, Large, & Ross, 2012; Nozaradan et al., 2011, 2012). Beat induction has been observed in new-born infants (Winkler et al., 2009), suggesting that the capacity to perceive the beat may be innate. The ability to couple movement to the beat, requiring more advanced motor controls, surfaces later during development. Synchronization to a metronome in children from the age of 2 1/2 can be attained when drumming in a social context (e.g., with an adult social partner; Kirschner & Tomasello, 2009), confirming the tight link existing between synchronization and social bonding.

In summary, **rhythmic skills are ubiquitous and highly rooted in human biology**. Because rhythmic skills are tightly linked with other functions such as social bonding, communication, and sexual selection, understanding the underlying mechanisms of rhythm skills is of major interest.

1.2. Timing and rhythm: definitions, theories, & models

'Events are perceivable but time is not' is the title of a conference proceeding paper of James Gibson (1975). This clever statement implies that as it is dependent on the perception of events, the processing of time, also referred to as *timing*, is not a monolithic phenomenon in humans. Timing is influenced by factors such as memory, the nature of the event(s) perceived, or the emotional and body state of the individual (Allman, Teki, Griffiths, & Meck, 2014; Wittmann, 2013), and thereby carries a high level of subjectivity (Wittmann, 2016). Overall, the heterogeneity of timing mechanisms makes it difficult to study timing as a general cognitive capacity. A single definition of timing is impossible as its meaning varies with the different theoretical frameworks. For instance, traditional approaches tend to consider timing as a linear representation of time by an internal pacemaker represented by a specialized area or a distributed network in the brain (Buhusi & Meck, 2005; Petter & Merchant, 2016). In parallel, other models consider that there is no centralized or distributed clock in the brain or explicit mechanism that provides a linear metric of time. State-dependent networks, for instance, consider that neurons and neuronal networks are inherently capable of temporal processing as a result of time-dependent changes (Karmarkar & Buonomano, 2007). From the perspective of the dynamical system approach, processing of time is modelled by internal neurocognitive oscillators that drive attention to expected points in time (Fujioka, Trainor, Large, & Ross 2012; Large & Jones, 1999; Nozaradan, Peretz, Missal, & Mouraux, 2011). This implies that the paradigms, the methods, and the stimuli that are used to study timing vary from one theoretical approach to the other and are different in duration-based and beat-based timing.

However, it is possible to overcome these difficulties by segmenting the phenomenon studied. A first categorization concerns the distinction between **explicit** and **implicit** timing. In general, explicit timing is involved in tasks requiring voluntary motor production (e.g., duration reproduction—Kagerer, Wittmann, Szelag, & Steinbüchel, 2002; synchronization with a pacing stimulus—Dalla Bella et al., 2017a; Repp, 2005; Repp & Su, 2013) or perceptual discrimination of a timed duration (e.g., duration discrimination; Allan & Kristofferson, 1974) and perceptual detection of irregularity in rhythmic sequences (anisochrony detection; Ehrlé and Samson, 2005; Hyde and Peretz, 2004). In contrast, implicit timing is associated with tasks that do not explicitly test timing (e.g., an auditory working memory task; Cutanda, Correa, & Sanabria, 2015), but in which temporal prediction affects the performance (Coull, 2009; Coull & Nobre, 2008; Lee, 1976; Nobre, Correa, & Coull, 2007; Piras & Coull, 2011; Sanabria et al., 2011). I will first describe the explicit dimension and its corresponding models of duration-based and beat-based (or interval-based) timing and then present the implicit form of timing.

1.2.1. Explicit timing: duration-based and Beat-based models of timing

Paul Fraisse (Fraisse, 1984) identified two different concepts in the experience of time: the concept of duration, which, as Fraisse puts it, 'applies to the interval between two successive events' (p.2), and the concept of succession, which 'corresponds to the fact that two or more events can be perceived as different and organized sequentially' (p.2). This classification anticipates the distinction between duration-based (also called interval-based timing; Allan & Kristofferson, 1974; Grondin, 1993; Ivry & Schlerf, 2008; Merchant & De Lafuente, 2014; Wittmann, 2013) and beat-based timing (Dalla Bella et al., 2017a; Grahn & Rowe, 2009; Lewis & Miall, 2003; Repp, 2005; Repp & Su, 2013). Duration-based timing (or absolute timing) concerns tasks involving estimation, comparison, or production of single durations (Grondin, 2008; Grube, Cooper, Chinnery, & Griffiths, 2010; Teki, Grube, Kumar, & Griffiths, 2011). Beat-based timing (or relative timing) consists of tasks such as synchronization to stimuli with an underlying beat (Dalla Bella et al., 2017a; Repp, 2005; Repp & Su, 2013; Wing & Kristofferson, 1977a; Wing & Kristofferson, 1977b), detecting changes in regular sequences of sounds (Dalla Bella et al., 2017a; Ehrlé & Samson, 2005), or estimating whether a sequence of metronome is aligned to the beat of music or not (Beat Alignment Test [BAT]; Iversen & Patel, 2008). Different models have been developed to account for duration-based and beat-based timing mechanisms. It is important to note that both forms of timing are generally studied with two different kinds of tasks, **perceptual tasks** (e.g., estimation of duration, detection of irregularities in a sequence) and **motor tasks** (e.g., production of duration or finger tapping).

Duration-based models. It is important to note that the first studies on time perception in psychophysics aiming at quantifying the sensory response to physical stimuli (Gescheider, 1997) were carried out on duration-based timing (Allan & Kristofferson, 1974; Merchant & De Lafuente, 2014). The psychophysical approach has proven successful for identifying differential thresholds in domains such as vision (e.g., the threshold to discriminate two nuances of colour; Wyszecki & Stiles, 1982) or audition (e.g., the threshold to discriminate two different pitches; Micheyl, Delhommeau, Perrot, & Oxenham, 2006). The same approach was used for estimating thresholds in timing (e.g., the threshold to discriminate two durations; Allan & Kristofferson, 1974). This approach showed that in spite of the fact that no specific organ is dedicated to the perception of time, time perception and perception by other senses as vision and audition had properties in common (Allman & Meck, 2012; Gibbon, Malapani, Dale, & Gallistel, 1997). Specifically, in order to perceive the difference, a certain physical difference between the stimuli needs to be exceeded.

In tasks typically used in duration-based timing, a stimulus, called standard duration, is presented first (Figure 1.1). In duration reproduction tasks, the participant is then asked to reproduce the duration of this stimulus, for example, by pressing a button. In perceptual tasks, a second sound is presented (comparison duration). The comparison duration is either exactly the same length as the standard duration or longer/shorter. The participant has to judge whether the comparison duration is the same or not. Perception and production of time intervals appear to be governed by two scalar properties (Wearden & Lejeune, 2008; Malapani & Fairhurst, 2002). First, *mean accuracy* states that mean estimation or production of timed intervals vary linearly and accurately with the imposed temporal standard (see Figure 1.1). Second, *scalar variability* (or Weber's Law) predicts that the variance of the perception is dependent on the magnitude of a physical stimulus (Allan, 1991; Wearden, 2001) (i.e., estimation of a duration is more variable when the length of the stimulus increases).

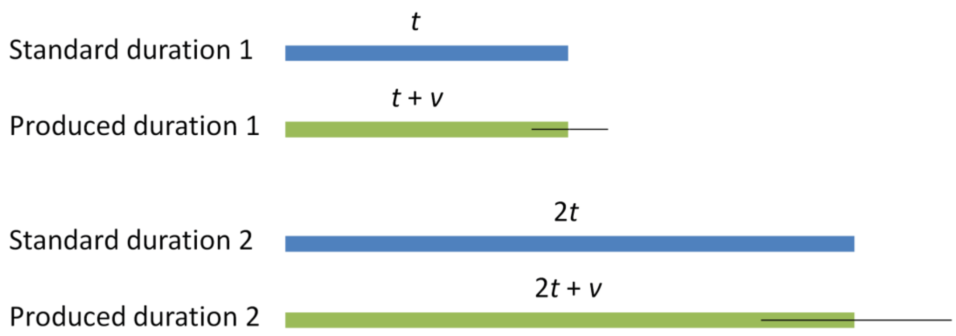

Figure 1.1. Example of a standard duration reproduction task in which the participants has to reproduce the duration (Produced duration) of a stimulus (Standard duration). The first standard duration is of length *t*. The response (Produced duration 1) is of length *t* with a variability (*v*) (variability is represented by black bars). When the duration of the standard duration is doubled (Standard duration 2), the mean time of the produced duration is also doubled, as it varies linearly with the standard duration (*mean accuracy* property). The absolute variability is increased with the longer stimulus (*scalar variability* property).

Much evidence supporting these two scalar properties in human and nonhuman timing behavior has been put forward (Allan, 1998; Gibbon, 1977). This is based on tasks such as temporal bisection (the participant judges whether a target duration is longer or shorter than a standard duration; Church & DeLuty, 1977) or temporal generalization (the participant decides whether a target duration is the same or different to a learnt standard; Church & Gibbon, 1982) However, it is important to note that they can be violated under particular conditions (e.g., with very short durations; Lejeune & Wearden, 2006; Wearden & Lejeune, 2008).

In research on time processing, the observation of scalar properties fuelled the scalar expectancy theory (SET; Gibbon, 1977; Gibbon & Church, 1990) (see Figure 1.2). In SET, a clock (or pacemaker-accumulator) is the component that provides 'raw' representations of durations (Wearden, 2003). A memory component then stores the durations of the signal perceived. For example, in a task that consists in a comparison between two sounds, the first sound is first perceived and then its duration is stored. Finally, a decision stage compares the stored duration with the new perceived duration (Gibbon, Church, & Meck, 1984).

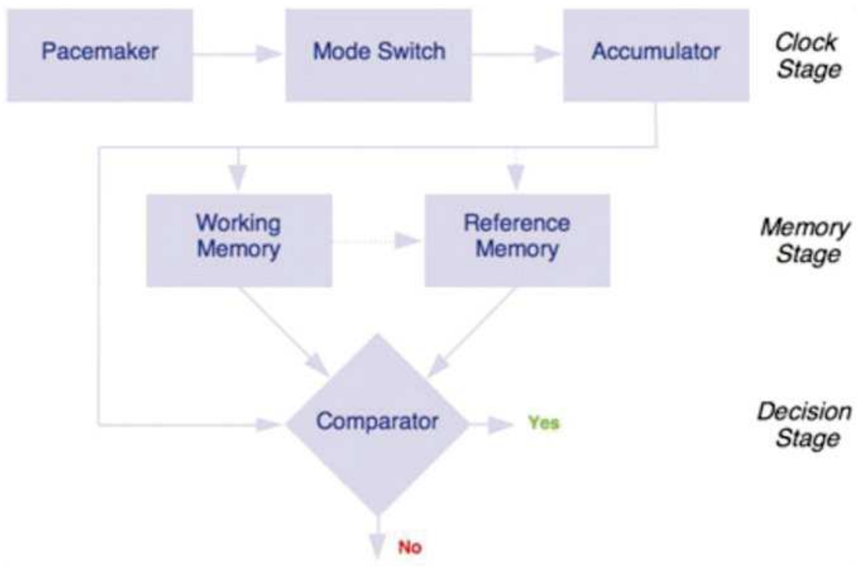

Figure 1.2. SET is an information processing model that divides the temporal processing system into three components, a clock (or pacemaker-accumulator) that is the perception component, a memory component that stores the signal duration, and a decision stage that compares the duration stored and the duration perceived. From Allman & Meck (2012), adapted from Gibbon, Church, & Meck (1984).

Beat-based models. Beat-based timing implies the processing of external events that are predictable on the basis of their periodicity (i.e., leading to perceive an underlying beat). In simple sound sequences such as a metronome, the underlying beat is evident in the temporal structure as it corresponds to each occurrence of a tone. However, in more complex rhythmic sequences (e.g., music), the beat has to be extracted from the durational properties of the sequence.

Note that perception of the beat and synchronization of movement to a beat can occur with visual or tactile stimuli (Repp, 2003; Repp & Penel, 2004). However, perception of temporal structures is typically more accurate in the auditory modality (Aschersleben, 2002; Iversen, Patel, Nicodemus, & Emmorey, 2015) and motor synchronization to auditory rhythms (e.g., via finger tapping) is not as precise with visual stimuli (Repp, 2003; Repp & Penel, 2004). For these reasons, most of the studies on rhythm used auditory stimulation.

Models that account for beat-based timing can be split into two main categories (Torre & Balasubramaniam, 2009), corresponding to a cognitive perspective (e.g., Mates, 1994; Prinz, 1997) and a dynamical systems perspective (Haken, Kelso, & Bunz, 1985; Schöner & Kelso, 1988): information processing models (Repp, 2005, 2006; Vorberg & Wing, 1996; Wing & Kristofferson, 1973ab) and nonlinear-coupled oscillator models (Drake, Jones, & Baruch, 2000; Jones, Moynihan, Mackenzie, & Puente, 2002; Large & Jones, 1999).

Beat-based timing is often studied via sensorimotor synchronization (Phillips-Silver et al., 2011; Repp, 2005; Repp & Su, 2013; Sowiński & Dalla Bella, 2013; Tranchant, Vuvan, & Peretz, 2016). Sensorimotor synchronization consists of coordinating movements to a referential event (Pressing, 1999) such as the sounds of a metronome. It is tested in a variety of tasks in which an action (e.g., finger tapping or body sway) is coordinated to a perceived stimulus (e.g., a metronome or musical beat). When someone is asked to synchronize with a pacing stimulus, the participant tries to execute movements (e.g., finger taps) at the time of occurrence of each perceived beat. However, human synchronization is not perfect; people usually do not match exactly their movements to the time of the stimuli. Synchronization is assessed in terms of accuracy and variability of the performance. Accuracy refers to the capacity to match the timing of the movements to the timing of the pacing stimulus. Variability indicates how participants are consistent in moving in time with the stimuli.

The information-processing modelling framework aims at accounting for the variability of the synchronized movement through sequential and autoregressive corrections of the periods of the timed movements (e.g., finger taps) and asynchronies with the pacing stimulus (see Figure 1.3). It postulates a linear relationship between a central timekeeper (or internal clock) attributed to the central nervous system that integrates perceptual information and peripheral motor processes that implement the motor response (Mates, 1994; Wing & Kristofferson, 1973ab). The total variance of the timing of rhythmic movements (i.e., the variance of the intervals between tap times) results from these two additive components (Repp, 2006; Wing & Kristofferson, 1973ab). The central variance is dependent of the length of the inter-tap interval (ITI) whereas the motor variance is relatively constant. When the ITI increases, the central variance increases, while the contribution of the motor variance decreases (Wing, 1980).

This two-level model accounts for unpaced tapping, in particular in a synchronization-continuation task, in which a pacing stimulus is presented and the subject has to continue tapping at the same pace after the stimulus stopped. An extension is needed to adapt this model to sensorimotor synchronization. In sensorimotor synchronization, the ITI is dependent on the interval of the pacing stimulus (inter-onset interval, IOI). Therefore, the variance that is entered in the model is no longer between each tap but between the taps and the beats. In addition, error correction is necessary to adapt motor events to the stimulus timing, which is mandatory to maintain synchronization over time (Aschersleben, 2002; Mates, 1994; Vorberg & Schulze, 2002). Without error correction, the inherent variability of the movement may accumulate at each time of occurrence of successive actions (e.g., at each tap) and would yield large asynchronies, eventually preventing sensorimotor synchronization to be achieved and sustained (Repp, 2005; Worberg & Wing, 1996).

Two types of error corrections have been distinguished: phase correction and error correction (Mates, 1994; Repp, 2005). Correction of movement in a synchronization task concerns the adjustment of the moment of the action to each pulse (e.g., each metronome tick or musical beat) of the pacing stimulus. In linear models, phase correction corresponds to a correction of a proportion of each asynchrony between the taps and the beat (Schulze, 1992) without modifying the period of the internal timekeeper. In contrast, period correction is an adaptation of the period of the internal timekeeper relative to the IOI of the stimulus. In period correction, the proportion of the difference between the preceding period and the IOI is adjusted at each new tap (Mates, 1994). In general, period correction is considered a more central process than is phase correction; that is, the former is supposed to be more dependent on cognitive control and less automatic than the latter (Mates, 1994; Repp, 2001).

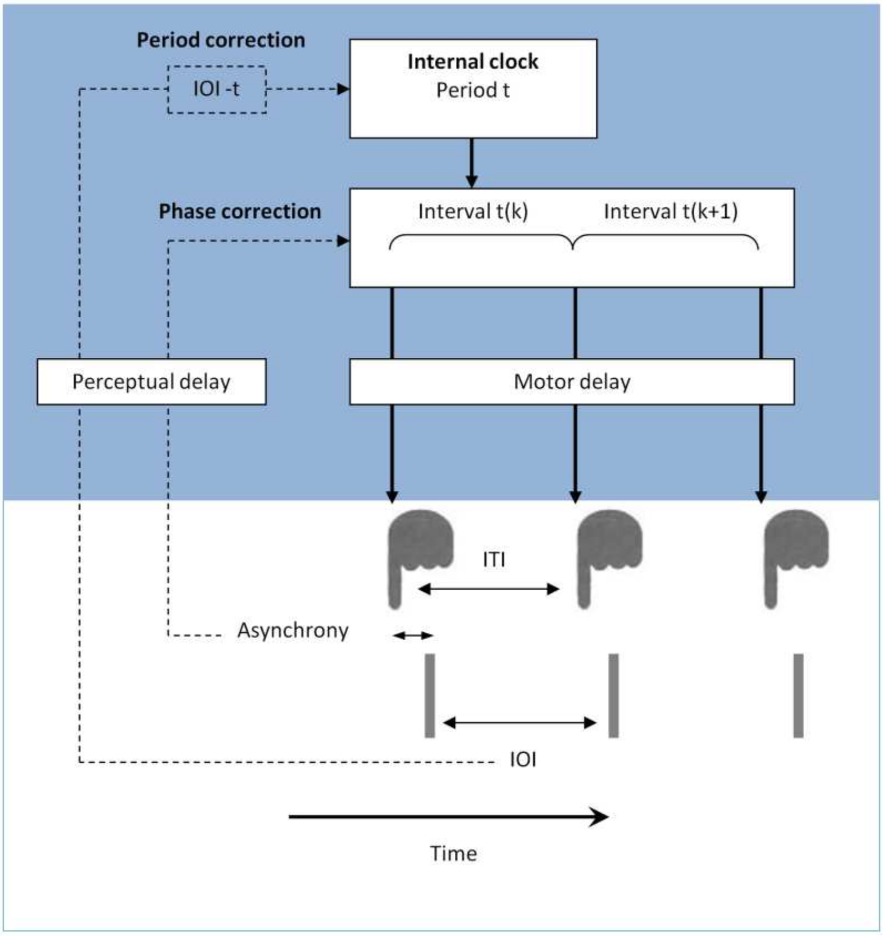

Figure 1.3. Two-process model for sensorimotor synchronization. Internal processes (central timekeeper) are represented above (blue frame) and directly observable processes (motor implementation) below (white frame). IOI = Inter-Onset Interval. ITI = Inter-Tap Interval. The central timekeeper controls the successive intervals between the taps [*t*(k), *t*(k+1)] and adjusts them on the basis of the perceived asynchronies between tones (or beats) and taps (Period and Phase correction). Reproduced from Repp (2006), Mates (1994), and Wing (2002).

In dynamical system theory, the perception of the beat with or without alignment of the motor actions (e.g., dance, body sway) to that beat is called *rhythmic entrainment* (Large & Palmer, 2002; Merchant & Honing, 2014). Entrainment occurs when the frequency of an entrainable system (e.g., an oscillator, a group of coupled oscillators; Large & Jones, 1999; McAuley & Jones, 2003) adapts to the frequency of a beat. The continuous motor response is represented by an oscillator that is coupled to an environmental rhythmic stimulus (Schöner & Kelso, 1988). According to the original formulation of the dynamic attending theory (DAT; Drake, Jones, & Baruch, 2000; Large & Jones, 1999), these oscillations allow the orientation of attention toward points in time that correspond to the beat.

Interestingly, the perception of a beat is reflected in the dynamical brain activity in response to periodic sounds, with modulation of beta-band oscillations following the tempo of sound stimulation in mere listening activities (Fujioka, Trainor, Large, & Ross 2012; Nozaradan, Peretz, Missal, & Mouraux, 2011). When a motor response like finger tapping is added, entrainment is reinforced as enhanced brain responses to the frequency of the rhythm are observed (Chemin, Mouraux, & Nozaradan, 2014).

In complex stimuli that are not strictly periodic or with embedded periodicities at multiple time scales (e.g., music; Large & Snyder, 2009; Lerdahl & Jackendoff, 1983; Patel, Iversen, Cheng, & Repp, 2005), the temporal structure of the rhythmic sequence evokes intrinsic neural oscillations at different frequencies (Nozaradan, Peretz, Missal, & Mouraux, 2011; Nozaradan, Peretz, & Mouraux, 2012). However, the amplitude of neural oscillations is enhanced at harmonic frequencies of beat perception, confirming that beat perception mechanisms may be underpinned by entrainment of neural oscillations.

Note that other kinds of tasks were used to refine models of beat-based timing. For example, in perturbation studies, an unpredictable variation is inserted in an otherwise periodic sequence (e.g., modification of the period between each event; Michon, 1967; Repp, 1999, 2000). In this case, adaptation to the perturbation is studied. In adaptive tapping tasks, the task is the same as in synchronization-continuation, but a perturbation of the pacing stimulus is added (Dalla Bella et al., 2017a; Repp & Keller, 2008; Schwartze, Keller, Patel, & Kotz, 2011). Global perturbation affects every event from a certain point in the sequence (i.e., change in the period or of the phase of the sequence) and local perturbation affect only one event (Repp, 2005). Internal timing mechanisms (e.g., the presence of natural frequencies) in the absence of a stimulation can also be studied via unpaced tapping (Dalla Bella et al., 2017a; Drake, Jones, & Baruch, 2000). Unpaced tapping consists of tapping as regularly as possible without pacing stimuli either at a spontaneous tempo (spontaneous tapping) or under a specific condition (e.g., as fast as possible).

Beat-based timing mechanisms can also be studied in purely perceptual tasks such as anisochrony detection (Dalla Bella & Sowiński, 2015; Ehrlé & Samson, 2005; Hyde & Peretz, 2004), consisting of judging if a sequence of metronome or music is regular or not, or the BAT (Bégel et al., 2017; Dalla Bella et al., 2017a; Iversen & Patel, 2008), in which a sequence of a metronome is superimposed on regular music either aligned with the beat of the music or not. The goal of the task is to detect misalignments of the metronome with respect to the musical beat. Other tasks consist, for example, in judging if a rhythmic sequence has a duple (march) or triple (waltz) meter on the basis of relative-intensity differences between accented and unaccented tones (Fuji & Schlaug, 2013; Grahn & Brett, 2007; Grahn & Rowe, 2009; Peretz, Champod, & Hyde, 2003), or estimating if a beat-based sequence is slowing down or speeding up (Fuji & Schlaug, 2013; Grahn & McAuley, 2009).

Even if the cognitive and dynamical systems approaches have been clearly separated in the literature, some authors claimed that the two frameworks can be compatible as linear models of error correction and can be considered as providing a good approximation to dynamic systems (Pressing, 1999; Repp, 2005). It seems that they are rather complementary since, arguably, they are two variants of a general control equation for rhythmic behavior. Evidence suggesting that the two class models account for two different synchronization processes involved as a function of movement, and consequently two different ways to achieve synchronization, has been put forward (Torre & Balasubramaniam, 2009; Balasubramaniam, Wing, & Daffertshofer, 2004). Indeed, the computational framework mainly focuses on discrete, sequential structure of movement timing (e.g., times intervals between taps and asynchronies with pacing stimuli; Repp, 2005; Repp & Su, 2013), while dynamical systems theory is associated with continuous within-cycle coupling movements (Balasubramaniam, Wing, & Daffertshofer, 2004; Delignières, Lemoine, & Torre, 2004; Zelaznik, Spencer, & Ivry, 2002).

The goals of the present dissertation are to refine methods for assessing systematically rhythmic skills and to propose a method for training rhythmic skills by improving beat tracking capacities of the participants. Therefore, beat-based timing is central to this thesis. I will shortly introduce duration-based models before focusing on beat-based models.

In this dissertation, studies will be designed and results will be interpreted in the context of the computational framework. This choice is motivated by the fact that the studies presented focus on the discrete dimension of timing, which is more associated with the computational framework. On top of that, to date, this framework has been proven to be the most appropriate to highlight differences between individuals (e.g., Palmer, Lidji, & Peretz, 2014; Phillips-Silver et al., 2011) and between patient populations (e.g., Falk, Müller, & Dalla Bella, 2015; Grahn & Brett, 2009). Thus, it is more appropriate to study dissociations of processes in rhythm skills (Sowiński & Dalla Bella, 2013) and changes in time as a result of training (e.g., Benoit et al., 2014; Dalla Bella et al., 2015).

1.2.2. Implicit timing

In implicit cognitive processes, the stimuli are processed or learned independently of conscious attempts. For instance, the acquisition of knowledge of tonal structure of music may result from mere exposure to music, i.e., without music training (Tillmann, Bharucha, & Bigand, 2000). Implicit cognitive processes are dissociated from explicit processes in domains such as learning (Reber, 1989), memory (Schacter & Graf, 1986), vision (Weiskrantz et al., 1974), and language (Ellis, 2005). Implicit processing of the signal is deemed more robust than explicit treatment, since patients with deficits in the explicit dimension have usually spared implicit skills. In the pitch domain, for example, individuals with congenital amusia are benefitting from harmonic priming, a form of implicit processing, to process musical structures (Tillmann, Peretz, Bigand, & Gosselin, 2007).

Explicit timing involves overt estimation or production of durations. Unlike explicit timing, implicit timing arises in tasks in which the goal is not temporal but the temporal framework of the stimuli or the motor response influences the performance. For example, it is necessary to estimate the time of arrival of a car in order to cross the street. Even if we do not do it explicitly, the estimation of the time before an object reaches us (*Time To Contact;* Lee, 1976) helps us in realizing non-temporal tasks such as catching a ball or avoiding a vehicle when crossing the road. In this example, implicit timing requires the processing of single intervals. However, as in explicit timing, other tasks require the extraction of a beat or the production of a rhythmic motor sequence. As the focus of this dissertation is on beat-based timing, I will present example of tasks involving a beat.

Implicit timing tasks are divided into two main categories (Coull & Nobre, 2008): tasks requiring emergent timing and tasks building temporal expectation. In emergent timing, timing of a motor output is controlled implicitly as an emergent property of other control processes. For instance, in continuous rhythmic movement such as circle drawing, temporal consistency reflects processes associated with trajectory formation and control but does not necessitate an explicit representation of individual temporal intervals. It has been shown that emergent timing reflects the operation of other parameters than just explicit synchronization (i.e., discrete finger tapping with a metronome; Spencer, Verstynen, Brett, & Ivry, 2007; Zelaznik, Spencer, & Ivry, 2002). Studies on patients with cerebellar lesions who exhibit deficits in discrete movements such as finger tapping but not in continuous circle drawing confirmed the dissociation between explicit discrete timing production and implicit emergent timing (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003).

Temporal expectation is a form of priming in which the temporal predictability of a perceived stimulus helps in realizing a non-temporal task. For example, temporal orienting of attention by presenting a regular temporal pattern before a target is known to reduce reaction time, as compared to an irregular sequence (Lange, 2010; Sanabria, Capizzi, & Correa, 2011; Sanabria & Correa, 2013).

In summary, **different categories of tasks contribute to the understanding and modelling of timing capacities**, varying the nature of the stimuli (repeated versus single intervals) and of the processes involved in their realization (implicit versus explicit timing). These distinctions are illustrated in Figure 1.4. However, note that even if these distinctions are valuable, the mechanisms underpinning each category of timing concepts may be in part overlapping, as shown by the partially shared neural networks observed between implicit and explicit timing (Coull, Cheng, & Meck, 2011). For example, Piras and Coull (2011) provided evidence suggesting that implicit and explicit timing rely on the same internal representation of duration. They showed that in a visual task involving either implicit or explicit timing for a single interval, performance in both cases was consistent with scalar properties (i.e., mean accuracy and scalar variability; Malapani & Fairhust, 2002; Wearden & Lejeune, 2008). In addition, the nature of the stimuli constituting the tasks may, in some cases, be considered as pertaining to both duration-based and beat-based timing. Anisochrony detection, for example, may be viewed as a short series of single intervals repeated over time or as a sequence implying a beat. Thus, given the short length of the stimulus, the beat may not be extracted and each interval may be treated separately. Therefore, even if the stimulus is periodic, non-periodic mechanisms may be involved. Mechanisms engaged when making timing judgments are likely to be different between individuals as the activation of cortical beat-based circuits is more important in certain subjects in a timing judgment task of stimuli with ambiguous tempos (Grahn & McAuley, 2009).

In this dissertation, for simplicity, I will use the term 'rhythm' to refer to beat-based timing mechanisms and rhythmic skills or rhythmic capacities when referring to the capacity of processing beat-based stimuli. Note that in the experimental section of this dissertation, a comparison of explicit and implicit timing was done with rhythmic stimuli. The term 'beat tracking', often used in the dissertation, will refer specifically to the capacity of perceiving and synchronizing to the beat of music.

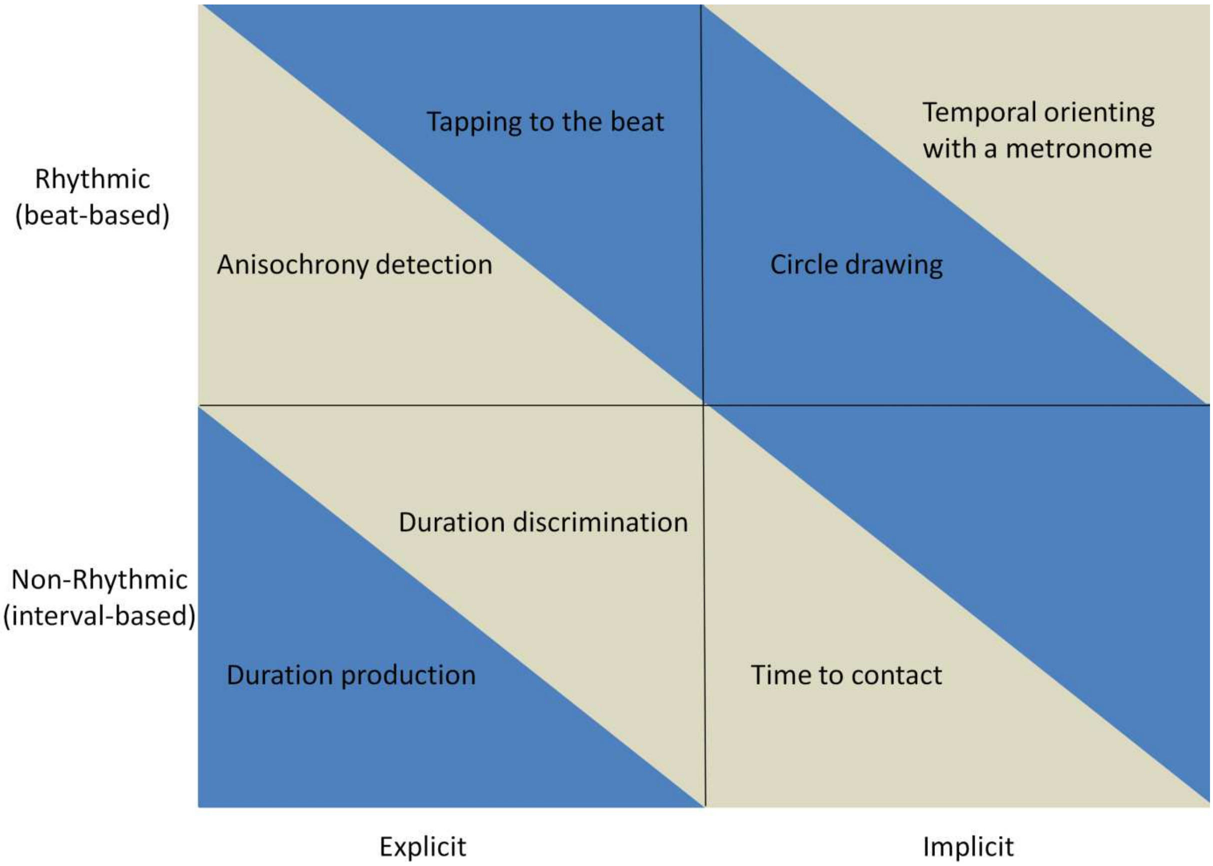

Figure 1.4. Classical view of different categories of timing tasks (the list of tasks is not exhaustive). The blue stripes correspond to sensorimotor tasks; the grey stripes correspond to perceptual tasks. For simplification, circle drawing is treated as beat-based timing because it involves successive cycles, even if the goal of the task is to produce continuous movements.

1.2.3. Neuronal basis of timing

In parallel with the considerable efforts made to model timing capacities at the behavioral level, the neuronal underpinnings of time perception and production have been thoroughly investigated over the past decades. Main areas involved in timing are presented in Figure 1.5. Partially separate pathways and regions underlie the different mechanisms involved in timing. In general, auditory-motor processing of time is likely to be underpinned by auditory regions (auditory cortex, superior temporal gyrus; Grahn & Brett, 2007; Zatorre, Chen, & Penhune, 2007), motor areas of the brain (e.g., basal ganglia, motor and pre-motor cortices; Grahn & Brett, 2007; Grahn & Rowe, 2009; Zatorre, Chen, & Penhune, 2007), as well as motor coordination regions (e.g., the cerebellum; Coull, Cheng, & Meck, 2011; Grube, Cooper, Chinnery, & Griffiths, 2010; Schwartze & Kotz, 2013; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003; see Figure 1.5).

Explicit and implicit timing mechanisms have been linked with partially different neuronal networks. A basal-ganglia-cortical network is associated with explicit timing (Coull & Nobre, 2008) in both rhythmic and non-rhythmic (duration-based) tasks. These critical regions for timing processing are selectively activated depending on the tasks and the mechanisms involved. Medial regions of the basal ganglia, including the caudate and globus pallidus, the superior region of the pre-SMA, are thought to be involved in perceptual timing while lateral regions of basal ganglia, SMA proper, and inferior pre-SMA would be more involved in motor timing (Coull, Chen, & Meck, 2011). The contribution of the cerebellum in explicit timing is particularly important in motor tasks (Bengtsson, Ehrsson, Forssberg, & Ullén, 2005; Bueti, Walsh, Frith, & Rees, 2008; Coull & Nobre, 2008). For example, children with cerebellar medulloblastoma, a tumor of the cerebellum, show intact rhythm discrimination but disrupted sensorimotor synchronization (Provasi et al., 2014).

There is also evidence that duration-based timing and beat-based timing also engage different brain regions. For example, a meta-analysis of 46 studies showed a functional dissociation of pre-SMA and SMA-proper (Schwartze, Rothermich, & Kotz, 2012). The pre-SMA tends to be activated in perceptual duration-based timing of supra-second intervals, while activations of the SMA-proper are observed preferentially in sensorimotor sequential timing (see also Kotz & Schwartze, 2011). It has been shown that patients with cerebellar degeneration are impaired in the estimation of single intervals requiring absolute measurements of time but not in the analysis of rhythmic patterns based on a beat (Grube, Cooper, Chinnery, & Griffiths, 2010). Thus, the role of the cerebellum appears as crucial for the processing of single intervals (Buhusi & Meck, 2005). A functional neuro-imagery study confirmed the role of the cerebellum (i.e., the vermis and deep cerebellar nuclei including the dentate nucleus), in interactions with the inferior olive during duration-based timing (Teki, Grube, Kumar, & Griffiths, 2011).

Notably, the specific involvement of these regions in different tasks is still debated. However, it is clear that synchronization to a musical beat is sustained by a complex neuronal network, including perceptual regions (superior temporal gyrus; Chen, Penhune, & Zatorre, 2008a; Schwartze & Kotz, 2013; Thaut, 2003), motor regions (the basal ganglia; Chen, Penhune, & Zatorre, 2008b; Grahn & Brett, 2007; Grahn & Rowe 2009), as well as sensorimotor integration areas (e.g., dorsal premotor cortex; Chen, Zatorre, & Penhune, 2006; Zatorre, Chen, & Penhune, 2007). Interestingly, beat extraction in the absence of an explicit motor response recruits motor regions of the brain, such as the basal ganglia (e.g., putamen), the SMA, or the premotor cortex (Grahn & Brett, 2007; Grahn & Rowe, 2009; Chen, Penhune, & Zatorre, 2008), in addition to the auditory cortex.

Implicit timing is sustained by an inferior parietal-premotor network (Coull & Nobre, 2008; Coull, Warren, & Meck, 2011; Kotz & Schwartze, 2010; Nobre & Coull, 2010; Schwartze & Kotz, 2013; Zelaznik, Spencer, & Ivry, 2002). This network is linked to the cerebellum and the basal ganglia to support temporal prediction. In contrast, the cerebellum is less involved (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003; Spencer, Verstynen, Brett, & Ivry, 2007).

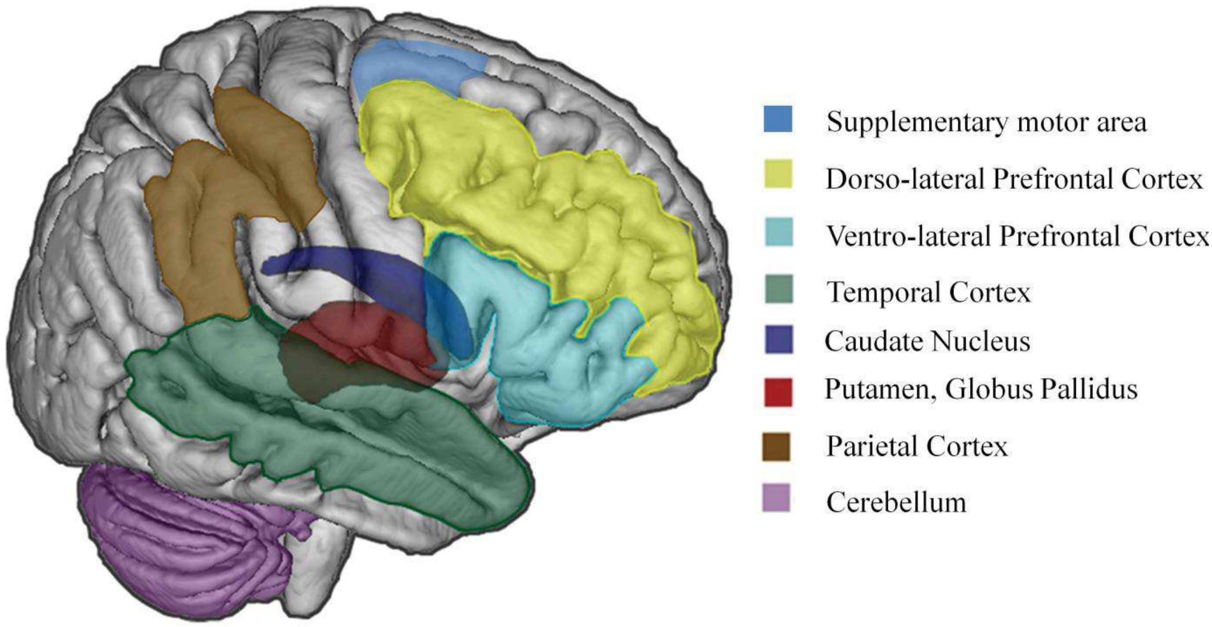

Figure 1.5. Adapted from Piras et al. (2014). Main areas involved in timing processing. These areas are selectively activated depending on the task, reflecting different mechanisms. For instance, synchronization to musical beats involves the temporal cortex (superior temporal gyrus), motor (Putamen, Globus Pallidus) and pre-motor regions (dorsal pre-motor cortex), and the SMA.

1.3. Links between rhythm, movement, and cognitive abilities

1.3.1. Rhythm and movement

There exists a tight link between rhythm and movement that is evident in the way we react to music. Spontaneously or intentionally, we sway our body or tap our feet to the beat of music. This natural bodily reaction to rhythmic stimulations suggests that our brain is hard-wired for processing rhythm and for moving in response to the beat. Studies in ethnomusicology have shown that motor responses to music are observed across groups and cultures worldwide (Nettl, 2000; Richter & Ostovar, 2016). The observation that rhythm perception without a motor response involves motor regions of the brain (Chen, Penhune, & Zatorre, 2008; Grahn & Brett, 2007; Grahn & Rowe, 2009) confirms this link and points toward common evolutionary roots of rhythm and movements. This link is also seen in pathology. For example, studies on patients with movement disorders (e.g., with Parkinson's disease) quite consistently show impaired rhythm capacities in both perception and production (Benoit et al., 2014; Grahn & Brett, 2009; Pastor, Artieda, Jahanshahi, & Obeso, 1992). More information on studies of patients' rhythm capacities will be provided in **Chapter 2**.

1.3.2. Rhythm and cognitive capacities

There is growing evidence that cognitive abilities are closely tied to timing (Matthews & Meck, 2016). Language skills are a good example in this respect. For instance, speech is organized as a rule-based system in which the appropriate sequencing of events is critical for communication. This is linked with predictive temporal sampling and coding of events (Goswami, 2011; Kotz & Schwartze, 2010; Tallal, 2004). Specifically, predictive coding postulates that a temporal sampling of speech by neuronal oscillations encodes incoming information at different frequencies (Morillon, Hackett, Kajikawa, & Schroeder, 2015). This mechanism is likely to subtend the extraction of temporal information from perceived speech and the temporal organization of speech production.

Rhythmic perceptual capacities such as rhythm discrimination are positively correlated with reading skills (Huss et al., 2011), grammar skills (Gordon et al., 2014), and phonology and language (Corriveau, Pasquini, & Goswami, 2007; Huss et al., 2011; Grube, Cooper, & Griffiths, 2013) in children with and without specific language impairment (SLI) and dyslexia. In general, children with developmental dyslexia have inaccurate perceptions of metrical structure (Huss et al., 2011). Rhythm perception is also linked to reading skills (Bekius, Cope, & Grube, 2016; Tierney, White-Schwoch, MacLean, & Kraus, 2017) and verbal memory (Tierney, White-Schwoch, MacLean, & Kraus, 2017) in healthy adults. These studies show the tight link existing between rhythm perception skills, language, and reading skills.

Rhythm production and synchronization also relate to speech and reading. Sensorimotor synchronization relates to reading capacities (Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014) and stability of subcortical speech processing (Woodruff Carr, Tierney, White-Schwoch, & Kraus, 2016; Woodruff Carr et al., 2014). More precisely, neurophysiological studies have shown that children with the poorest synchronization capacities have greater variability (i.e., less consistency) in their neural responses to speech (Hornickel & Kraus, 2013; Woodruff Carr et al., 2014). Individuals with reading disorders show greater synchronization variability than controls in tapping to a beat (Corriveau & Goswami, 2009; Thomson, Fryer, Maltby, & Goswami, 2006). Tapping variability also positively correlates with sustained attention in children (Tierney & Kraus, 2013). Moreover, in a recent study we conducted in our laboratory (Puyjarinet et al., under revision; see Annex), we tested the capacity of children and adults with attention-deficit/hyperactivity disorder (ADHD) in both perceptual and motor rhythmic tasks. ADHD is a condition characterized by poor concentration, impulsivity, and visible signs of hyperactivity (Polanczyk & Rohde, 2007). We showed for the first time core deficits in tracking the beat of music in ADHD children and adults in both beat perception and sensorimotor synchronization tasks (more details are provided in **Chapter 2**). On top of that, ADHD children and adults who are poor beat trackers (i.e., they have difficulties in perceiving and synchronizing to the beat of music) exhibited poorer performance than good beat trackers in cognitive tasks testing inhibition and flexibility.

Altogether, these studies indicate that an array of cognitive functions spanning language, reading, attention, and executive functions are associated with rhythmic skills. However, it is not clear yet whether the specific relation between rhythm and other cognitive functions reflects a causal link or a simple correlation indicating that there may be latent common processes. Attempts to clarify this link have been done in the past few years. For example, it has been proposed that interval timing and working memory can originate from the same oscillatory processes (Gu, Van Rijn, & Meck, 2015; Meck, Matell, & Lustig, 2005). Notably, predictable auditory stimuli sequences positively influence recognition memory (Agres, Abdallah, & Pearce, 2017). This result suggests that rhythm may play a role in memory. Finally, it is important to note that rhythm capacities as measured by finger tapping to a regular beat is correlated with general intelligence (i.e., IQ measures; Madison et al., 2009; Ullén, Mosing, & Madison, 2015). Therefore, rhythmic skills are likely to be influenced by general intelligence, and correlations found between rhythmic skills and cognitive functions might be partially explained by the common influence of mental capacities.

Chapter short summary

In summary, the neurosciences of timing and rhythm have provided evidence for the prominence of timing processes and of a variety of well-distinct rhythmic abilities in humans. The capacities for beat processing are likely to be hard-wired in the brain and are inherently tied to motor skills, as some brain areas dedicated to the processing of time and rhythm are the same as those associated with movement. Rhythmic skills play also an important role in language and cognitive skills. Thus, rhythmic capacities are supposedly crucial to master essential activities of human behavior.

2. **Chapter 2**. Rhythmic disorders

In spite of the fact that the majority of humans can track a beat, this ability can be disrupted in specific populations such as patients with neurodegenerative diseases (e.g., Parkinson's disease), or neuro-developmental disorders such as ADHD, dyslexia, or stuttering (Allman & Meck, 2011; Benoit et al., 2014; Falk, Müller, & Dalla Bella, 2015). Poor rhythmic skills are also apparent in beat deafness, a specific condition in which individuals encounter particular difficulties in moving to the beat in the absence of brain lesions or deficits in other cognitive functions (Palmer et al., 2014; Sowiński & Dalla Bella, 2013). In this section, I will review evidence pointing to impaired rhythmic skills in various groups of subjects. First, I will focus on beat deafness. In the second part, I will review research on Parkinson's disease. Finally, I will present studies focusing on neuro-developmental disorders.

2.1. Beat deafness

Beat deafness is a specific form of rhythmic disability in the absence of brain damage (Palmer, Lidji, & Peretz, 2014; Phillips-Silver et al., 2011; Sowiński & Dalla Bella, 2013). This condition has also been referred to as 'dysrhythmia' (Launay, Grube, & Stewart, 2014). It is a form of congenital amusia, a neuro-developmental disorder confined to music perception and production (Peretz & Hyde, 2003; Stewart, 2008). Difficulties in beat processing observed in beat deafness differ from the deficits observed in 'tone deafness', another form of congenital amusia. Indeed, the core deficit in congenital amusia pertains to pitch processing (Ayotte, Peretz, & Hyde, 2002; Dalla Bella, Giguère, & Peretz, 2009). In general, rhythm deficits often co-occur in tone deafness (Dalla Bella & Peretz, 2003), but depend on the presence of pitch variations in music. When pitch variations are removed from music, rhythm deficits disappear (Foxton, Nandy, & Griffiths, 2006). It was initially thought that rhythm deficits were a by-product of pitch deficits (Dalla Bella & Peretz, 2003; Peretz, Champod, & Hyde, 2003). First evidence that rhythm deficits can occur in isolation was provided in a recent study by Phillips-Silver et al. (2011) and confirmed in further studies (Launay, Grube, & Stewart, 2014; Mathias et al., 2016; Palmer, Lidji, & Peretz, 2014; Sowiński & Dalla Bella, 2013; Tranchant, Vuvan, & Peretz, 2016).

The fact that rhythm capacities can be malfunctioning as a result of a congenital anomaly in beat deafness offers a window for the understanding of normal rhythm processing. Interest in beat-deafness is growing as it is a means to study rhythm perception and production and to refine models of beat processing. Indeed, heterogeneous profiles of beat-deaf individuals reflect the complexity of perception-action mechanisms (Mathias et al., 2016; Palmer, Lidji, & Peretz, 2014; Sowiński & Dalla Bella, 2013).

The first systematically-described case of beat deafness is the case of a young man named Mathieu (Phillips-Silver et al., 2011; Palmer, Lidji, & Peretz, 2014), who was unable to bounce accurately to the beat of music while showing good synchronization to a simple metronome. His poor synchronization is likely resulting from a perceptual disorder, as he was also quite inaccurate in estimating whether a dancer was on or off the beat of the music in a video. It is worth noting that Mathieu is a pure case of beat deafness, given that he did not exhibit poor pitch perception, as tested with the Montreal Battery of the Evaluation of Amusia (MBEA; Peretz, Champod, & Hyde, 2003). Thus, Mathieu's difficulties in beat processing differ from the deficits observed in 'tone deafness'.

The case of Mathieu points toward a perceptual explanation of poor synchronization to the beat. Inaccurate beat tracking may bring about poor alignment of movement to the beat. In particular, extracting the beat from a complex auditory signal (e.g., music), which involves the processing and integration of several periodicities at different embedded time scales (meter; London, 2012), may prevent beat-deaf individuals from synchronizing movements to the beat of music. Yet, detecting the beat of a simpler isochronous sequence (i.e., a single periodicity) can be spared. Recently, Launay, Grube and Stewart (2014) also described three cases of individuals who showed poor rhythm perception, beat extraction, and synchronization with metrical rhythms while presenting intact synchronization with a metronome and spared pitch perception. Synchronization to the beat was tested with a finger tapping task to various rhythmic sequences (isochronous, with a strong beat and with a weak beat).

Although previous case reports suggest that poor beat perception may be the major cause of poor synchronization in beat deafness, evidence is growing in favor of sensorimotor integration deficits in this condition. Notably, poor beat perception does not seem to be mandatory for poor synchronization to the beat. When testing approximately 100 participants without musical training with tapping tasks and rhythm perception tasks (i.e., anisochrony detection and rhythm discrimination from the MBEA), different profiles of rhythm impairments were found (Sowiński & Dalla Bella, 2013). Unlike Mathieu, two participants were poor synchronizers to the beat of music while showing, spared beat perception. These two cases, exhibiting a selective sensorimotor integration deficit, did not show evidence of tone deafness amusia as indicated by their normal performance in the MBEA. In addition, Palmer, Lidji, and Peretz (2014) compared the synchronization to isochronous sequences with unpredictable perturbations in two beat-deaf participants, including Mathieu. They showed impaired adaptation to perturbations in an isochronous sequence in terms of error correction, associated with impaired beat perception. This result points to difficulties in coupling perception and action in beat deafness in conjunction with poor perception. Altogether, these findings raise the possibility that poor sensorimotor mapping can underpin poor synchronization in beat deafness. More generally, they show that poor synchronization may stem from different sources, resulting from the malfunctioning of different components of the rhythm system. A recent study (Mathias et al., 2016) showed that Mathieu has abnormal P3 responses to deviant omissions of the beat in a musical sequence, but not Marjorie, another beat deaf individual, suggesting that deficits in beat processing are likely to differ in their nature from one individual to the other.

The dissociation between beat perception and synchronization found in two poor synchronizers (Sowiński & Dalla Bella, 2013) is intriguing because it suggests that perception and action in the rhythm domain may be partially independent. However, task factors such as difficulty, attention, and memory demands, may contribute to explain these differences. For example, as synchronization requires both tracking the beat and generating a motor response, it may be more demanding than a simple perceptual task. More studies on beat deafness are needed to determine whether perception and synchronization may be dissociated in the domain of rhythm. If so, this would mean that the mechanisms sustain perception and action are partially independent. This point was addressed in the third study of this dissertation (Bégel et al., 2017).

2.2. Parkinson's disease

Parkinson's disease (PD) is a neurodegenerative disease characterized by major motor, cognitive, and affective impairments (Jankovic, 2008). The three cardinal motor symptoms of PD are resting tremor, limb rigidity, and bradykinesia or akinesia. This severely debilitating disease is caused by a progressive loss of dopamine-producing neurons in the substantia nigra pars compacta (Jones & Jahanshahi, 2009; Smith, Wichmann, Factor, & DeLong, 2012), a mid-brain structure that projects to the basal ganglia via the striatum. Depletion of dopaminergic neurons is responsible for the motor symptoms observed in PD as it causes disruptions of the basal ganglia-thalamo-cortical network involved in motor control.

2.2.1. Gait disorders in Parkinson's disease

Gait disorders are among the most disabling symptoms of PD as they are in part resistant to dopaminergic replacement medication in PD (L-Dopa; Blin, Fernandez, Pailhous, & Serratrice, 1991; Smith, Wichmann, Factor, & DeLong, 2012). Gait deteriorates with the progression of the disease and is characterized by reduced stride length and shuffling gait patterns (Morris et al., 2001). Patients may also experience freezing of gait, a sudden loss of the ability to start or continue walking, particularly when turning or approaching an object (Almeida & Lebold, 2010; Giladi et al., 1992), and festination (i.e., involuntary quickening of gait; Azevedo Coste et al., 2014; Bloem, Hausdorff, Visser, & Giladi, 2004). Variability of the stride-to-stride time is markedly increased in PD, yielding an arrhythmic and unsteady control of gait (Almeida et al., 2007; Hausdorff et al., 2003; Hausdorff, 2009).

2.2.2. Timing deficits in PD

As the basal ganglia-thalamo-cortical network, disrupted in PD, is involved in timing mechanisms, it is not surprising that timing deficits also arise in PD (Benoit et al., 2014; Dalla Bella et al., 2015; Grahn & Brett, 2009; Jones & Jahanshahi, 2014; Pastor, Artieda, Jahanshahi, & Obeso, 1992). Typically, PD patients exhibit impaired temporal processing in duration-based timing, both in perception (e.g., increased thresholds in duration discrimination and overestimation of durations; Artieda, Pastor, Lacruz, & Obeso, 1992; Pastor, Artieda, Jahanshahi, & Obeso, 1992) and in production of timed intervals (e.g., they tend to product longer time intervals; Pastor, Artieda, Jahanshahi, & Obeso, 1992). In perceptual beat-based timing, PD patients exhibit deficits in discrimination of rhythmic sequences (Grahn & Brett, 2009) and in extraction of the beat of music (Benoit et al., 2014). The fact that purely perceptual rhythm skills are impaired in PD shows that deficits in timing processing are not limited to impaired motor control.

PD patients have a tendency to tap less accurately to the beat than healthy subjects (Benoit et al., 2014), and display more variability than controls in self-paced tapping tasks (O'Boyle, Freeman, & Cody, 1996) and in repetitive wrist movements paced by a metronome (Pastor, Jahanshahi, Artieda, & Obieso, 1992). Nevertheless, studies reporting rhythm deficits are quite inconsistent (Ivry & Spencer, 2004; Jones et al., 2011), probably because of inter-individual differences in the duration of illness, which is a marker of disease severity (Ivry & Spencer, 2004; Jones & Jahanshahi, 2014; Merchant et al., 2008).

Notably, in general, timing skills are improved with L-Dopa. When tested in ON-state (i.e., when patients are under regular L-Dopa medication dosages), patients perform better in motor and perceptual timing tasks than when in OFF-state. They are less variable in their tapping performance (Merchant et al., 2008; O'Boyle, Freeman, & Cody, 1996; Pastor, Jahanshahi, Artieda, & Obieso, 1992), more accurate when reproducing durations (Malapani et al., 1998), and errors in the estimation of elapsed time are reduced (Pastor, Jahanshahi, Artieda, & Obieso, 1992; Rammsayer & Classen, 1997). Recently, it has been shown that patients are also better in rhythm discrimination in ON-state as compared to OFF-state (Cameron, Pickett, Earhart, & Grahn, 2016). L-Dopa compensates for the dopaminergic loss in the substantia nigra and consequently contributes to reactivating the timing and movement-related basal ganglia-thalamo-cortical network, typically malfunctioning in PD (Dalla Bella et al., 2015; Jones & Jahanshahi, 2014; Rammsayer, 1993; Smith, Wichmann, Factor, & DeLong, 2012).

2.3. Neuro-developmental disorders

Timing deficits may also arise as a consequence of neuro-developmental disorders. For instance, they occur in a wide range of language disorders. Children and adults with developmental dyslexia exhibit difficulties in perception and motor reproduction of rhythms when asked to tap to a metronome (e.g., they have a tendency to anticipate the beat by tapping too early) and when they compared two musical sequences in which accented notes differed (Huss et al., 2011; Thomson, Fryer, Maltby, & Goswami, 2006; Wolff, 2002). Similarly, children with specific language impairment (SLI), a condition in which expressive and receptive oral language is impaired, have difficulties in perceiving single durations (Corriveau, Pasquini, & Goswami, 2007) as well as in paced tapping to the beat of a metronome (Corriveau, & Goswami, 2009). Language and literacy outcomes are linked to the severity of impairment in timing processing skills in these children. For instance, performance in paced tapping to the beat in children from seven to eleven years of age with SLI is positively correlated with vocabulary (i.e., selecting a picture corresponding to a word) and reading (e.g., word and non-word reading; Corriveau, & Goswami, 2009).

There is evidence that children and adolescents who stutter may have difficulties in beat perception (Wieland, Mcauley, Dilley, & Chang, 2015) as well as synchronization to the beat of simple and complex rhythmic stimuli (Falk, Müller, & Dalla Bella, 2015). These deficits are associated with the severity of stuttering symptoms (Falk, Müller, & Dalla Bella, 2015).

Another example is provided by ADHD, which is marked by impaired timing skills both in paced and unpaced finger tapping (Toplak & Tannock, 2005; Rubia et al., 2003), and in perception of durations (Noreika, Falter, & Rubia, 2013; Toplak et al., 2003; but see Toplak, Dockstader, & Tannock, 2006). Interestingly, ADHD has been consistently associated to structural anomalies of timing and rhythm-related brain areas such as and the cerebellum (Bledsoe, Semrud-Clikeman, & Pliszka, 2011) and the basal ganglia (Ortiz et al., 2015), yielding malfunctioning in basal-ganglia-cortical connectivity and fronto-cerebellar network both in children and in adults (van Ewijk et al., 2012; Hart, Radua, Mataix-Cols, & Rubia, 2012). Thus poor beat-based timing skills in ADHD would be expected. This was tested in a recent study in our laboratory in which we examined perceptual and sensorimotor timing abilities in children and adults with ADHD (Puyjarinet et al., under revision. See Annex). To this aim, participants were submitted to tasks from BAASTA, a battery for the assessment of rhythmic skills (Dalla Bella et al., 2017a). We showed that children and adults with ADHD displayed difficulties in beat tracking, namely in perception of—and synchronization to—a musical beat. They performed poorly when asked to judge if a metronome is aligned with the beat of music or not in the BAT (see Figure 2.1) and are more variable when synchronizing with music (see Figure 2.2), as compared to age-matched healthy controls.

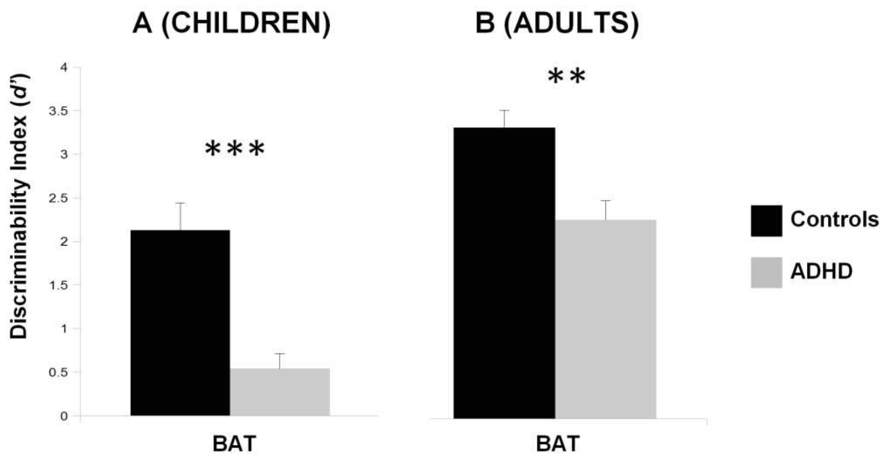

Figure 2.1. Performance of adults with ADHD and controls tested with the Beat Alignment Test (BAT). Error bars are SEM. *** $p < .0001$, ** $p < .01$.

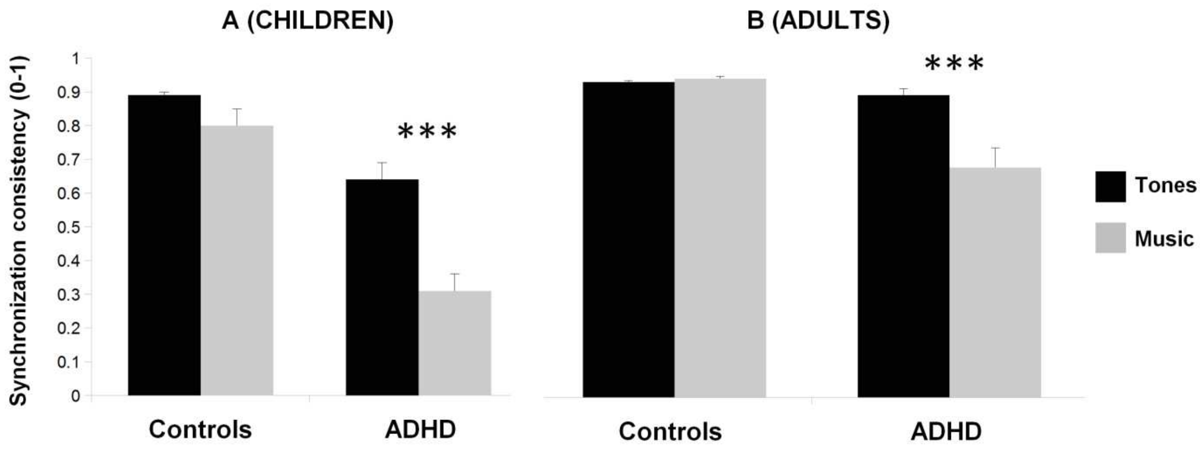

Figure 2.1. Performance of children and adults with ADHD and healthy controls when they tapped their finger to the beat of tone sequences and to music. Performance is expressed by the consistency of synchronization, from 0 to 1. Greater values indicate better synchronization to the beat. Error bars are SEM. *** $p < .0001$.

Finally, deficits in temporal processing are also found in autism spectrum disorders (ASD; Allman, Pelphrey, & Meck, 2012; Allman, 2011). Most studies on timing skills in ASD focused on duration-based timing (Allman, DeLeon, & Wearden, 2011; Wallace & Happé, 2008), showing deficits in temporal reproduction and duration perception. This is consistent with the neuronal underpinnings of ASD showing malfunctioning of the timing-related area such as the basal ganglia (Haznedar et al., 2006; Hollander et al., 2005) and cerebellum (Allen, Müller, & Courchesne, 2004). To date, little is known on beat-based perceptual and motor skills in ASD.

Chapter short summary

In this chapter, studies showing deficits in timing in different populations (beat deafness, Parkinson's disease, neuro-developmental diseases) have been reviewed. These disorders typically affect brain areas involved in perception and production of duration-based and beat-based timing, resulting in selectively disrupted timing capacities.

Moreover, evidence showing links between timing skills and other capacities such as motor control and cognitive functions have been reviewed in previous sections. One important question that follows is to what extent training timing skills could have an effect on other functions such as cognition and motor control. Long term musical training and intensive training over a short period of time as well as rhythmic stimulation are likely to be beneficial to rhythmic skills, with a potential positive effect on cognition and motor skills.

3. **Chapter 3**. Training rhythmic skills

Given the aforementioned links between rhythmic and cognitive skills, one may expect that training rhythmic skills may foster improvements of more general cognitive abilities. As rhythm is typically an important component of musical training and musical expertise, studies comparing musicians and non-musicians are likely to shed light on the effect of rhythmic training conveyed via musical training. Below I will review the studies that tested the effect of music training over short periods of time. Second, I will consider studies investigating the differences between long-term trained musicians and non-musicians. Finally, studies on the effect of rhythmic training in the context of rehabilitation or remediation will be considered.

3.1. Musical training

Learning rhythmic structures is part of musical training, even though this form of training is more general and not specifically targeted toward rhythm in particular. It has been shown that music training including rhythm, pitch, melody, voice, and basic musical concepts displayed over a short period of time has positive effects on verbal intelligence and executive function (Moreno et al., 2011). A couple of longitudinal studies have focused on the effects of musical training on language, literacy, and phonological skills (for a review, see Gordon, Fehd, & McCandliss, 2015). For instance, in healthy children, music training over a period of two years has proved to be better than painting training for the acquisition of speech segmentation skills (François, Chobert, Besson, & Schön, 2013). In children with neurodevelopmental disorders, Flaugnacco et al. (2015) showed that reading and phonological abilities in children with dyslexia were improved after a five-week musical training program with a specific focus on rhythm (e.g., rhythmic body movements accompanying music, sensorimotor synchronization games) as compared to a painting training. Attempts to test the effect of pure rhythmic training on literacy outcome measures in dyslexia have been made, yielding encouraging results (Thomson, Leong, & Goswami, 2013). Poor readers may also benefit from musical intervention, as a music training based on rhythm and a method based on rhyme training was proven efficient in improving reading and phonological skills (Bhide, Power, & Goswami, 2013).

Music training in patient populations with neurologic disorders is mostly confined to enhance movement capacities using instrument-based interventions (e.g., learning piano melodies) in stroke (Altenmüller, Marco-Pallares, Münte, & Schneider, 2009; Moumdjian et al., 2016; Ripollés et al., 2015) or multiple sclerosis (Gatti et al., 2015). One feasibility study

(Pohl, Dizdar, & Hallert, 2013) assessed the effect of a music training program (Ronnie Gardiner Rhythm and Music [RGRM]™) composed of rhythmical exercises like clapping to music in PD, suggesting that the intervention improves movement and cognition. In sum, recent evidence points toward a positive effect of music training on movement capacities in patients with neurological disorders.

It is not totally surprising that musical training boosting cognitive and movement skills may rely on rhythmic exercises. Indeed, in order to observe a transfer effect from a trained capacity to a non-trained one, overlapping processing components that are sustained by shared neural processes are needed (Moreno et al., 2011; Jonides, 2004). In the previous sections of the dissertation, I provided evidence that rhythm and cognitive capacities such as language may by underpinned by some shared processing components (i.e., neuronal oscillations that encode incoming information; Morillon, Hackett, Kajikawa, & Schroeder, 2015). However, it is important to note that mechanisms other than rhythm can explain the effect of musical training, such as arousal, motivation, and emotional engagement (Schellenberg, 2011; Ullén, Söderlund, Kääriä, & Madison, 2012).

3.2. Musical expertise

For decades, the musician's brain has been studied to investigate cerebral plasticity resulting from the acquisition of skilled performance and abilities (Schlaug, 2001; Dalla Bella, 2016). Musicians' skills include enhanced rhythm perception and production (Chen, Penhune, & Zatorre, 2008; Matthews, Thibodeau, Gunther, & Penhune, 2016; Repp, 2010) as well as better temporal processing in a non-rhythmic context (Repp, 2010; van Vugt, & Tillmann, 2014). In a recent study, we compared rhythmic skills of 40 musicians and 40 non-musicians (Dalla Bella et al., in preparation) using BAASTA (Dalla Bella et al., 2017a). In most of the tasks, results showed better performance in musicians than in non-musicians.

These differences between musicians and non-musicians are underpinned by brain changes in areas and mechanisms typically sustaining cognitive and motor functions well beyond music processing. Neuronal underpinnings of musicianship include increased cortical matter in selective regions of the brain (auditory and parietal cortex—Gaser & Schlaug, 2003; motor cortices—Elbert et al., 1995; cerebellum—Hutchinson, Lee, Gaab, & Schlaug, 2003; planume temporale—Keenan, Thangaraj, Halpern, & Schlaug, 2001; Zatorre et al., 1998; corpus callosum—Schlaug et al., 1995). Note that these structural changes relate to the age at which musical training begins and its intensity (Gaser & Schlaug, 2003; Zatorre, Chen, &

Penhune, 2007). It has been shown that these changes do not stem from pre-existing or innate differences (Norton et al., 2005), but individuals' predisposition to the anatomical and functional properties of neural architecture might also play a role in learning musical skills (Dalla Bella, 2016; Zatorre, 2013). Electrophysiological brain response differences between musicians and non-musicians have also been reported (e.g., faster timing brainstem response to a speech presented in a noisy background; Parbery Clark, Skoe, & Kraus, 2009; see also Chobert et al., 2011; van Zuijen et al., 2005). Because of instrumental musical training, sensorimotor integration, necessary for synchronizing movements to sounds, as well as the capacity to perform complex motor sequences and fine-grained finger movements, are better developed in musicians (for reviews, see Herholz & Zatorre, 2012; Zatorre, Chen, & Penhune, 2007).

It turns out that some neural pathways that are recruited to process sounds are relevant for both music and language; thus, musical practice and training bring about effects visible in both domains (François & Schön, 2007; Strait & Kraus, 2011, 2014). Musicians' capacity to discriminate pitch discrepancies and temporal gaps between sounds better than non-musicians (Parbery-Clark et al., 2011; Strait, Kraus, Parbery-Clark, & Ashley, 2010) extend to language (Magne, Schön, & Besson, 2006). For example, musically trained children and adults show an advantage for processing speech in noise (Parbery-Clark, Skoe, & Kraus, 2009; Parbery-Clark, Skoe, Lam, & Kraus, 2009). These enhanced capacities for language processing in musicians may be rooted in their improved skills in auditory attention and working memory (Kraus & Chandrasekaran, 2010; Pallesen et al., 2010; Strait, Kraus, Parbery-Clark, & Ashley, 2010). Moussard and collaborators (2016) found a reduced error rate in musicians in a go/no-go task, suggesting that they have better executive control (see also Schroeder, Marian, Shook, & Bartolotti, 2015). This result was correlated with event-related potential recordings (i.e., larger N2 and P3 effects), confirming that brain changes sustain the behavioral gains observed in musicians.

3.3. Rhythmic training

In the previous section, I reviewed the studies that were likely to train rhythm and timing skills among other capacities as part of music training. A few examples of the benefits of protocols based on rhythmic stimulation to train patients' cognitive and motor capacities also exist.

A good model of the beneficial effects of rhythmic training is Parkinson's disease. Previously, I reviewed the studies showing that PD patients had deficits in timing in general, and more specifically in beat tracking. In PD, non-pharmacological treatments for improving gait, such as physiotherapy exercises, strength training, or dance interventions, have been proposed to compensate for the limited effects of dopaminergic treatment (Bloem, de Vries, & Ebersbach, 2015). Among the non-pharmacological approaches, rhythmic auditory stimulation (RAS) can be used as a tool to retrain gait in Parkinson's disease and has been given much interest over the past twenty years (Benoit et al., 2014; Dalla Bella et al., 2015; Thaut et al., 1996; for reviews, see Lim et al., 2005; Nombela, Hughes, Owen, & Grahn, 2013; Spaulding et al., 2013). RAS consists of presenting a rhythmic stimulus with an underlying beat (e.g., a metronome or music) to a patient when he is walking in order to provide cues that inform when a movement should be executed. Beneficial effects of RAS on spatio-temporal features of gait are visible during and immediately after a single auditory cueing session. RAS increases gait speed and step length in most PD patients (Howe et al., 2003; McIntosh, Brown, Rice, & Thaut, 1997; Rubinstein, Giladi, & Hausdorff, 2002; Spaulding et al., 2013). It also reduces gait variability (Hausdorff et al., 2007) or reinstates normal gait variability patterns (i.e., natural fractal 1/f structure; Hove et al., 2012; Dotov et al., 2017). Extended rehabilitation programs using RAS over periods of up to several weeks have been proven to have carry-over effects on gait in everyday life (Benoit et al., 2014; Dalla Bella et al, 2017b; Rochester et al., 2010; Thaut et al., 1996). However, the effects are highly variable among patients and are likely to be linked to sensorimotor skills, as the success of RAS can be predicted by the severity of gait impairment and by the possibility that some rhythmic skills may still be spared in some patients (Dalla Bella et al., 2017b). Note that the effect of RAS in PD is not limited to the improvement of gait parameters. There is some evidence that the motor control of speech, which is impaired in PD (Lieberman et al., 1992) mostly due to disrupted speech timing control mechanisms (Ludlow, Connor, & Bassich, 1987), can also be enhanced by RAS, ultimately improving speech intelligibility (Thaut, McIntosh, McIntosh, & Hoemberg, 2001).

Neuronal underpinnings of RAS are still poorly understood. A neuro-functional model of temporal processing and predictive coding of events has been put forward to account for RAS (Dalla Bella et al., 2015; Kotz & Schwartze, 2010; Schwartze & Kotz, 2013). This model assumes a stimulation-driven allocation of attention toward relevant points in time, ultimately fostering movement planning based on temporal prediction (Kotz & Schwartze, 2011; Schwartze & Kotz, 2013). Temporal prediction is the estimation of when an event occurs and requires an internal representation of the temporal structure of events (Schwartze & Kotz, 2013). Two distinct neuronal networks are deemed to sustain temporal prediction (Figure 3.1). The basal ganglia-thalamo-cortical network is involved in action initiation and explicit timing. It is affected in PD (Jones & Jahanshahi, 2014; Teki, Grube, Kumar, & Griffiths, 2011; see above, **Chapter 2** [2.2]). The second network is the cerebello-thalamo-cortical network, involved in the encoding of duration-based temporal structure and in synchronization of motor response to exogenous cues (Bengtsson, Ehrsson, Forssberg, & Ullén, 2005; Coull & Nobre, 2008; Grube, Cooper, Chinnnery, & Griffiths, 2010; Provasi et al., 2014). The residual activity of the basal ganglia-thalamo-cortical network, driven by the stimulation, is possibly responsible for the beneficial effects of RAS in PD. Alternatively, a compensatory mechanism sustained by the cerebello-thalamo-cortical network, which is spared in PD, is likely to take over on the basis of external temporally predictable cues that generate temporal expectations (Dalla Bella et al., 2015; Sen et al., 2010; Del Olmo et al., 2006).

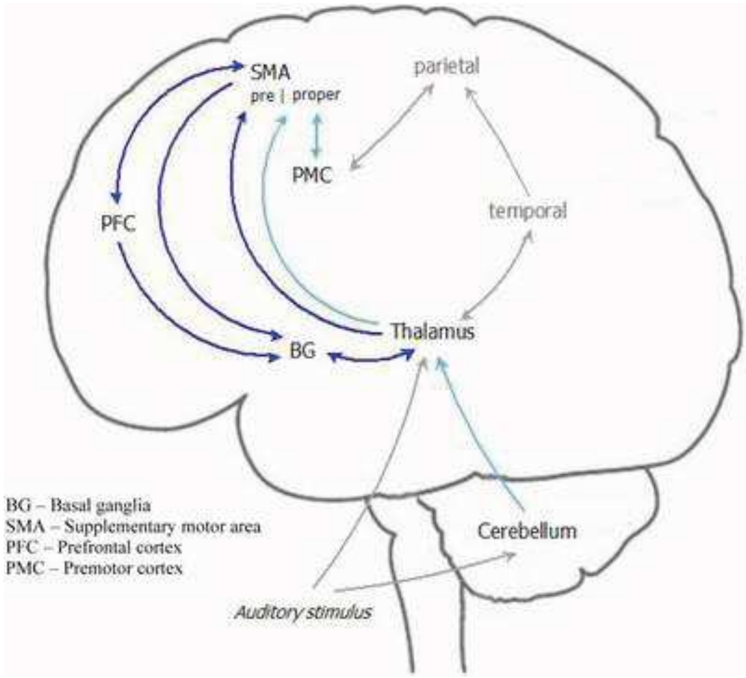

Figure 3.1. From Dalla Bella et al. (2015). Representation of the basal ganglia–thalamo-cortical and the cerebello-thalamo-cortical networks involved in RAS in Parkinson's disease. Blue arrows represent the basal ganglia–thalamo-cortical circuitry impaired in PD, whereas cyan highlights the cerebello-thalamo-cortical network which is likely to be recruited during RAS. Gray indicates additional circuitry involved by auditory cueing but not part of the compensatory network *per se*.

Note that the effect of rhythmic stimulation on gait has also been showed with visual (Morris, Iansek, Matyas, & Summer, 1996) and tactile (Ivkovic, Fisher, & Paloski, 2016; van Wegen et al., 2006) stimuli. However, it seems that the auditory modality is the most efficient (Lim et al., 2005; Spaulding et al., 2013).

Parallel to PD, RAS is successfully used to re-train movement in other patient populations (for a review, see Thaut & Abiru, 2010). RAS in rehabilitation of stroke patients improves gait parameters such as symmetry and stride length, the balance of muscular activation patterns, and the bearing time on the paretic side (Ford, Wagenaar, & Newell, 2007; Prassas, Thaut, McIntosh, & Rice, 1997; Thaut, McIntosh, Rice, & Prassas, 1993). Long-term effects of rehabilitation programs as a result of a training using RAS have been demonstrated (Thaut et al., 2007). Upper limb movement amplitude (arm swing) during walking is increased when the patient is asked to synchronize his arm movement to a metronome (Ford, Wagenaar, & Newell, 2007). The effect of rhythmic stimulation on arm movement extends to specific arm function. Indeed, post-stroke paretic upper limb motor performance is increased by arm training with RAS (Luft et al., 2014; Whitall et al., 2000).

Finally, gait facilitation using RAS has also been shown in patients with traumatic brain injury (Hurt, Rice, McIntosh, & Thaut, 1998), in children and adults with cerebral palsy (Kim et al., 2011), and in multiple sclerosis (Conklyn et al., 2010). Finally, in recent studies, stimulation of speech with rhythm yielded promising results. Rhythmic speech cueing (Mainka & Mallien, 2014) consists of aligning speech with an auditory (metronome or rhythmic sequence) or visual stimulation in order to control speech rate and is a way to treat dysarthria (e.g., in PD or in traumatically brain injury; Pilon, McIntosh, & Thaut, 1998; Thaut, McIntosh, McIntosh, & Hoemberg, 2001). In addition, it is possible to boost performance by using regular sequences as primes before a language task. Przybylski and collaborators (2015) presented either regular or irregular rhythmic sequences before grammatically correct or incorrect sentences. They showed that children with specific language impairment and with dyslexia, as well as healthy controls, judged better if the sentence was correct or not when the priming sequence was regular. The priming effect of a beat-based regular rhythmic sequence was also found in a task of association between target phonemes and pseudo words in healthy adults (Cason & Schön, 2012). The authors showed a reduced reaction time when the pseudo words' beat and meter matched the ones of the priming sequence. This effect was furthermore enhanced when participants received a sensorimotor training beforehand (Cason, Astésano, & Schön, 2015). The different electrophysiological responses to phonemes, namely, flattened P300 response to off-beat phonemes and enhanced N100 response to metric mismatch, were also tagged with EEG (Cason & Schön, 2012).

Notably, rhythmic training may also play an important role for the rehabilitation of speech in patients with non-fluent aphasia. A common method for the rehabilitation of post-stroke aphasia is melodic intonation therapy (Norton, Zipse, Marchina, & Schlaug, 2009; Sparks, Helm, & Albert, 1974), a treatment that uses singing to recover speech capacities. Stahl and collaborators (2011) conducted a study on 17 non-fluent aphasics and showed that production of rhythmic speech was better than production of arrhythmic speech. The authors claimed that the effect of rhythm has been neglected in melodic intonation therapy in speech recovery, especially in patients with basal ganglia lesions. They concluded that rhythmic stimulation, such as rhythmic hand tapping performed while talking, could be sufficient in language rehabilitation. These results pave the way to the development of new rhythm-based interventions in aphasia therapy and in other conditions in which speech is impaired, such as PD, dyslexia, specific language impairments, or stroke (Kotz & Gunter, 2015; Kotz & Schmidt-Kassow, 2015; Schön & Tillmann, 2015).

Chapter short summary

To summarize, a substantial body of studies in several domains such as rehabilitation and music training points toward a beneficial effect of rhythm on behavior and brain plasticity. Motor capacities and language are likely to be improved by rhythmical stimulations. On top of that, musical training over a period spanning from several weeks to several years or decades have been proven to boost cognitive skills such as language, literacy, attention, and executive control. However, it is important to note that, to the best of our knowledge, there are no studies that assessed the effect of a training protocol that targets selectively rhythmic skills, i.e., a rhythmic training displayed independently on training of other skills such as gait or speech.

4. **Chapter 4**. Rhythm training by the means of serious games

The development of digital technologies in the last few years opens up new avenues for devising training and rehabilitation protocols. In this regard, serious games implemented on digital platforms (e.g., tablets, consoles) represent a good example of low-cost and accessible ways to provide dedicated training in an entertaining and motivating fashion (Annetta, 2010; Kato, 2012). In addition, the growth of music multimedia technologies (e.g., digital formats such as WAV or MIDI) has provided an unprecedented way to engage people in interactions with music (music mediation technology; Leman, 2008). Altogether, new possibilities to study music cognition through music-triggered movements recorded with digital technologies are emerging (Leman, 2010). In this context, using multimedia technologies to implement rhythmic training protocols is highly relevant.

This section aims at presenting what is a serious game and how it can be used to train specific skills. On top of that, I review the games readily available in the market that can potentially serve as useful tools for rhythmic training. The peripheral used to capture and record the response, the type of response, and the output measure served as criteria to assess whether they are well-suited for rhythmic training.

4.1. Serious games[1]

A serious game is a game designed specifically for training and education purposes, such as providing a dedicated training for rehabilitation/remediation, in an entertaining and motivating fashion, while being widely accessible to the targeted public and remaining low-cost (Annetta, 2010; Kato, 2010). A great deal of work over the last two decades has been devoted to devise and promote games for training patients and for rehabilitation. This stream of research has been encouraged by low-cost and widespread new technologies offering unprecedented opportunities to implement training protocols. An increasing number of technologies are designed to improve health and well-being, from smartphone applications to control dietetics (Withings *Wi-Fi Scales*) to movement-based rehabilitation tools using motion capture (Chang, Chen, & Huang, 2011; Weiss, Sveistrup, Rand, & Kizony, 2009; Zhou & Hu, 2008). Among them, video games provide a way to entertain people while targeting serious goals, such as the rehabilitation of impaired movement skills (e.g., *Hammer and Planks,* Di

[1] This Chapter was published as a review paper in *Frontiers in Human Neuroscience.*
Bégel, V., Di Loreto, I. Seilles, A., & Dalla Bella, S. (2017). Music games: potential application and considerations for rhythmic training. *Frontiers in Human Neuroscience, 11*, 273.

Loreto, Lange, Seilles, Andary, & Dyce, 2013; *Nintendo Wii* games, Saposnik et al., 2010) or cognitive re-entrainment (e.g., *RehaCom*, Fernández et al., 2012) in neurological diseases (for a review and classification of serious games in health, see Rego, Moreira, & Reis, 2010). In particular, movement-based rehabilitation games exploiting motion capture devices such as the *Wii* or the *Kinect* are a promising way to use technology in the context of re-education (for a review, see Webster & Celik, 2014). This method is referred to as "Exergaming". Note that video games for entertainment may also be used in a serious manner. For example, off-the-shelf video games are often used by physicians for therapeutic purposes, such as *Nintendo Wii* or *Kinect* games (Barry, Galna, & Rochester, 2014; Karahan et al., 2015; Lange, Flynn, & Rizzo, 2009). Exergaming has been proven efficient in several pathologies such as stroke (Webster & Celik, 2014), Parkinson's disease (Harris, Rantalainen, Muthalib, Johnson & Teo, 2015) as well as in healthy elderly (Sun & Lee, 2013).

During the past few years, studies have focused on the cognitive and neuronal underpinnings of the benefits of health-targeted serious games (Connolly, Boyle, MacArthur, Hainey, & Boyle, 2012). On top of the physical and physiological benefits associated with serious games (e.g., via dedicated physiotherapeutic exercises), the effects of this type of training extend to cognition. Cognitive functions such as language and memory can also be enhanced by serious games (for review, see Wouters, van Nimwegen, van Oostendorp, & van der Spek, 2013), an effect which is likely to be accompanied by plastic changes of the brain. For example, structural brain changes associated with learning have been observed due to the use of videogames (Anguera et al., 2013; Kühn, Gleich, Lorenz, Lindenberger, & Gallinat, 2014). These promising results indicate that implementing training protocols via serious games may be particularly valuable for enhancing brain functions as well as for therapy and rehabilitation.

In summary, serious games are promising tools that can be exploited to improve or retrain movement and cognition. A training of rhythm skills implemented in a serious game would be a mean to set up training protocols which may serve rehabilitation of different patient populations. The aim of the next section is to provide an overview of the existing rhythm games and to assess whether they could be well-suited for training purposes. We conducted a survey in which we used criteria such as the precision of the recorded response or the modality of the stimuli provided to evaluate benefits and limitations of each game.

4.2. Limits and advantages of the existing games

To the best of our knowledge, only one music-based training program that uses a game setting has been successfully devised for arm rehabilitation in stroke patient (Friedman et al., 2014; Friedman, Reinkensmeyer, & Bachman, 2011). However, this protocol is not training rhythmic skills *per se* but is rather a music-based adaptation of a standard rehabilitation protocol (i.e., conventional tabletop exercises therapy, Dickstein, Hocherman, Pillar, & Shaham, 1986). To examine whether existing games involving rhythm conveyed by auditory stimuli could be potentially used as training tools, we selected games based on the following inclusion criteria. First, the game has to **focus on rhythmic skills**. The player must be instructed to synchronize movement (or voice) with stimuli (auditory or visual) which can be predicted on the basis of their temporal structure (e.g., an underlying beat). To our knowledge, no rhythm games currently on the market use purely perceptual tasks, in which the player's task is to judge the rhythmic features of music. All the games presented below involve movement synchronized to auditory or visual cues. Second, the game device must **record the temporal precision of the player's responses**. The scores, levels, difficulty and feedback given to the player must depend on her/his temporal precision in performing the movement. Once the games were selected, they were categorized by (a) the **peripheral** used to capture and record the response, (b) the **type of response** that is recorded, and (c) the *output*. The peripheral is important to judge if the game is readily usable for training (e.g., in a clinical context). In addition, note that most of the studies in cognitive psychology of rhythm use finger tapping, since this is a simple and objective way to study rhythmic skills (Repp, 2005; Repp & Su, 2013), but other reponses are possible (e.g., full-body motion). Finally, the output is relevant as it indicates whether the games provide an outcome measure or score on the precision of the performance reflecting a participant's rhythmic skills. These categories are helpful for evaluating the therapeutic potential of each game. For example, a game requiring finger tapping is likely to have a different effect on behavior than a game requiring full body motion, such as dance.

Twenty-seven games on a variety of devices (Wii, PlayStation, PC, Tablet/Smartphone, Xbox, Gameboy) fulfilling the aforementioned criteria were considered for the analysis (see Table 4.1). These games were classified in 4 categories as indicated below.

4.2.1. Games that involve full-body movement recorded via an external interface (e.g., Kinect, Wii)

Here we refer mostly to dance games (e.g., *Just Dance*). These games have interesting applications in physiotherapy for patients with spinal cord injury, traumatic brain injury and stroke (Lange, Flynn, & Rizzo, 2009). They focus more on physical exercise and activity than on rhythm *per se*. Indeed, the ability of these games to record and score the rhythmic precision of the player is rather poor. Because these games focus on discrete movements/actions instead of repeated movements (i.e., rhythmic) they cannot be used for delivering specific training of rhythmic skills. For example, *Just Dance* consists in reproducing movements that are illustrated through images displayed on the screen. The player's score depends on the precision of the movements as compared to a model action sequence. The player has to execute the movements in a given temporal window. Yet, the task is not purely rhythmic and synchronization to the musical beat is not recorded. In spite of the fact that these games do not measure rhythmic skills *per se*, they provide a motivating setting to perform dance while monitoring the player's movements. Adding a rhythm component to some of these games, as in the case of dance, may be a valuable strategy to translate them into a training program.

4.2.2. Games that involve rhythmic finger tapping on a tablet

An example of these games is *Beat Sneak Bandit*. Here, the player has to tap precisely to the beat in order to make the character progress, avoid the enemies, and so forth. This kind of feature is used in serious games dedicated to learning, such as *Rhythm Cat*, designed to learn music rhythm notation. For the purposes of training rhythmic skills, one major drawback of these games is that the timing precision of the software is very poor. The time window in which a response is considered as good is very wide (i.e., up to several hundreds of milliseconds) and the temporal variability of the recording is high. In addition, no output of the rhythmic performance of the player is provided.

4.2.3. Computer or console games that involve finger tapping on keys

These games can be played on a keyboard, using a joystick, or on special devices. One of the most famous is *Guitar Hero.* In this game the player plays on a guitar replica with five keys, and has to push the keys in correspondence of images presented on a screen. Rhythm precision of the responses is recorded and used to compute a performance score. The response must appear in a specific temporal window to be considered as good. The same concept is used in many PC games, but keyboards key (e.g., arrows) are used instead of guitar replica. As in the case of tablet games, the main weakness of these games is their low temporal precision in recording rhythmic performance (around 100 ms in *Guitar Hero*). Nevertheless, these games are interesting as they represent a good starting point to develop serious-game applications aimed at training rhythmic skills.

4.2.4. Console games involving singing (e.g. *Sing Star*)

In these games, the player is asked to sing in synchrony with the music. This is not a rhythmic task *per se*, but the performance involves a rhythmic component. As in classical karaoke, lyrics are presented on the screen. In this case, a feedback (score) is provided to the player while she/he sings and a final global score is given at the end of the performance, including temporal precision (the response must appear in a given temporal window to be considered as good) but also pitch precision. Here, the potential benefit for health rests upon the fact that singing is a good way to restore speech abilities (e.g., fluency) in aphasia following stroke (see for example Norton et al., 2009).

Even though some of the aforementioned games present good ground for training rhythmic skills, their main drawback is that their temporal precision when recording movement relative to the beat is rather poor. Thus, the output measures provided by these games are insufficient to isolate rhythmic features of the performance (e.g., variability of the motor performance, precision of the synchronization with the beat, etc.). Moreover, in none of these games the rhythmic complexity of musical stimuli has been manipulated. Difficulty is manipulated only through the amount of responses required during the game (e.g., number of visual tags which the player has to react to) which is not a rhythmical feature. For example, using music with various degree of beat saliency would allow introducing rhythm-based difficulty levels in the game. This has the advantage that rhythms with increased complexity could be trained progressively throughout the game, thus potentially leading to improved beat-tracking skills.

Table 4.1. Classification of rhythm-based games based on 3 criteria (peripheral, modality of the stimuli, type of response recorded). The last row concerns online PC games (available at http://www.musicgames.co/games-by-category/rhythm-games/) having similar characteristics.

Game	Peripheral	Type of response recorded	Output
Dance Dance Revolution /Dancing Stage	Dance Pad (PS2, PC)	Impacts of feet (PS2)/fingers (PC)	Incrementing score
Donkey Konga	Bongos	Impacts of Hands	Incrementing score
Dancing With The Star	Wiimote, Nunchuk (Wii), keyboard (PC)	Hands movement (Wiimote), Key tapping (PC)	Incrementing score
DJ Hero	Turntable Replica (Wii, PS 2 & 3, Xbox 360)	Hands and fingers movement on the Turntable	Incrementing score
Everyone sing	Microphone (Wii, PS 3, Xbox 360)	Voice	Incrementing score
Guitar Hero	Guitar replica, joystick (Wii, PS 3, Xbox 360), keyboard (PC), screen (tablet, Androîd)	Left-hand key tapping, right-hand key moving up and down (Wii, PS3, Xbox 360), screen tapping (tablet), Joystick button pressing (Wiimote, pS3, Xbox 360)	Incrementing score
Just Dance	Wiimote (Wii), PS camera, PS move (PS4, PS3), Kinect (Xbox 360, Xbox one)	Hand movement (Wiimote), all-body movement (PS move, PS camera, Kinect)	Incrementing score
Rhythm Paradise (USA: Rhythm Heaven Fever)	Nintendo DS, Wiimote	Finger tapping on the screen, hand movement (stylus) (DS), key tapping (Wii)	Incrementing score
Rock Band	Guitar, Drums replica, Microphone (Wii, Xbox 360, PS3), Tactile screen (Iphone, Ipod Touch), Nintendo DS, PSP	Left-hand key tapping, right-hand key moving up and down (mediator-like), feet impact (bass drum), drumsticks impact (Wii, PS3, Xbox 360, Nintendo DS, PSP), screen tapping (Iphone, Ipod), Joystick button	Incrementing score

		pressing (Wiimote, pS3, Xbox 360), voice (microphone)	
140	Keyboard (PC)	key pressing	Progression in a level
Osu	Mouse (PC)	key pressing	Incrementing score
Beatmania	Turntable Replica (Arcade, PS1, PS2), Nintendo Gameboy	Hands and fingers movement on the Turntable (Arcade, PS1, PS2), key pressing (Gameboy color)	Incrementing score
Patapon	PSP	Key tapping	Progression in a level
Rhythm Cat	Tablet, Smartphone	Screen tapping, holding, swiping	Incrementing score
Groove Coaster Zero	Tablet, Smartphone	Screen tapping, holding, swiping	Incrementing score
IgoBeat	Tablet, Smartphone	Screen tapping, holding, swiping	Incrementing score
Beat Brite	Tablet, Smartphone	Screen tapping, holding, swiping	Incrementing score
Online PC Games	keyboard	Screen tapping	Progression in a level/ Incrementing score

4.3. Discussion and summary of the Chapter

We reviewed 27 rhythm-based games already in the market that could be used in a rhythmic training protocol. Unfortunately, based on our criteria, none of the aforementioned games is satisfying for this purpose. First, in most of the games, the task consists in reacting to visual stimulations while music is presented. Thus rhythmic skills are not selectively trained. Second, the number of stimuli, instead of the rhythmic characteristics of the music, is varied to change the difficulty of the game. Third, in spite of the fact that the regularity of rhythmic patterns can influence the performance in the game, the response provided by the player is not targeted at the rhythmic aspects of the stimuli. For example, the player touches the screen at the right moment to catch objects or makes full-body movements to imitate model-actions in dance games. In addition, note that the reviewed games do not offer opportunities for controlled functional movement training. For example, none of them provide a guidance to achieve desired movement trajectories. This problem may be overcome in the future by providing relevant feedback when the player approaches optimal movement trajectories (e.g., via sonification, Effenberg et al., 2016). The tasks implemented in these games are vaguely reminiscent of implicit timing tasks (Lee, 1976; Zelaznik, Spencer & Ivry, 2002; Coull & Nobre, 2008). Explicit and implicit timing have been treated as relatively independent processes in cognitive neuroscience (Coull & Nobre, 2008, Coull, Cheng, Meck, 2011; Zelaznik, Spencer, & Ivry, 2002). The former is associated with tasks requiring voluntary motor production (e.g., synchronized tapping tasks; Repp & Su, 2013; Repp, 2005) or overt estimation of stimulus duration (e.g., Duration Discrimination; Grondin, 1993). In contrast, implicit timing is tested with tasks unrelated to timing (e.g., avoiding a vehicle when crossing the road), but in which temporal prediction affects the performance (judging the time before the vehicle reaches us, Lee, 1976; for more details, see Coull & Nobre, 2008; Coull, 2009; Nobre, Correa, & Coull, 2007). In particular, temporal prediction fostered by a regular temporal pattern (e.g., a metronome) of sensory stimuli improves performance in non-temporal tasks (e.g. working memory, Cutanda, Correa, & Sanabria, 2015; pitch judgment, Jones, Moynihan, MacKenzie, & Puente, 2002; language judgments, Przybilsky et al., 2013).

Despite the available music games are not explicitely targeted at rhythmic training, they may still foster training timing implicitly, in combination with other more explicit processes (e.g., focusing on spatial and pitch accuracy). There is evidence that the implicit dimension of timing may be more robust than explicit timing, for example in beat deafness (Bégel et al., 2017). It is possible that participants with timing disorders (e.g., Parkinson's disease or developmental stuttering; Falk, Müller & Dalla Bella, 2015; Grahn & Brett, 2009) may still be able to capitalize on partly spared implicit timing functions to re-learn rhythmic skills via a training program. Note, however, that so far beneficial effects of rhythm-based training protocols typically made use of explicit timing tasks (e.g., walking with an auditory rhythm; e.g.; Benoit et al., 2014; Lim et al., 2005, Spaulding et al., 2013). This may suggest that tasks which recruit explicit timing mechanisms may be a particularly good candidate to build a successful protocol for rhythmic training. In only one the the reviewed games (*Beat Sneak Bandit*), the goal is to tap to the beat of music, which is an explicit timing task. In sum, almost all of the reviewed games do not require participants to perform explicitly rhythmic tasks. Yet, they are likely to engage implicit timing mechanisms. Whether training rhythm implicitely in the context of a music game can lead to positive effects comparable to those found with explicit rhythmic tasks deserves further enquiry.

Chapter short summary

In summary, the games currently on the market, albeit they are not optimal for rhythmic training, provide at least interesting ideas that might pave the ground to devise successful training programs. Games on portable devices (e.g., tablets or smartphones) using tapping to the beat provide the simplest solution to implement a rhythm training protocole. They are low-cost while offering a motivating and user-friendly environment to train rhythmic skills with a playful interface. Although this solution has some potential, there are two problems, encountered in the available games, that will have to be solved. The precision of movement recording relative to the beat, and the ensuing measures of rhythm precision, need significant improvement. To deal with the first issue, methods used to analyze synchronization to the beat in the neurosciences of rhythm (Dalla bella et al., 2017a; Kirschner & Tomasello, 2009; Pecenka & Keller, 2009; Woodruff Carr et al., 2014) should be applied to games designed for rhythm training. This will ensure that a precise feedback on the rhythmic performance can be provided and that the stimuli and game progression can be tailored to individual learning curves. Moreover, to ensure that the training program specifically targets rhythmic skills, stimulus (or response) will have to be varied in rhythmic difficulty. This can be achieved, for example, by selecting musical excerpts based on their rhythmic complexity. Using stimuli with increasing difficulty in beat tracking (e.g., with a less salient beat) throughout the game might allow to progressively fine tune the player's rhythmic skills. These guidelines should be taken into account to devise efficient protocols for training rhythmic skills.

Summary of the theoretical section

In the review of studies presented above, a clear link between rhythmic skills and other abilities such as language and movement has been highlighted. Rhythmic abilities consist of multiple facets assessed with a variety of tasks, yielding different individual profiles in both healthy and patient populations. On top of that, previous studies point to beneficial effects of rhythmic stimulation on movement and cognition, suggesting that a pure rhythmic training is likely to have positive consequences for health and well-being, such as promoting an active lifestyle, reducing motor and cognitive decline in patient populations, or reducing the need for healthcare services. However, to the best of our knowledge, to date no training protocol has been designed to train rhythm skills selectively, independently of other skills. We propose that this could be done by the means of a serious video game. We reviewed the games readily available on the market that can potentially serve as useful tools for this purpose. None of them provide sufficient temporal precision in stimulus presentation and/or data acquisition. In addition, games do not train selectively rhythmic skills. Thus, we argue that a serious game for the training of rhythm skills should be designed following the guidelines that are provided above.

Goals of the present dissertation

The first goal of this dissertation is to improve knowledge of inter-individual differences by evaluating rhythm skills in the healthy population in order to better understand the mechanisms underlying rhythmic skills. To this aim, I used the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA) and an implicit timing task to systematically test and characterize subjects' perceptual and sensorimotor timing skills. I expected that BAASTA would be efficient to evaluate different facets of rhythmic skills, especially by proving high sensibility to inter-individual differences. Study 1 (**Chapter 5**) presents the methodology of the BAASTA and a proof of concept study on 20 healthy young adults. Study 2 (**Chapter 5**) is a test-retest study over a period of 15 days on older adults to evaluate the reliability of the battery. Finally, in Study 3 (**Chapter 5**) I present the cases of two beat-deaf individuals tested with BAASTA and show specific patterns of impaired rhythmic skills (i.e., poor rhythm perception and spared synchronization to the beat in explicit timing tasks, while showing spared implicit timing capacities).

The second goal of the dissertation is to devise and provide preliminary testing of a serious game for training rhythmic skills (*Rhythm Workers*). Study 4 (**Chapter 6**) included two experiments. The first experiment served to select the musical material, with the goal of selecting musical excerpts with increasing rhythmic complexity. The second experiment includes a description of a training protocol based on *Rhythm Workers*. The protocol was tested in a proof of concept study in which I tested the effect of a 2-week training with the game on rhythmic abilities as well as the compliance and motivation in playing the game on 20 healthy young adults.

Experimental section

Introduction to the experimental section

The experimental section is divided into two parts: the first part consists of the **evaluation** of rhythm and timing skills and the second part deals with the **training** of these skills.

The first part includes Studies 1, 2 and 3. **These studies were designed to assess timing and rhythm skills** in the general population with a particular attention to individual differences. In the previous sections, I provided evidence that rhythm skills are likely to be rooted in human biology and that they are linked with cognitive functions (language, reading, attention and executive functions) and movement. These skills may be disrupted by neurological and neuro-developmental disorders. However, methods, tools and tasks used to evaluate rhythmic skills are not homogeneous in the literature. Therefore, developing systematic tools to assess rhythm skills is highly relevant, both for identifying different profiles of impairment and for devising the appropriate treatment (e.g., by rhythmic training). For this purpose, we developed the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA), a battery that aims at thoroughly characterize individual differences in timing and rhythmic skills. BAASTA methodology is presented in Study 1, along with a pilot study in a group of 20 young adults. I hypothesized that BAASTA can provide a profile of participants' timing and rhythm abilities capable to capture individual differences in the temporal domain.

The battery was then submitted to a test-retest validation study in a group of 20 older adults (Study 2). This step is crucial to demonstrate that BAASTA is a reliable tool for the evaluation of timing and rhythm skills.

Finally, BAASTA was tested with the purpose of uncovering specific profiles of rhythm impairment in beat deafness. The goal of this study was to prove that BAASTA was to bring out new profiles of beat-deaf individuals. In this study, I also tested implicit timing skills in beat-deaf individuals for the first time in order to test whether their perceptual deficits extend to an implicit timing task.

The second part of the experimental section is dedicated to the training of rhythmic skills. I present a new protocol for training rhythm skills implemented in a music game called *Rhythm Workers.* In Study 4, a first experiment was devoted to selecting the musical material for the protocol. A second experiment is a proof-of-concept pilot study in a group of healthy adults to assess usability of the game and compliance. We also tested whether rhythm skills can be trained with *Rhythm Workers* in this population.

5. **Chapter 5**. Evaluation of timing and rhythmic skills

5.1. Study 1: BAASTA: Battery for the Assessment of Auditory Sensorimotor and Timing Abilities[2]

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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[2] This study was published in *Behavior Research Method.*
Dalla Bella, S., Farrugia, N., Benoit, C. -E., Bégel, V., Verga, L., Harding, E., & Kotz, S. A. (2017). BAASTA: Battery for the Assessment of Auditory Sensorimotor and Timing Abilities. *Behavior Research Methods, 49*, 1128–1145.

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, 2003; 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 or, 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 limited 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, 2003; 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 5.1.

Table 5.1. BAASTA, test battery description

Tests	Duration (min.)	Outcome measures
Perceptual tasks	~60	
Duration discrimination	6 minutes	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 tones (i.e. a metronome) was assessed (Hyde & Peretz, 2003; 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 occured 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 7^{th} 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 (Schwartze 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.

Analysis

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*Interquartile range (IQR) or greater than Q3 + 3*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 *sychronization 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 Figure 5.1. 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 ($\chi^2(2) = 1.56$, $p = .46$)

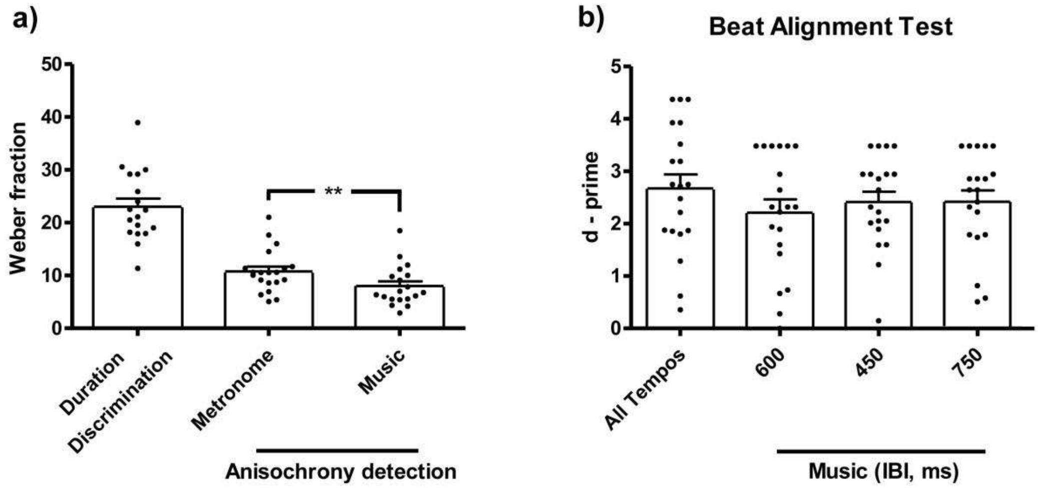

*Figure 5.1***.** Performance in the perceptual tasks of BAASTA. *Error bars* indicate the Standard Error of the mean. **p < .01

Production tasks

The results obtained in unpaced and paced tapping tasks are presented in Figures 5.2, 5.3 and 5.4, 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 toward 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 (Figs. 4a and 4b).

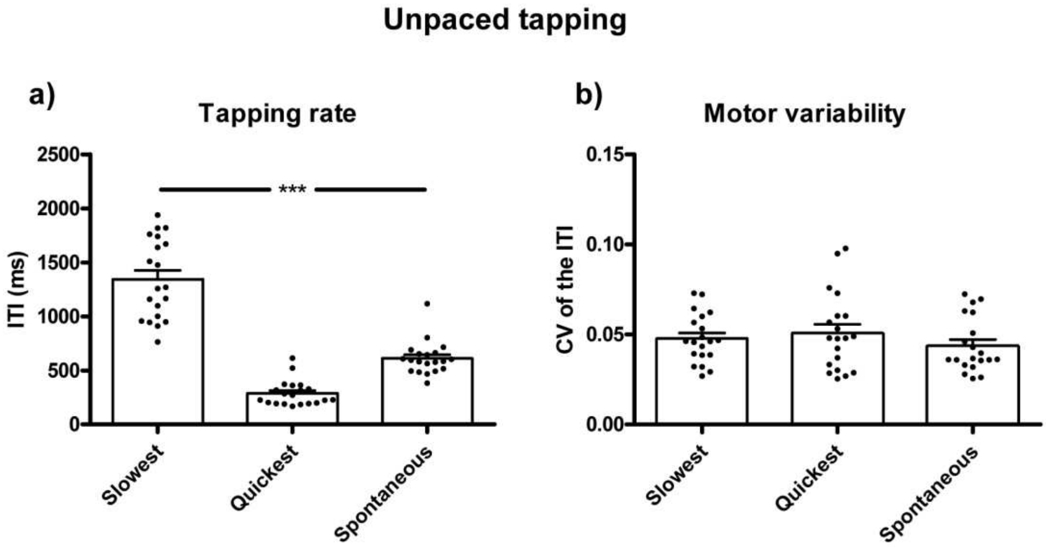

Figure 5.2. Performance in the unpaced tapping task of BAASTA. ***p < .001.

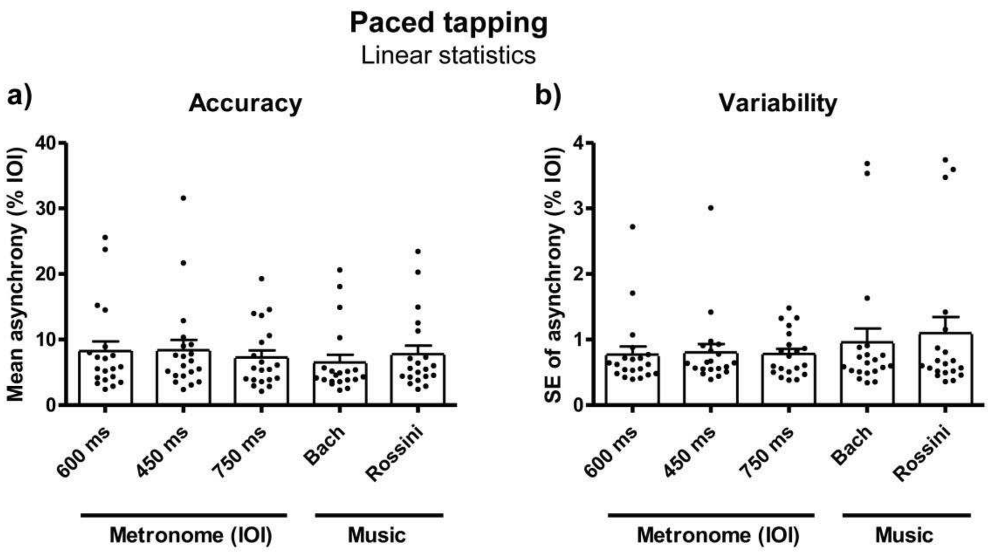

Figure 5.3. Performance in the paced tapping task of BAASTA using linear statistics.

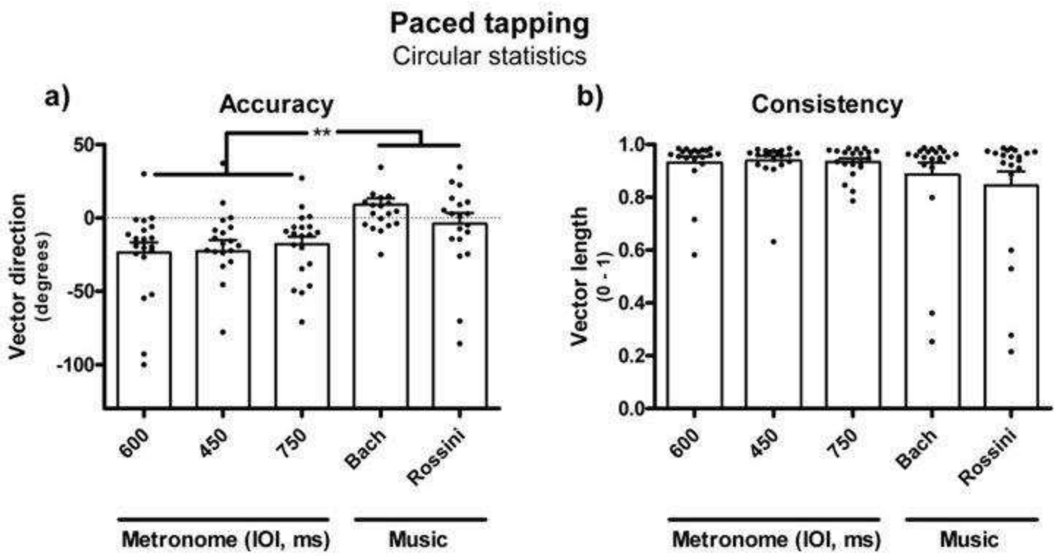

Figure 5.4. Performance in the paced tapping task of BAASTA using circular statistics. **p < .01.

Non-musicians' average performance in the synchronization-continuation and adaptive tapping tasks are presented in Figures 4.5, 5.6, and 5.7 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 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; $W = -171$, $p < .001$).

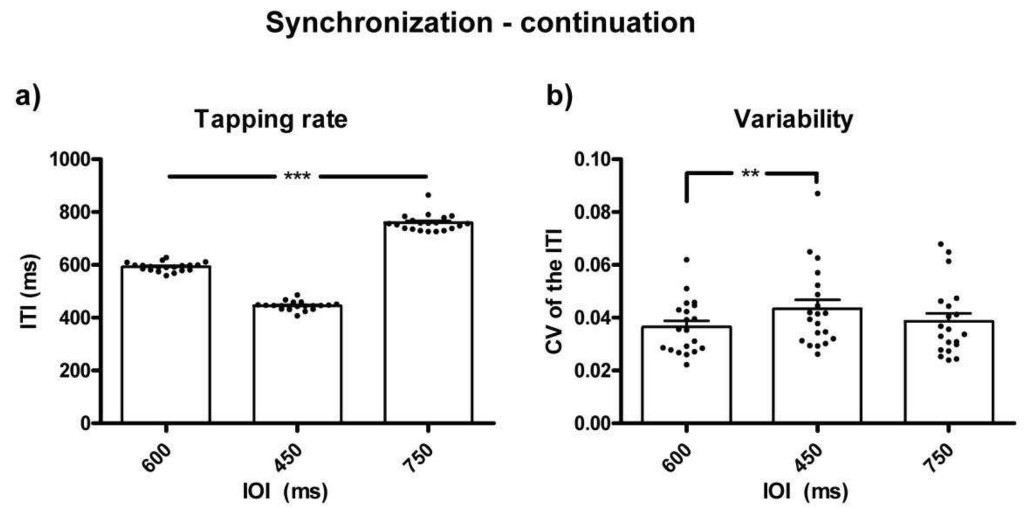

Figure 5.5. Performance in the synchronization-continuation task of BAASTA. Results from the continuation phase are reported. **p = .01; ***p < .001.

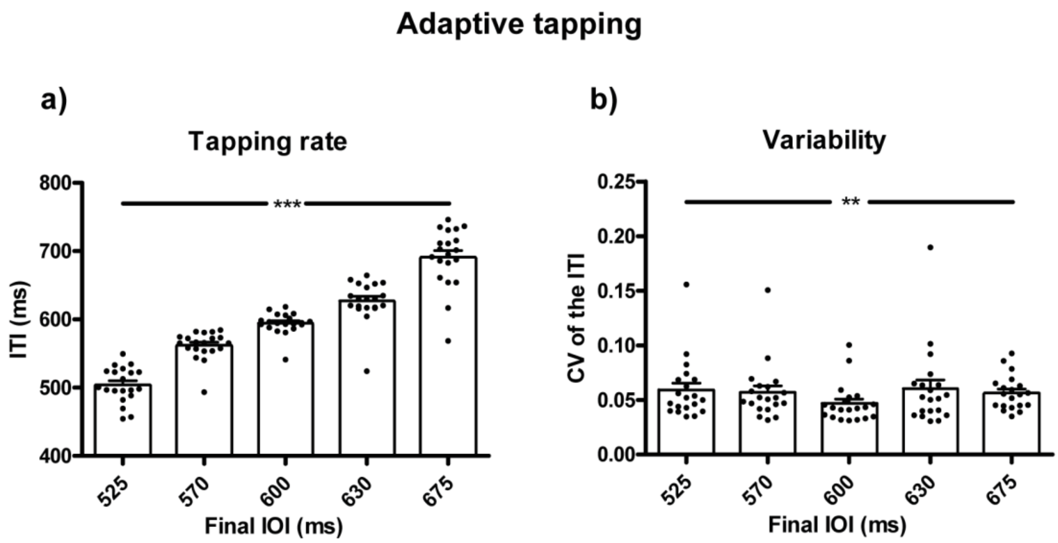

Figure 5.6. Performance in the adaptive task of BAASTA. Results from the continuation phase are reported. **p < .01; *** p < .001.

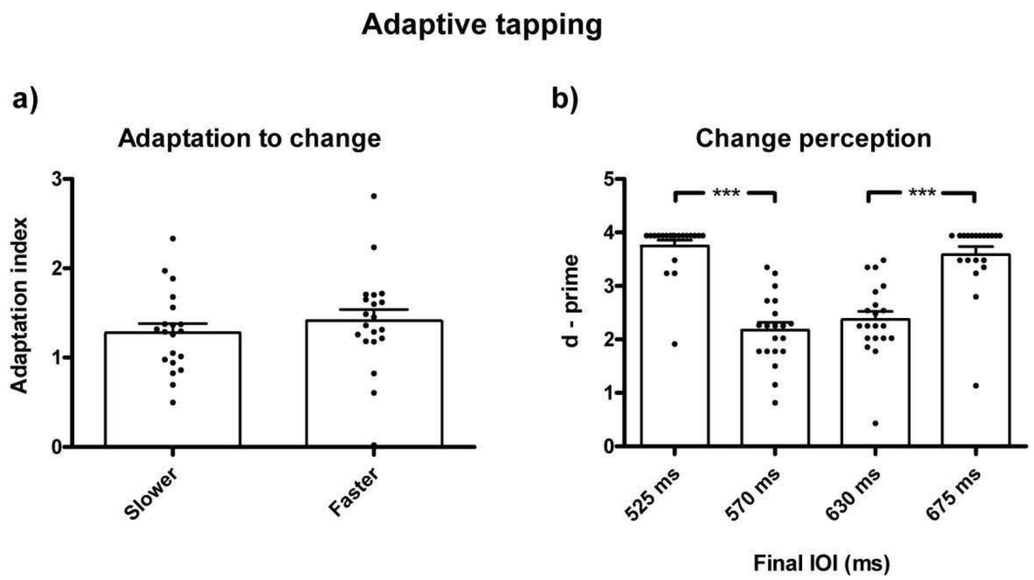

Figure 5.7. Performance in the adaptive tapping task of BAASTA. *** p < .001.

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 Figure 5.8. As can be seen, some tasks or measures are significantly correlated with others. For example, the performance in the Anisochrony detection task with tones (Prod2) 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 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 other independent components of the timing system(s).

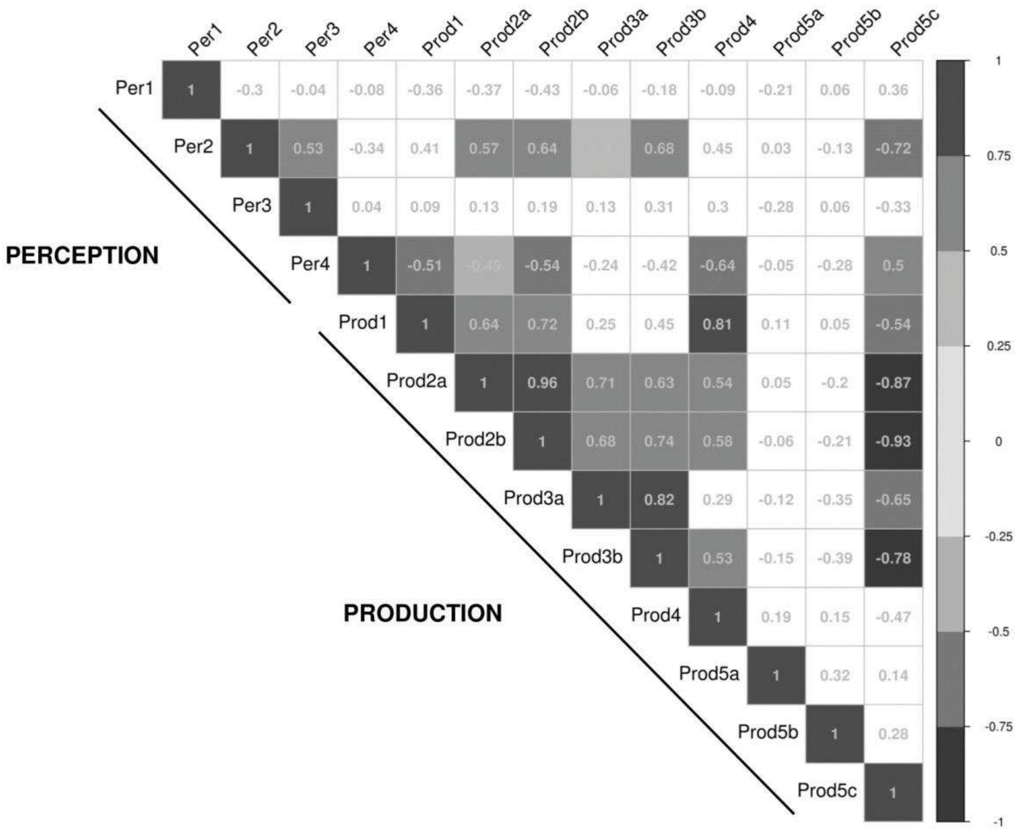

Figure 5.8. Correlation matrix between the Perceptual tasks (Per1, Per2, Per3, Per4) and the Production tasks (Prod1, Prod2a-b, Prod3a-b, Prod4, Prod5a-b-c) in BAASTA. Pearson correlation coefficients are reported. Significant correlations ($p < .05$) are highlighted in *gray*. Per1, Duration discrimination; 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.

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

Table 5.2. 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

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 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.

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 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 the 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 randomizd 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 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 Figure 5.9. 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) 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).

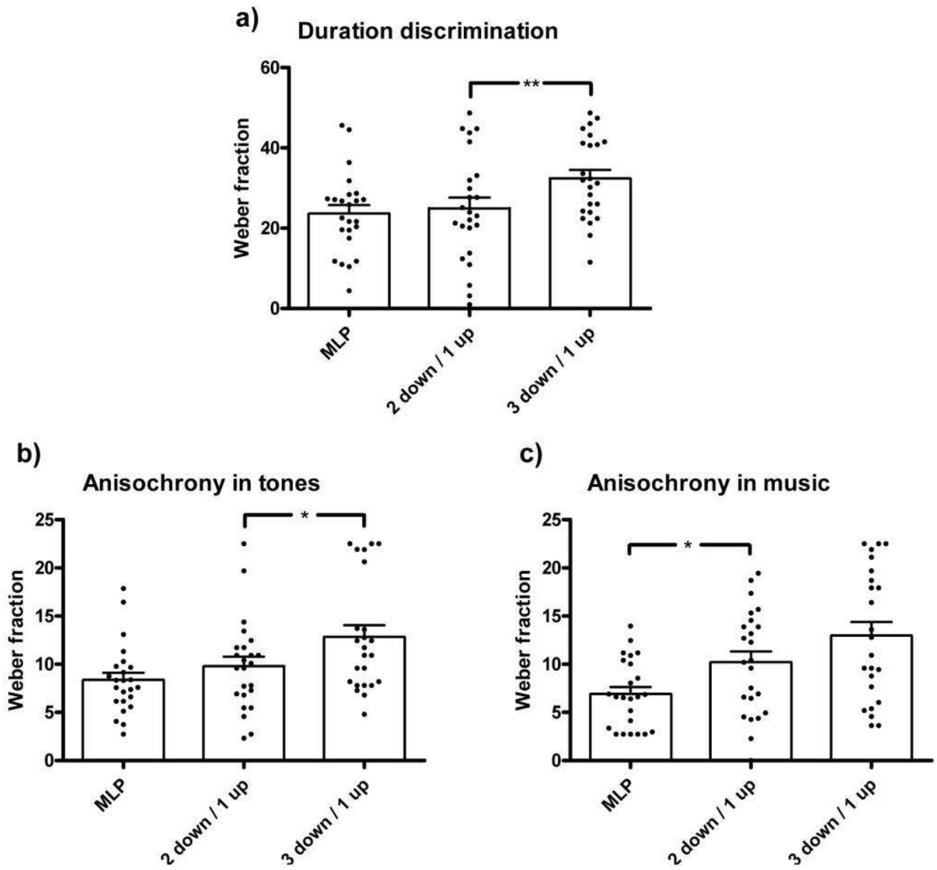

Figure 5.9. Performance in the perceptual tasks of the BAASTA using different adaptive methods for threshold estimation. *p < .05; **p < .01.

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 particulary 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. Slighly 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 Figure 5.8, 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 preescholers 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 anticipate the beat more than controls. 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 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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5.2. **Study 2: Test-retest reliability of the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA)**[3]

Abstract: Perceptual and sensorimotor timing skills can be comprehensively assessed with the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA). The battery has been used for testing rhythmic skills in healthy adults and patient populations (e.g., with Parkinson's disease) showing sensitivity to timing and rhythm deficits. Here we assessed test-retest reliability of BAASTA in a group of twenty healthy adults. Participants were tested twice with BAASTA, implemented on a tablet interface, within a two-week interval. They were submitted to 4 perceptual tasks, namely Duration discrimination, Anisochrony detection with tones and music, and the Beat Alignment Task (BAT). Moreover, they completed motor tasks via finger tapping, including Unpaced and Paced tapping with tones and music, Synchronization-continuation, and Adaptive tapping to a sequence with a tempo change. In spite of high variability among individuals, the results showed stable test-retest reliability in most of the tasks. An improvement of the performance from test to re-test was found in tapping with music, thus possibly reflecting a learning effect. In general, BAASTA was proven as a reliable tool for the evaluation of timing and rhythm skills.

Keywords: Rhythm perception, Rhythm performance, Sensorimotor synchronization, Reliability, Test-retest, Timing, Rhythm

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[3] This study is currently under revision in *Annals of Physical and Rehabilitation Medicine*. Bégel, V., Verga, L., Benoit, C. -E., Kotz, S. A., & Dalla Bella, S. (under revision). Test-retest reliability of the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA). *Annals of Physical and Rehabilitation Medicine*

Introduction

Humans are well equipped to process the temporal information of events in the environment. Most of us have a good grasp of the duration of events ranging from a few milliseconds to several years (Grondin, 2008). This highly developed skill is particularly visible in the capacity to perceive and move along to a regular stimulus such as the beat of music or the ticking of a clock. These abilities, shared by musicians and non-musicians alike (Repp, 2010; Sowiński & Dalla Bella, 2013), are sustained by a complex neuronal network involving both subcortical (e.g. the basal ganglia and the cerebellum) and cortical brain structures (e.g., premotor cortex and the supplementary motor area) (Coull, Cheng, & Meck, 2011; Coull & Nobre, 2008; Merchant, Harrington, & Meck, 2013; Schwartze & Kotz, 2013; Schwartze, Rothermich, & Kotz, 2012).

In the last two decades, testing of timing abilities has been carried out with a variety of paradigms, including perceptual tasks such as comparison of duration (duration discrimination Grondin, 1993; Merchant & De Lafuente, 2014), detection of shifts in regular sequences (anisochrony detection Dalla Bella & Sowiński, 2015; Ehrlé & Samson, 2005; Hyde & Peretz, 2004; Sowiński & Dalla Bella, 2013) and sensorimotor tasks (e.g., finger tapping with regular sequences Repp, 2005; Repp & Su, 2013). Data collected with these paradigms have fueled the development of a few influential models and theories such as the Scalar Expectancy Theory (e.g., Gibbon, Church & Meck, 1984), neural-integration based models (Taatgen, Rijn, & Anderson, 2007; Wing & Kristofferson, 1973a; Wing & Kristofferson, 1973b), and the Dynamic Attending Theory (Large & Jones, 1999). A surge of interest in timing and rhythmic skills in recent years is motivated by growing evidence that these skills are linked with important cognitive abilities such as working memory and reading skills (Tierney & Kraus, 2013; Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014), and may play a role in literacy and language learning (Gordon et al., 2014; Kotz & Gunter, 2015; Schwartze & Kotz, 2013). In addition, malfunctioning of rhythm processing co-exist with motor or cognitive deficits in several pathologies (for a review, see Allman & Meck, 2011), such as Parkinson's disease (Benoit et al., 2014; Jones & Jahanshahi, 2013; Kotz & Schwartze, 2011), ADHD ADHD (Noreika, Falter, & Rubia, 2013), or Autism (Allman, 2011). In these cases, rhythmic stimuli can serve as useful tools for rehabilitation. For example, auditory rhythmic stimulation, consisting in presenting rhythmic stimuli (metronome or music) to a patient, is known to have beneficial effects on motor behavior (e.g., gait in Parkinson disease, Benoit et al., 2014; Thaut et al., 1996; Thaut & Abiru, 2010) and speech perception and production

(Hoemberg, 2001; Kotz & Gunter, 2015; Kotz & Schmidt-Kassow, 2015; McIntosh, & Mainka & Mallien, 2014; Przybylski et al., 2013; Schön & Tillmann, 2015; Stahl, Kotz, Henseler, Turner & Geyer, 2011; Thaut, McIntosh,).

In the last few years, tools for the systematic assessment of timing abilities have been devised. For example, Fuji and Schlaug (2014) proposed the Harvard Beat Alignment Task (H-BAT), based on the original Beat Alignment Test (BAT, Iversen and Patel, 2008). These batteries include perceptual and sensorimotor beat-based tasks, aimed at testing the ability to extract a beat from a complex auditory sequence. These tasks consist in judging if a sequence of isochronous tones is superimposed on the beat of music or not, to compare duple or triple meters, and to perceive the changes in sequences of tones (perception tasks). Moreover, the battery includes tapping tasks to the beat of music or metrical sequences (production tasks). Merchant and collaborators (Merchant et al., 2008) developed a battery of duration-based (categorization, discrimination, and reproduction of durations) and beat-based tests with non-musical material (synchronization-continuation, i.e. continue tapping at the same rate right after an isochronous sequence is presented, and synchronization by circle drawing). They showed that the battery allowed discriminating between different profiles of timing impairments in Parkinson's disease.

Recently we proposed an alternative tool for testing timing and rhythmic skills, namely the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA) (Benoit et al., 2014; Dalla Bella et al., 2017a). The battery includes nine tasks (4 perceptual and 5 motor) for testing beat-based and duration-based timing skills. Perceptual tasks include Duration discrimination, Anisochrony detection (with tones and music), and a version of the BAT. Production tasks are spontaneous tapping, paced tapping (with tones and music), synchronization-continuation and adaptive tapping.

In recent studies (Bégel et al., 2017; Benoit et al., 2014;Dalla Bella et al., 2017a; Falk, Müller & Dalla Bella, 2015), we have demonstrated that BAASTA is sensitive to rhythm deficits. The battery is efficient in detecting different profiles of beat deafness Bégel et al., 2017; see also Dalla Bella & Sowiński, 2015; Sowiński & Dalla Bella, 2013), a condition in which healthy individuals have difficulties with the perception and/or production of rhythm (Launay, Grube & Stewart, 2014; Mathias et al., 2016; Palmer, Lidji, & Peretz, 2014; Phillips Silver et al., 2011). BAASTA was also used to uncover rhythm impairments in patient population (children suffering from developmental stuttering, Falk, Müller & Dalla Bella, 2015; Parkinson's disease, Benoit et al., 2014; Dalla Bella et al., 2017a] and to assess the change of timing performance following a rhythm-based training in Parkinson's disease

(Benoit et al., 2014; Dalla Bella et al., 2017b). These studies were particularly successful in revealing that perceptual and sensorimotor timing skills improved in a longitudinal test-retest design. However, a learning effect may contribute to explaining these findings as the tasks from BAASTA were repeated. Thus an evaluation of test-retest reliability for BAASTA is meaningful and needed to validate its efficacy.

The goal of this study was therefore to conduct a test-retest reliability study (Fleiss, 1986) of BAASTA in a sample of twenty older adults. This target group was selected as it is comparable to the age group of participants in the aforementioned training study (Benoit et al., 2014; Dalla Bella et al., 2017b). Participants repeated all tests of BAASTA twice at a 2-week interval. Test-retest reliability was expected to provide a good index of the consistency of measures of individuals' scores (Weir, 2005).

Material and methods

Participants

Twenty older adults recruited from the data base of the Max Planck Institute for Human Cognitive and Brain Sciences (Leipzig, Germany) took part in the study. They were aged between 50 and 76 years (*M* = 62.95 years; *SD* = 5.92), and were mostly non-musicians (mean number of years of formal musical training = 2.25; *SD* = 3.21). Two participants received 7 and 12 years of formal musical training).

Tests and procedure

BAASTA (Dalla Bella et al., 2017a) consists of four perceptual tasks (*Duration discrimination*, *Anisochrony detection with tones*, *Anisochrony detection with music,* and the *Beat Alignment Test*) and five production tasks (*Unpaced tapping*, *Paced tapping to an isochronous sequence*, *Paced tapping to music*, *Synchronization-continuation* and *Adaptive tapping*), implemented on a tablet interface (LG G Pad 8.0 model). The stimuli were delivered over headphones (Sennheiser HD201). The interval between test and retest was of approximately two weeks (*M* = 16.25 days, *SD* = 3.92). Ten participants received the perceptual tasks before the production tasks; the other participants performed the tasks in the reverse order. The order within each group of tasks was fixed as indicated above.

Perceptual tasks

In the first 3 tasks (Duration discrimination, Anisochrony detection with tones and with music), a 2 down /1 up staircase procedure (Levitt, 1971; see Dalla Bella et al., 2017a) was used to obtain the perceptual threshold. Each task included two trials, which were preceded by four examples and four practice trials with feedback.

Duration discrimination: the goal of this task was to test participants' ability to compare durations. Two tones (frequency = 1 kHz) were presented successively. The first tone (standard duration) lasted 600 ms and the second one (comparison duration) lasted between 600 and 1000 ms. After the presentation of the tones, the participant judged whether the second tone was longer than the first one.

Anisochrony detection with tones: in this task, we assessed the participants' abilities to detect a time shift in a sequence of isochronous tones. Sequences of 5 tones (1047 Hz, tone duration = 150 ms) with a mean Inter-Onset Interval (IOI) of 600 ms were presented. The 4th tone was presented up to 30% of the IOI earlier than expected and the task was to judge whether the sequence was regular or not.

Anisochrony detection with music: as in Anisochrony detection with tones, the participants judged whether a sequence was regular or not. In this task the sequence was a musical excerpt (i.e., two bars from Bach's "Badinerie" orchestral suite for flute, BWV 1067, played with a piano timbre). The music's Inter-Beat Interval (IBI) was 600 ms. The IBI was constant (regular) or not (irregular; the 4th beat occurred earlier than expected by up to 30% of the IBI) as in the preceding task.

Beat Alignment Test: the goal of the task was to assess the participants' ability to perceive the beat. The stimuli (n = 72) were based on two musical fragments of 20 beats each (beat = quarter note) from Bach's "Badinerie" and two from Rossini's "William Tell Ouverture", played with a piano timbre. Each stimulus was played at three different tempos (with 450, 600, and 750-ms IBIs). From the 7th musical beat, a metronome with a percussion timbre was superimposed onto the music. The metronome could be aligned or not with the beat. The metronome sounds were either phase shifted, when presented before or after the musical beats by 33% of the music IBI while keeping the tempo, or period shifted when the tempo of the metronome changed by + or - 10% of the IBI. The task was to judge if the metronome was aligned or not with the musical beat.

Production tasks

Unpaced tapping: the goal of the task was to assess the mean Inter-Tap Interval (ITI) and the variability of tapping in the absence of a pacing stimulus. The participants tapped with their index finger at their preferred rate without a pacing stimulus for 60 seconds.

Paced tapping with an isochronous sequence: the purpose of this task was to assess participants' ability to synchronize with a metronome. The task was to tap with the index finger to a sequence of 60 piano tones (frequency = 1319 Hz) presented at 3 tempos (600-, 450- and 750-ms IOI). The task was repeated twice for each excerpt and was preceded by one practice trial.

Paced tapping with music: this task was similar to the previous one, but music was used as the pacing stimulus. Participants tapped to the beat of two musical excerpts taken from Bach's "Badinerie" and Rossini's "William Tell Ouverture". The IBI of each musical excerpt was 600 ms. The excerpts contained 64 beats (quarter notes). The task was repeated twice and was preceded by one practice trial.

Synchronization-continuation: this task tested the ability to continue tapping at the rate provided by a metronome. A metronome (10 tones isochronous tones) was first presented at three tempos (600-, 450-, and 750-ms IOI). The participants synchronized with the metronome and continued tapping at the same rate after the sequence stopped. The duration of the continuation phase was equivalent to 30 IOIs of the pacing stimulus. The task was repeated twice at each tempo and was preceded by one practice trial.

Adaptative tapping: the goal of this task was to assess participants' ability to adapt their tapping rate to a tempo change in a synchronization-continuation task. As in the previous task, an isochronous sequence (10 tones) was presented, but in 40% of the trials, the IOIs between the last 4 tones increased or decreased by 30 or 75 ms, or remained constant. The participants were instructed to tap to the tones in the sequence, to adapt to the tempo change, and to keep tapping at the new tempo after the stimulus stops (the continuation phase corresponds to 10 IOIs). Then, they judged whether they perceived a change in stimulus tempo (acceleration, deceleration, or no change) after each trial. Trials were presented in random order. A training block preceded the first experimental trial.

Analysis

Perception tasks

In the Duration discrimination and Anisochrony detection tasks, the task stopped after 8 turnaround points (i.e., the values corresponding to the direction changes from up to down or from down to up) in the staircase paradigm. The threshold was calculated by averaging the last four turnaround points. This is expressed in the percentage of the standard duration in the three tasks (Weber fraction). The trials including more than 30% of False Alarms (FAs, scored when the participant reported a difference while there was none) were rejected. The mean thresholds across the two trials in each task were presented. In the BAT, the *d'* was calculated by dividing the number of Hits (when a misaligned metronome was correctly detected) by the number of FAs (when a misalignment was erroneously reported).

Production tasks

Pre-processing of the data included the following steps: the first ten taps were discarded in Paced and Unpaced tapping. Trials containing less than ten continuous taps and more than 30 (length of the continuation phase) were discarded in the synchronization phase of the Synchronization-continuation task. To be valid, trials in the Adaptive tapping task needed to contain at least eight taps in the continuation phase, and in the synchronization phase at least 4 taps had to be in the vicinity of the metronome sounds. Taps leading to inter-tap intervals (ITIs) smaller than 100 ms were considered as artifacts. Outliers, defined as taps for which the ITI between the actual tap and the preceding tap was smaller than Q1 – 3*Interquartile range (IQR) or greater than Q3 + 3*IQR (Q1=first quartile, Q3=third quartile) were rejected.

Mean ITI and *motor variability* (CV of the ITI) for Unpaced tapping and motor variability for the continuation phase of Synchronization-continuation and Adaptive tapping were calculated. Circular statistics (Fisher, 1995) were used for the analysis of synchronization performance as done in previous studies (Dalla Bella & Sowiński, 2015; Falk, Müller, & Dalla Bella, 2015; Kirschner & Tomasello, 2009; Pecenka & Keller, 2011; Sowiński & Dalla Bella, 2013; Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014). In circular statistics, a circle of 360° degrees represents the Inter-Stimulus Interval (ISI) where zero degrees on the circle indicate the sound or beat. Each tap is represented by an angle of the circle (dot on the circle) and refers to a unit vector. A resultant vector *R* is calculated on the basis of the unit vectors for all taps in a trial. The length of *R*, between 0 and 1, is an index of *consistency* of the performance and reflects the variability of the relative phase between taps and pacing stimuli. One means that all the taps and pacing stimuli appear exactly at the same time, and 0 means that the distribution is totally random (i.e., lack of synchronization). The direction of *R* is expressed in degrees and represents the *accuracy* of synchronization, namely, whether taps occurred before or after the pacing stimulus. A positive direction means that the taps occurred on average after the tones or beats, and a negative one means that the taps anticipated the tones or beats (180° is the antiphase). If the participants' synchronization was below chance, as assessed by the Rayleigh test for circular uniformity [(Fisher, 1995; Wilkie, 1983), accuracy was not calculated. A logit transformation was applied to vector length before further statistical analyses (Bégel et al., 2017; Dalla bella et al., 2017a; Falk et al., 2015). The mean performance of the two trials is presented for Paced tapping and Synchronization-continuation.

Finally, an *adaptation index*, defined by the value of the slope of a regression line fitted to the slopes of ITIs function of the final sequence tempo, and a sensitivity index (*d'*) for detecting tempo changes, were calculated for Adaptive tapping.

Test-retest analysis

We compared the first and the second testing sessions with standard *t* tests when the distributions were normal in both sessions and with Wilcoxon-Mann-Whitney *U* tests when at least one of the distributions was not normal (Shapiro-Wilks test). Rejection of the null hypothesis would imply a significant difference between the two sessions and reveal a systematic error that may result from an experimental bias such as the influence of weariness or learning. To control for sources of error due to chance (random error; e.g. biological variability), we calculated the Intraclass Correlation Coefficient ($ICC_{3,1}$). $ICC_{3,1}$ is considered as a good index of test-retest reliability with the same experimenter as it does not include variance associated with systematic error (bias) (Brozek & Alexander, 1947; Fleiss, 1986; Weir, 2005). ICC is commonly used as a measure of relative reliability, namely, the consistency of the relative position of one individual in a group (Vaz et al., 2013).

Following Shrout & Fleiss (1979), ICC values are interpreted as follows: > 0.75 is excellent, 0.40–0.75 is good and < 0.40 is poor. The other form of reliability is absolute reliability (Fleiss, 1986; Weir, 2005). Absolute reliability deals with the degree to which measurements vary and provide an index of the expected trial-to-trial noise in the data. SEM, SEM%, and coefficient of reliability (CR, also referred to as the smallest real difference, or minimum difference) were used to assess absolute reliability. The SEM is expressed in the same unit as the measurement of interest and quantifies the variability between the two sessions. It is calculated as the square root of the within-subjects error variance. CR represents the 95% confidence interval, a value for which any retest score outside that interval would be interpreted as having 95% chances to reflect a real difference. It is calculated by multiplying the SEM by 2.77 ($\sqrt{2}$ times 1.96). For comparison between tasks in different units, the SEM% and CR% were calculated by dividing the SEM or the CR by the mean of all measurements from both sessions and multiplied by 100.

Results

Results are presented in Table 5.3. Systematic error tests showed a significant change from test to retest for synchronization consistency ($t(19) = -3.91$, $p < .05$ with Bonferroni correction) only in paced tapping with music. In all the other tasks there were no significant differences between the two times of testing. In the perceptual tasks, the ICC was just below the limit for good reliability in Duration discrimination (.39) and was good to excellent (.45 to .94) in the other tasks. In the production tasks, the ICC was excellent for accuracy and consistency in all the paced tapping tasks (.75 to .96). However, it was poor in Unpaced tapping, Synchronization continuation, and Adaptive tapping (.01 to .32) except for the adaptation index in Adaptive tapping (.84). The SEM% was between 13.08 and 22.65 in the perception tasks and between 12.43 and 109.94 in the production tasks. The CR% ranged from 34.54 to 305.18.

Table 5.3. Measures of reliability for BAASTA

Task	Variable	Session 1 Mean (*SD*)	Session 2 Mean (*SD*)	Relative Reliability Indices		Absolute Reliability Indices			
				P	ICC	SEM	SEM%	CR	CR%
Duration Discrimination	Threshold (Weber fraction)	16.49 (5.45)	18.08 (3.47)	.06	.39	3.29	19.06	9.13	52.82
Anisochrony Detection with tones	Threshold (Weber fraction)	13.67 (3.27)	12.92 (2.86	.18	.68	1.74	13.08	4.82	36.25
Anisochrony Detection with music	Threshold (Weber fraction)	11.06 (3.54)	13.20 (3.86)	.12	.45	2.75	22.65	7.61	62.75
Beat Alignment Test	*d'*	1.67 (1.36)	1.82 (1.49)	.21	.94	.36	20.69	1.00	57.22
Paced tapping	Metronome (consistency)	.91 (.12)	.91 (.11)	.76	.75	.46	16.45	1.29	45.71
	Metronome (accuracy)	-3.84 (4.21)	-3.63 (4.01)	.72	.80	.46	-12.43	1.29	-34.54
	Music (consistency)	.73 (.20)	.77 (.19)	.02*	.96	.24	16.62	.67	45.80
	Music (accuracy)	.21 (6.68)	1.88 (6.03)	.62	.77	.24	23.28	.67	64.16
Adaptive tapping	Adaptation index (acceleration)	1.76 (1.00)	1.47 (.55)	.46	.83	.34	20.95	.94	58.16
	Adaptation index (deceleration)	1.05 (.76)	1.06 (.93)	.82	.01	.84	79.65	2.32	220.18
	d' (acceleration)	.61 (2.46)	.56 (2.70)	.41	.20	.53	20.95	1.46	55.97
	d' (deceleration)	.54 (.08)	.65 (.11)	.30	.16	.54	21.11	1.51	58.54
Synchronization-Continuation	Motor Variability	.08 (.13)	.11 (.12)	.19	.31	.10	107.66	.28	293.26
Unpaced tapping	ITI	493.20 (167.66)	537.73 (264.89)	.93	.32	182.74	35.35	506.18	97.91
	Motor Variability	.12 (.15)	.16 (.19)	.62	.17	.15	109.94	.43	305.18

Note. P-values are obtained with standard *t*-tests or Wilcoxon-Mann-Whitney *U* tests depending on the normality of the distributions. P-values marked with * are significant values (<.05) presented with Bonferroni correction.

Discussion

We conducted a test-retest study of BAASTA, a tool for the systematic assessment of perceptual and sensorimotor timing skills (Dalla Bella et al., 2017a). Twenty adults were submitted to the battery on two occasions, two weeks apart. The results of the two measurements were compared using reliability indices. First, a standard comparison of the mean differences with repeated measures tests served to assess the systematic error (Weiss, 2005). A significant improvement (4.05%) in terms of synchronization *consistency* of the tapping performance with music was observed. Participants tend to improve their performance, which is less variable, when synchronizing with the beat of the music at retest. This improvement is likely to reflect a learning effect as the same music excerpts were used to assess synchronization with music at both times of testing. Apart from synchronization with music, the mean of all the other tasks remained stable at the second time of testing. Thus, the performance in these tasks was not affected by a learning effect or annoyance brought about by repeating the tasks.

ICC index was used to assess the consistency of the performance at the level of each individual. It is encouraging to observe that ICC values ranged from satisfactory to excellent especially in the perceptual tasks and in Paced tapping with a metronome and music. However, test-retest reliability was poor for ITI in Unpaced tapping and for variability in Unpaced tapping and Synchronization-continuation. In addition, three out of the four variables of Adaptive tapping yielded poor ICCs, in perception (*d'* for acceleration), and in production (adaptation index for deceleration).

Finally, indices of absolute reliability were provided. The SEM was used to define the boundaries around which a participant's true score lies, and the CR is useful to estimate whether a performance in a test-retest experiment is likely to reflect a real difference (i.e., an improvement or a deterioration of a performance). These indices will be valuable in future studies to consider the performance of individuals, in particular in older adult populations, in the light of test-retest reliability.

Acknowledgments

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5.3. **Study 3: "Lost in time" but still moving to the beat**[4]

Abstract: Motor synchronization to the beat of an auditory sequence (e.g., a metronome or music) is widespread in humans. However, some individuals show poor synchronization and impoverished beat perception. This condition, termed "beat deafness", has been linked to a perceptual deficit in beat tracking. Here we present single-case evidence (L.A. and L.C.) that poor beat tracking does not have to entail poor synchronization. In a first Experiment, L.A., L.C., and a third case (L.V.) were submitted to the Battery for The Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA), which includes both perceptual and sensorimotor tasks. Compared to a control group, L.A. and L.C. performed poorly on rhythm perception tasks, such as detecting time shifts in a regular sequence, or estimating whether a metronome is aligned to the beat of the music or not. Yet, they could tap to the beat of the same stimuli. L.V. showed impairments in both beat perception and tapping. In a second Experiment, we tested whether L.A. and L.C., and L.V.'s perceptual deficits extend to an implicit timing task, in which they had to respond as fast as possible to a different target pitch after a sequence of standard tones. The three beat-deaf participants benefited similarly to controls from a regular temporal pattern in detecting the pitch target. The fact that synchronization to a beat can occur in the presence of poor perception shows that perception and action can dissociate in explicit timing tasks. Beat tracking afforded by implicit timing mechanisms is likely to support spared synchronization to the beat in some beat-deaf participants. This finding suggests that separate pathways may subserve beat perception depending on the explicit/implicit nature of a task in a sample of beat-deaf participants.

Keywords: Beat deafness; Auditory-motor integration; Rhythm perception; Rhythm production; Sensorimotor synchronization; Implicit timing

[4] This study was published in *Neuropsychologia*.
Bégel, V., Benoit, C. -E., Correa, A., Cutanda, D., Kotz, S. A., & Dalla Bella, S. (2017). "Lost in time" but still moving to the beat. *Neuropsychologia*, *94*, 129-138.

Introduction

One of the most compelling reactions to music is to move to its beat. Humans spontaneously or intentionally tend to clap their hands, sway their body, or tap their feet to the beat of music. Synchronizing movement to the beat (Repp & Su, 2013; Repp, 2005) involves the coordination of a discrete action with a sequence of rhythmic auditory events (e.g., tones of a metronome or musical beats). This complex activity is supported by a neuronal network, including areas devoted to tracking the musical beat (e.g., the basal ganglia; Grahn & Brett, 2007; Grahn & Rowe, 2009) and motor coordination (e.g., the cerebellum; Coull, Cheng, & Meck, 2011; Grube, Cooper, Chinnery, & Griffiths, 2010; Schwartze & Kotz, 2013). Motor synchronization to the beat is likely to be hard-wired as it appears spontaneously and early during development (Drake, Jones, & Baruch, 2000; Kirschner & Tomasello, 2009; Phillips-Silver & Trainor, 2005). Accordingly, this skill is highly widespread in the general population (Repp 2010; Sowiński & Dalla Bella, 2013).

Even though the majority can move to the beat of music, some individuals, referred to as "beat-deaf" (Palmer, Lidji, & Peretz, 2014) encounter particular difficulties in synchronizing to the beat (see also Sowiński & Dalla Bella, 2013). This condition is considered to be a congenital anomaly in the absence of brain damage (Phillips-Silver et al., 2011; Sowiński & Dalla Bella, 2013). An example of beat deafness is the case of Mathieu (Phillips-Silver et al., 2011), a young man who was unable to bounce accurately to the beat of music while showing good synchronization to a simple metronome. His poor synchronization is likely to result from poor perception, as he was inaccurate in estimating whether a dancer is on or off the beat in a music video. Notably, Mathieu's deficits is not ascribed to a general impairment of music processing (e.g., Peretz & Hyde, 2003; Stewart, 2008, see also Dalla Bella & Peretz, 2003). His pitch perception is spared as tested with the Montreal Battery of the Evaluation of Amusia (MBEA; Peretz, Champod, & Hyde, 2003).

The case of Mathieu points toward a perceptual explanation of poor synchronization to the beat. Inaccurate extraction of the beat from complex auditory signals (e.g., music), including several periodicities at different embedded temporal scales (meter; London, 2012), may bring about poor synchronization (Phillips-Silver et al., 2011). This deficit may not be apparent with a simpler isochronous sequence (e.g., a metronome) though. Beat tracking with a metronome is still possible, while beat extraction and synchronization with metrical rhythms are impaired (Launay, Grube & Stewart, 2014). However, inaccurate beat perception is not mandatory to explain poor synchronization to the beat. In a large-scale study with around 100 students that were tested with a battery of rhythm perception and paced tapping tasks, we reported two cases (S1 and S5) who exhibited poor synchronization to the beat while showing spared rhythm perception (Dalla Bella & Sowiński, 2015; Sowiński & Dalla Bella, 2013). Additional evidence of sensorimotor deficits in beat deafness was provided more recently by Palmer and collaborators (Palmer, Lidji, & Peretz, 2014). They showed that two beat-deaf participants, including Mathieu, had difficulties in adapting their tapping to perturbations in an isochronous sequence, next to poor beat perception. Finally, a recent study (Mathias, Lidji, Honing, Palmer, & Peretz, 2016) reports that Mathieu but not Marjorie, another beat-deaf participant, showed an abnormal P3 response to the omission of a beat in a musical sequence. Altogether these data suggest that there are different individual profiles of beat deafness, depending on the impairment of beat perception and/or production.

The dissociation between beat perception and tapping to the beat that we reported in two poor synchronizers (Sowiński & Dalla Bella, 2013) is particularly intriguing. It suggests that perception and action in the rhythm domain may be partly independent. However, task factors such as difficulty, attention, and memory demands may explain these differences. For example, synchronization requires both tracking the beat and generating a motor response. Thus, it may be more demanding than a simple perceptual task. As the opposite dissociation - impaired beat perception with spared synchronization - has not been described so far, it is difficult to conclude whether there are two independent mechanisms involved. However, a functional separation of perception and action is not unusual, and is supported by a double dissociation in pitch processing (for reviews, see Dalla Bella, Berkowska, & Sowiński, 2011; Berkowska & Dalla Bella, 2009; Dalla Bella, 2016). A similar functional architecture may apply to rhythm. Beat perception and synchronization to the beat involve multiple components, which may be difficult to dissociate in the healthy brain, as motor and perceptual processes are usually strongly coupled (Kotz, Brown & Schwartze, 2016; Grahn, 2012; Repp & Su, 2013; Repp, 2005). Yet, first evidence that these processes can be disrupted separately as a result of brain damage or a developmental disorder (Fries & Swihart, 1990; Provasi et al., 2014; Sowiński & Dalla Bella, 2013) suggests some degree of functional separability.

Our goal is to present two cases of beat deafness (L.A. and L.C.) and to show that poor beat perception can occur while synchronization to the beat is spared. A third case, L.V. displays impairment of both beat perception and synchronization. With these data we also confirm the sensitivity of a battery of timing tests to detect both perceptual and synchronization deficits. In a first Experiment, participants' beat perception and synchronization to the beat were assessed with the Battery for The Assessment of Auditory

Sensorimotor and Timing Abilities (BAASTA; Dalla bella et al., 2017a; Benoit et al., 2014; Falk, Müller & Dalla Bella, 2015). An additional question was whether deficits in beat tracking observed in explicit timing tasks (e.g., Fujii & Schlaug, 2013; Phillips-Silver et al., 2011; Repp & Su, 2013; Repp, 2005; Sowiński & Dalla Bella, 2013) extend to implicit timing processes. In general, explicit timing is associated with tasks requiring either voluntary motor production (e.g., synchronized tapping tasks; Repp & Su, 2013; Repp, 2005), or perceptual discrimination of a timed duration (e.g., anisochrony detection, Ehrlé & Samson, 2005; Hyde & Peretz, 2004). In contrast, implicit timing is involved in tasks that do not explicitly test timing (e.g., detecting a deviant pitch in a temporally regular or irregular sequence), but in which temporal prediction affects performance (Coull & Nobre, 2008; Coull, 2009; Nobre, Correa, & Coull, 2007; Sanabria, Capizzi, & Correa, 2011). In particular, temporal prediction fostered by a regular temporal pattern of sensory stimuli improves performance in these tasks (e.g., reduces reaction times; Lange, 2010; Sanabria et al., 2011; Sanabria & Correa, 2013). Explicit and implicit timing are associated with distinct neuronal substrates, involving cortico-striato-cortical networks and inferior parietal-premotor networks with projections from the cerebellum (Coull & Nobre, 2008; Nobre & Coull, 2010; Zelaznik, Spencer, & Ivry, 2002; Coull, Warren, & Meck, 2011; Kotz & Schwartze, 2010; Schwartze & Kotz, 2013). Here we hypothesize that beat perception deficits characteristic of beat deafness as observed in explicit tasks may not carry over to implicit timing tasks. This hypothesis was tested in a second Experiment, in which L.A., L.C., and L.V. were asked to respond as quickly as possible to a target sound presented either after five sounds embedded in a temporally regular or an irregular sequence. Better performance following the regular sequence of sounds compared to the irregular sequence would be indicative of spared implicit timing processing.

Experiment 1

Participants

Cases Histories

L.A., L.C., and L.V. were 21-years-old female university students recruited at the University of Montpellier. L.A. and L.V. had not received any musical training. L.C., in spite of the fact that she received 5 years of non-formal piano lessons, considers herself a non-musician. She practiced less than 1 hour a week during her musical training, and has rarely played the piano in the last 7 years. L.V. complained about difficulties in finding the beat in music, especially while dancing, singing, or tapping the foot to the beat. In contrast, L.C. and L.A. reported no difficulties with beat tracking. Neither participant suffered from a brain injury or had undergone brain surgery. None reported previous neurological or psychiatric problems or an auditory deficit.

Control group

Seven female university students recruited at the University of Montpellier, matched to the three beat-deaf participants took part in the study. They were between 18 and 30 years old (*M* = 23.29 years; *SD* = 4.54), and were self-reported non-musicians (mean number of years of musical training = 1.29 years; *SD* = 1.89). They did not have any previous neurological or psychiatric problems. All participants provided informed consent for participating in the study.

Material and method

The participants were submitted to BAASTA (Dalla Bella et al., 2017a) as a way to assess their explicit perceptual and sensorimotor timing abilities (for a description of the methodology of BAASTA, see above, study 1). In addition, they performed the pitch-related tasks of the MBEA (i.e., Contour, Interval, and Scale subtests; Peretz et al., 2003) to assess their pitch perception.

Assessment of pitch perception: MBEA

To assess pitch perception of the three beat-deaf participants and to rule of the possibility of congenital amusia, participants were submitted to the three tasks of the MBEA focusing on pitch perception (Peretz et al., 2003): Contour, Interval, and Scale subtests.

Analysis

MBEA

A pitch composite score was computed for the MBEA, averaging the results from the three pitch tasks (maximum performance in each task = 30). The scores of the three beat-deaf individuals were compared to the normative data from a comparable group of 100 participants (Cuddy, Balkwill, Peretz, & Holden, 2005).

Single-case statistics

In order to determine whether the three beat-deaf participants performed poorly in the aforementioned tasks, their performance was compared to cut-off scores obtained from controls for each variable using statistics adapted for the analysis of single cases (*Singlims* program, Crawford & Garthwaite, 2002; Crawford & Howell, 1998). Thresholds for all the tasks are provided in Table 5.4. In addition, the Revised Standardized Difference Test (RSDT, Garthwaite & Crawford, 2004; Crawford & Garthwaite, 2005) was used to confirm the dissociations between perception and action previously found in explicit timing tasks for L.A. and L.C. RSDT compares the difference between the results obtained in two tasks for one participant relative to the performance of a matched control group, while controlling for Type I error.

Table 5.4. Cut-off scores in the tasks of the BAASTA based on the performance of the control group.

Task	Variable	Cut-off
Duration Discrimination	Threshold (Weber fraction)	32.96
Anisochrony Detection with tones	Threshold (Weber fraction)	13.30
Anisochrony Detection with music	Threshold (Weber fraction)	21.78
Beat Alignment Test	*d'* (slow tempo)	1.96
	d' (medium tempo)	1.20
	d' (fast tempo)	1.24
	% of errors (phase change)	12.17
	% of errors (period change)	33.28
Unpaced tapping	Motor Variability	.091
Paced tapping	Consistency (tones, slow tempo)	.89
	Consistency (tones, medium tempo)	.72
	Consistency (tones, fast tempo)	.89
	Consistency (music)	.89
Adaptive tapping	*d'* (acceleration, -75% IOI)	2.31
	d' (acceleration, -30% IOI)	1.12
	d' (deceleration, +30% IOI)	1.14
	d' (deceleration, +75% IOI)	1.66
	Adaptation index (acceleration)	.49
	Adaptation index (deceleration)	.25

Results

BAASTA

Perceptual timing tasks

The results of the perceptual tasks of the BAASTA are shown in Figure 5.9[1]. Perceptual thresholds for Duration discrimination, Anisochrony detection with tones and music, and *d'* values and error rates for the BAT are reported. In the Duration discrimination task, all three blocks were discarded for L.V. and for two controls (i.e., for them, there was no valid estimation of the threshold), two blocks were removed for two controls, and one block for one additional control participant. In the Anisochrony detection task with a metronome (600 ms), one block was discarded for two controls. Finally, in the Anisochrony detection task with music one block was removed for L.V. and for three controls. Removal of all these blocks was due to an excess of FAs. For L.A., thresholds could not be reliably computed using the MLP procedure, due to the inconsistency of her responses. In addition, she was unable to distinguish between the examples during the practice trials, in spite of the fact that maximum duration differences (60% of the intervals) were presented. L.A. exhibited very poor detection of misaligned beats in the BAT (i.e., very low *d'*), and a higher error rate for both period and phase change trials than controls. L.C. showed poorer performance than controls in the Anisochrony detection task with tones and in the BAT (higher error rate for phase changes). She also obtained a particularly high detection threshold in the Duration discrimination, but this result was not confirmed when the task was repeated (threshold = 17.31). Finally, L.V. exhibited difficulties in detecting anisochronies with tones and showed poor detection of aligned beats in the BAT (lower *d'* for fast and slow trials, higher error rates for both period and phase changes).

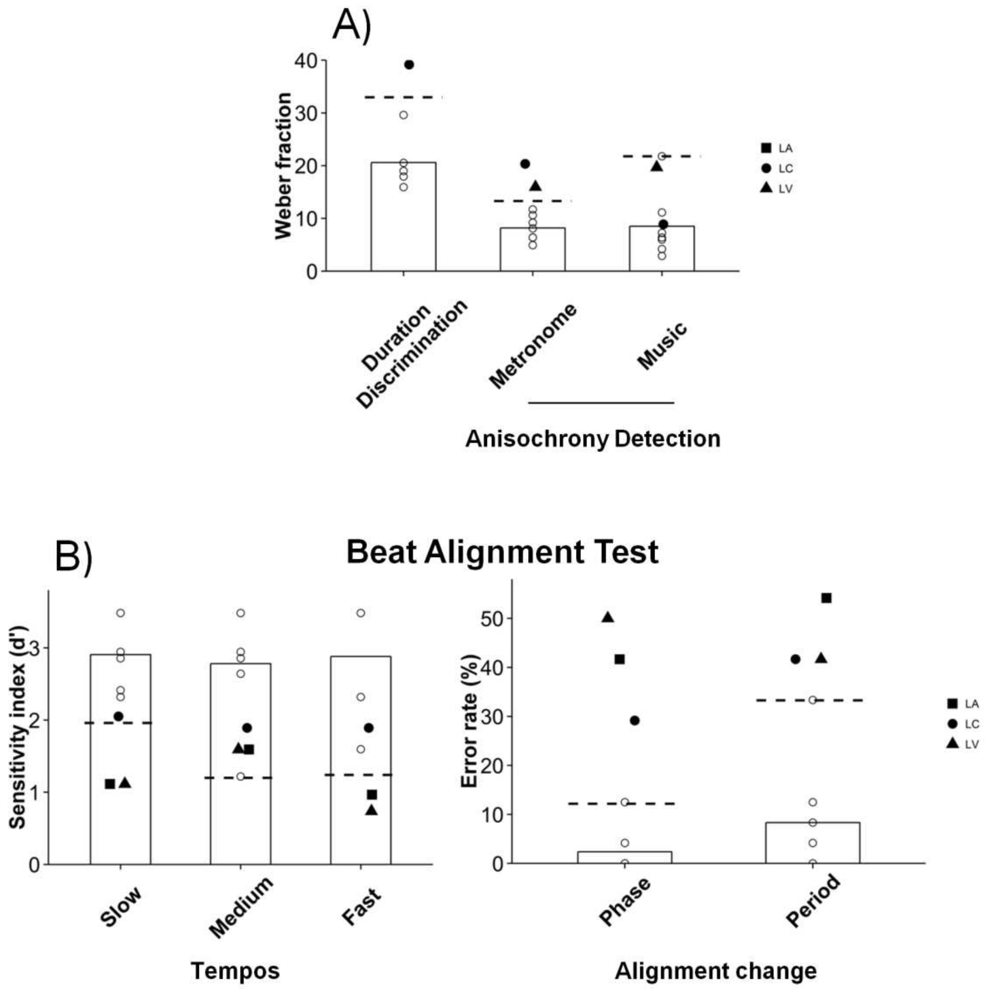

Figure 5.9. Results obtained by L.A., L.C., and L.V. and by matched controls in A) Duration discrimination, Anisochrony detection with tones and music, and B) in the BAT. Unfilled circles indicate controls' individual performances and bars represent controls' means. Dotted lines indicate the cut-off score.

Sensorimotor timing tasks

The results obtained by beat-deaf participants and controls in Unpaced and Paced tapping are presented in Figure 5.10. The three beat-deaf participants showed motor variability comparable to controls in the Unpaced tapping task. In addition, L.A. and L.C.'s spontaneous motor tempo (ITI = 681.10, 717.74 ms, respectively) did not differ from that of controls (mean ITI = 563.71, *SD* = 88.64). Only L.V.'s spontaneous tapping rate (ITI = 913.84 ms) was significantly slower as compared to controls ($t(6) = 3.26, p < .01$).

The results in the Paced tapping tasks showed that the beat-deaf participants were well above chance, as assessed by the Rayleigh's test, except for L.V., who could not synchronize with musical stimuli. L.A. and L.C. were as consistent as controls in synchronizing to both a metronome and to music. L.V., in contrast, was less consistent than controls when tapping to isochronous sequences (with 450-ms and 750-ms IOI), and to music.

The results of the Adaptive tapping task are reported in Figure 5.11. As can be seen, L.A. and L.C. performed poorly in the perception part of the task. Their performance was lower than that of controls in detecting small tempo accelerations (-30% of the IOI). In contrast, all three beat-deaf participants were capable to adapt their tapping to the temporal like controls did, as shown by the adaptation indexes.

Results in the Synchronization-continuation task from the three beat-deaf participants were comparable to controls' performance. Mean motor variability in the continuation phase (CV of the ITIs) for the control group was .03 (range = .02 - .06), and .04, .06, and .05 for L.A., L.C. and L.V., respectively.

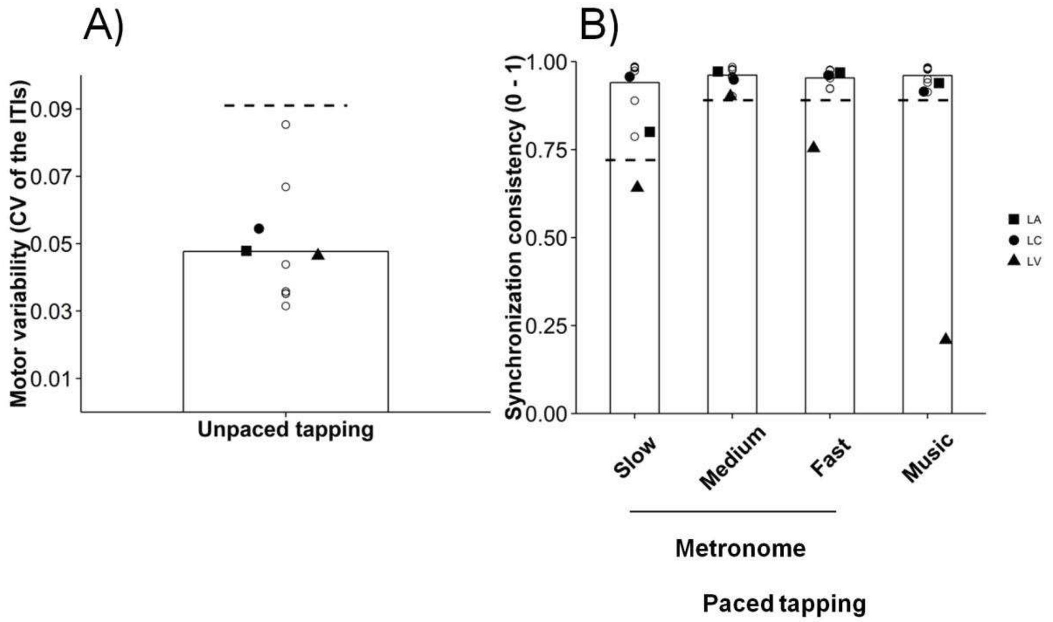

Figure 5.10. Results obtained by L.A., L.C., and L.V. and by matched controls in the tapping tasks of the BAASTA (A – Unpaced tapping; B – Paced tapping).

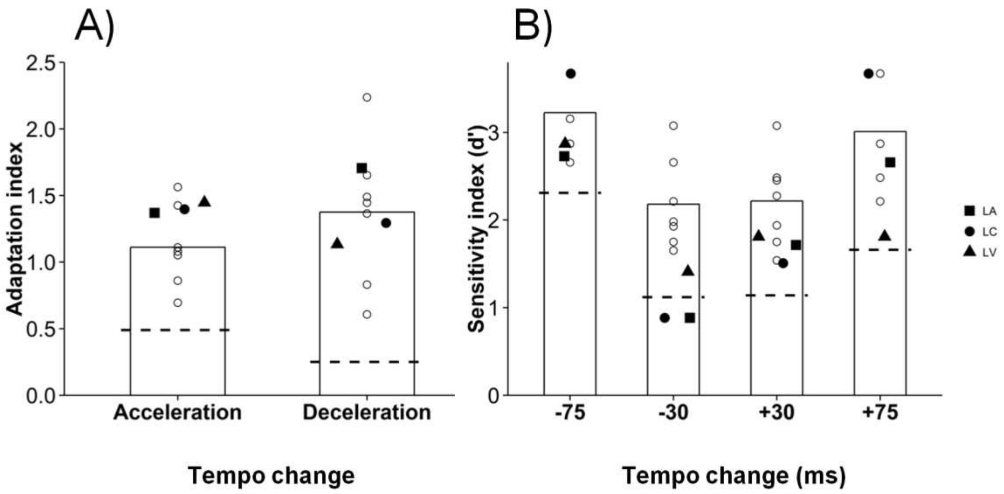

Figure 5.11. Results obtained by L.A., L.C., and L.V. and by matched controls in the Adaptive tapping task of the BAASTA (A – adaptation index; B – performance in the tempo change detection task).

Dissociation between perception and action

RSDT confirmed that perception and action dissociated in L.A. and L.C., showing impaired perception in the presence of spared synchronization relative to controls. Differences were found when comparing Anisochrony detection with a metronome and Paced tapping with a metronome for L.C. ($t(6) = 13.73$, $p <.0001$). In addition, a comparison of the BAT (error rate) and paced tapping with music (vector length) showed a significant dissociation of the two tasks for both L.A. (error rate, phase: $t(6)= 8.05$, $p <.0001$; error rate, period: $t(6) = 4.24$, $p <.001$) and L.C. (error rate, phase: $t(6) = 6.66$, $p <.0001$; error rate, period: $t(6) = 4.03$, $p <.001$). Finally, in Adaptive tapping, a dissociation was found between perception (*d’*) and synchronization (adaptation index for deceleration) in L.A. ($t(6) = 1.94$, $p <.05$).

MBEA

The pitch-composite scores obtained in the MBEA for L.A., L.C., and L.V. were 25.3, 27.0 and 25.3, respectively. These scores are well above the threshold for pitch perception deficits (20.1) from a comparable age group (Cuddy et al., 2005).

Discussion

In this first Experiment, we submitted three beat-deaf participants, L.A., L.C., and L.V. and a control group to an exhaustive battery of perceptual and sensorimotor timing tasks.

The results of L.A and L.C. indicate a dissociation between perception and action in explicit timing tasks. They both performed poorly when asked to detect a shift in an isochronous sequence, with thresholds above 14% of the interval between the tones. L.C. was also unable to judge whether a repeated tone was aligned or not to the musical beat. This is rather surprising as she was perfectly able to tap to the beat of the same excerpts. Indeed, in spite of their poor beat perception, L.A. and L.C. could synchronize to the beat of both simple and complex (i.e., musical) auditory sequences. Note that L.A. was very consistent in tapping to the beat. In addition, L.A. and L.C. could tap at a spontaneous tempo in the absence of a pacing stimulus comparable to controls. The performance in the adaptive tapping task is particularly critical to test the relation between perception and action. The task requires both a perceptual judgment of a change in the stimulus rate, and a motor adaptation to this change during synchronization. Interestingly, both L.A. and L.C. exhibited difficulties in the perceptual judgment, while they were fully capable to adapt to the change in tapping. Finally, the beat-deaf participants exhibited unimpaired pitch perception, as shown by the MBEA, which confirms that they were not tone-deaf.

Beat deafness was originally described as an impairment in beat processing, both in perception and performance (Palmer et al., 2014; Phillips-Silver et al., 2011). Impaired beat tracking and poor synchronization was found in L.V. showing that the tasks used in the present study (BAASTA battery) are sensitive to disorders in rhythm processing previously described in the literature. Some of the tasks of BAASTA were used in our previous studies to pinpoint individual differences in timing skill in the general population (Sowiński & Dalla Bella, 2013). In this study, some individuals showed poor synchronization to the beat with or without poor beat perception. Here, we report for the first time two cases (L.A. and L.C.) presenting the opposite pattern of impairment, namely poor beat perception with spared synchronization across various tasks. This finding may appear paradoxical, as we may expect that difficulties in beat tracking or in perceiving shifts in a regular sequence in explicit tasks negatively impinge on synchronization. The fact that beat-deaf participants can move to the beat suggests that temporal information, which cannot be overtly treated, may still be processed implicitly, and thereby subserves synchronization to the beat. Implicit timing skills have not been tested so far in beat deafness. The possibility that covert timing skills may be spared in beat-deaf participants was therefore tested in Experiment 2 using an implicit timing task.

Experiment 2

Methods

Participants

The three beat-deaf participants tested in Exp. 1 (L.A., L.C. and L.V.) participated in the Exp. 2. Five age-matched participants (3 females) who did not take part in Exp. 1[2] formed the control group (mean age: 25 years, *SD*: 3.39, range: 20-28).

Material and procedure

The implicit timing task is an adaptation of the classical temporal orienting task, as illustrated in Figure 5.12. The task consists in responding as fast as possible to a 50-ms target sound (pitch = 400 Hz) presented after a sequence of six 50-ms tones (pitch = 700 Hz). Participants were instructed to focus on the target sound without paying attention to the preceding sequence. The sequence preceding the target was either regular or irregular. In the regular sequence the IOI between the tones was constant (550 ms), while in the irregular sequences, the IOI was pseudo-randomly distributed around the mean of 550 ms (IOI range = 150, 350, 550, 750, or 950 ms). The target sound was always displayed for 1100 ms (2 x IOI) after the last sound of the preceding sequence. There were 240 trials (120 regular and 120 irregular trials) divided in 4 blocks of 60 trials each. Regular and irregular trials were presented in random order in each block. One block lasted 7 minutes, with a 1-min break between the blocks. The task was implemented in E-Prime 1.0 software (Psychology Software Tools, Pittsburgh, PA).

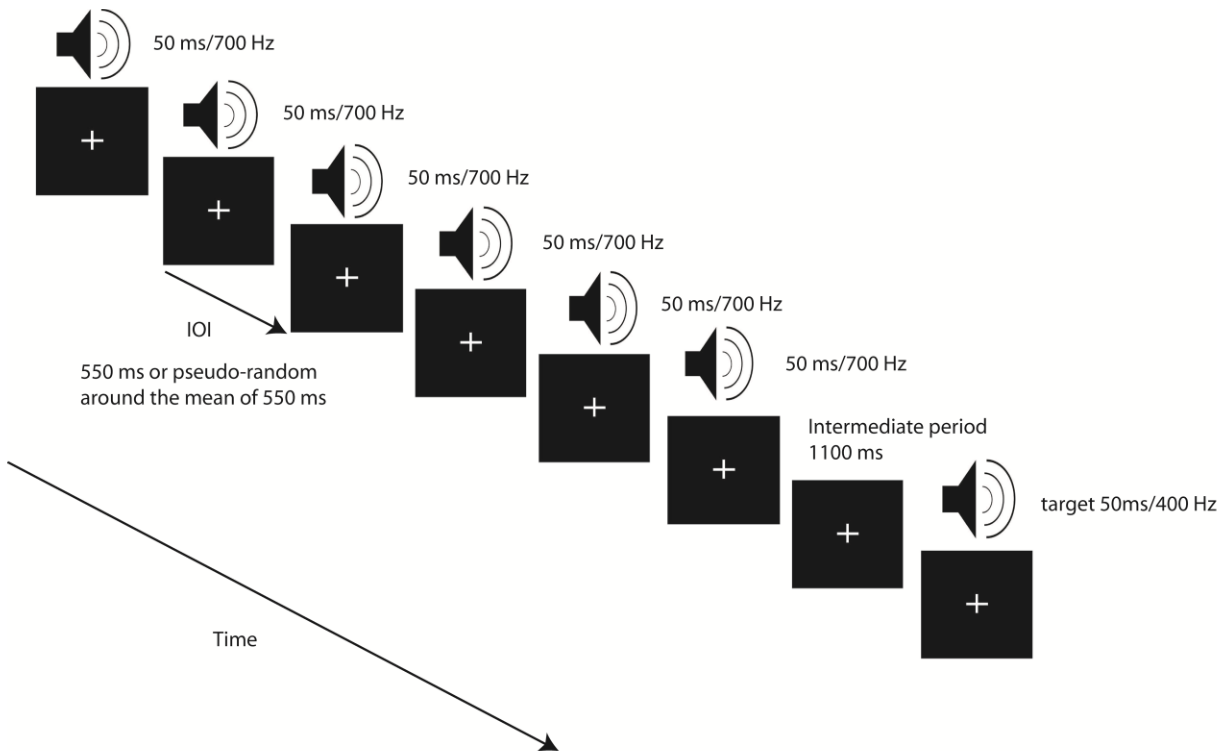

Figure 5.12. Schema of the implicit timing task

Results

Mean reaction times (RT, in ms) in the regular and in the irregular conditions were computed for L.A., L.C., L.V., and for control participants. Differences between the irregular and the regular conditions are reported in Figure 5.13. RTs for regular sequences (M = 247.43 ms, SD = 39.99) were lower than for irregular sequences (M = 269.15 ms, SD = 36.99) for the control group ($t(4) = 6.88$, $p < .01$). Similar to Exp. 1, the performance of the three beat-deaf participants was compared to that of controls using single-case statistics with the *Singlims* program (Crawford & Garthwaite, 2002; Crawford & Howell, 1998). No differences were found between the three beat-deaf participants and the control group, suggesting that they similarly benefited from the regularity in the preceding sequence.

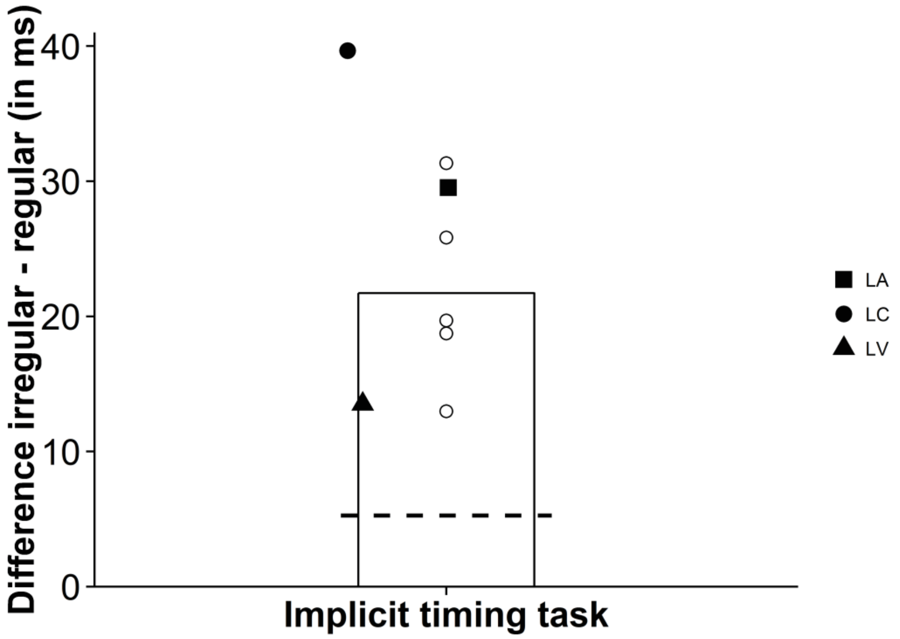

Figure 5.13. Individual results obtained from L.A., L.C., and L.V. and from the controls in the implicit timing task.

Discussion

The results obtained in the implicit timing task showed beneficial effects of temporal regularity of the sequence preceding target detection. Reaction times to a target were faster when a regular sequence was presented before the target rather than an irregular one. This finding is consistent with previous results obtained in the same task (Cutanda, Correa, & Sanabria, 2015; De la Rosa, Sanabria, Capizzi, & Correa, 2012). Exp. 2 showed that despite the fact that L.A., L.C., and L.V. had difficulties in performing explicit timing tasks, they could still track the beat covertly, and benefitted from regularity in a reaction time task. As the beat-deaf participants were sensitive to the temporal regularity of a sequence in a perceptual task, implicit timing processes may provide sufficient information to synchronize to the beat.

It has been suggested that explicit and implicit dimensions of timing engage distinct processes, which can be dissociated. Zelaznik, Spencer and Ivry (2002) showed that performing a continuous movement task (i.e., circle drawing) relies on an emergent, implicitly controlled timing mechanism that is independent of an explicit temporal representation of durations in tasks such as tapping or duration discrimination. Accordingly, implicit and explicit timing are likely to be supported by different neuronal substrates (Coull & Nobre, 2008; Coull, Cheng, & Meck, 2011). Whereas basal ganglia activity is typically observed in explicit timing tasks with co-activation of other brain regions depending on the task (e.g., pre-SMA, right inferior cortex in duration discrimination), implicit timing and temporal prediction recruit more parietal (e.g., left inferior parietal) and pre-frontal (pre-motor areas) cortical regions as well as the cerebellum (Schwartze & Kotz, 2013; Ivry & Keele, 1989). Thus, the present findings are in line with the existing literature on implicit and explicit timing, and provide first evidence that they can dissociate in beat deafness.

However, it is worth noting that there is growing evidence in favor of a common internal representation of duration in both explicit and implicit timing tasks (Piras & Coull, 2011). A shared internal representation seems to contrast the reported discrepancy between explicit and implicit timing in beat deafness. Still, our findings are not incompatible with the idea that an internal representation of duration is eventually spared, as beat-deaf participants can use it covertly in the implicit timing task. Beat deafness may result from a deficit in the conscious access to a spared representation of duration, leading to poorer performance in explicit beat tracking tasks. This possibility is discussed in more depth in the General discussion.

General discussion

Here we presented two cases of beat deafness (L.A. and L.C.) showing that poor beat perception can co-occur with spared synchronization to the beat. A third case (L.V.) displayed severe timing deficits encompassing perception and action. L.A. and L.C. showed poor perception of changes in regular auditory periodic sequences, or in judging whether a metronome is aligned or not to the beat of music. In spite of poor perception, however, they could tap to the beat of the same stimulus. To the best of our knowledge, this dissociation is reported here for the first time. These findings are reminiscent of the dissociation between perception and action found on the pitch dimension (in tone-deafness and poor-pitch singing; Berkowska & Dalla Bella, 2013; Dalla Bella, Berkowska, & Sowiński, 2011; Dalla Bella et al., 2009, 2015; Loui, Guenther, Mathys, & Schlaug, 2008), and confirm the existence of different phenotypes of rhythm disorders, resulting from either poor perception and/or deficient auditory-motor integration (Sowiński & Dalla Bella, 2013).

In the first reported case of beat deafness (Mathieu) it was hypothesized that this condition is the outcome of deficient beat perception (Phillips-Silver et al., 2011). Our findings, however, indicate that poor perception does not entail poor synchronization, and complement the dissociation showing poor synchronization in the presence of unimpaired beat perception already documented in patients with brain damage (Fries & Swihart, 1990; Provasi et al., 2014), and in healthy non-musicians (Sowiński & Dalla Bella, 2013). Notably, this finding does not preclude the possibility that in general beat perception and synchronization to the beat are highly coupled in individuals without rhythm disorders. Indeed, performance in perceptual and sensorimotor timing tasks is typically correlated (e.g., Keele, Pokorny, Corcos, & Ivry, 1985). This link between perception and action may weaken, however, as a result of brain damage (e.g., cerebellar damage, Provasi et al., 2014; Schwartze, Keller & Kotz, 2016) or of a developmental disorder (Sowiński & Dalla Bella, 2013).

To date, beat deafness has been associated with poor beat perception and with impaired sensorimotor mapping. As beat-deaf participants perform within the range of controls in pitch perception tasks requiring working memory or attention (e.g., from the MBEA; Peretz, Champod & Hyde, 2003) these cognitive processes are supposedly spared. Yet, there is some recent EEG evidence indicating attentional deficits, in at least some cases of beat deafness. Mathias and collaborators (Mathias et al., 2016) showed a normal Mismatch Negativity to beat irregularities in beat-deaf participants, indicating unimpaired pre-attentive processing. However, one case of beat deafness (Mathieu) revealed abnormalities in later attentional processes (reduced P3b response to deviant tones). This finding suggests that attentional deficits relate to beat deafness.

It is intriguing that poor beat perception uncovered by a battery of explicit timing tasks (BAASTA; Dalla Bella et al., 2017a) did not extend to an implicit timing task. The three beat-deaf participants were sensitive to the temporal regularity of a sequence, which facilitated the detection of a pitch difference in a reaction-time task. This finding points to some form of covert extraction of the beat, which is likely to afford synchronization. When moving to the beat listeners have to extract the beat of the stimulus to which they synchronize. If explicit beat tracking is not working properly, another mechanism has to provide the perceptual input needed to couple perception and action. A possibility is that different representations of durations are needed to track the beat, and to synchronize to it in explicit tasks. A representation of temporal duration built covertly may be sufficient to perform on an implicit timing task, and to provide perceptual input to support synchronization to the beat. This explanation, however, may not be as straightforward. Indeed, there is evidence suggesting that implicit and explicit timing rely on the same internal representation of duration (Piras & Coull, 2011). Another possible explanation is a deficit in the conscious access to the same internal representation. An intact internal representation of the beat, albeit not consciously accessible by L.A. and L.C. in explicit timing tasks, may be processed covertly in order to afford synchronization. This explanation is compatible with the observation that all beat-deaf participants showed covert beat processing.

The finding that beat deafness is associated with spared implicit processing of temporal regularity shows that implicit processing of rhythmic properties of the signal is probably more robust than its explicit treatment. A similar dissociation was observed in other domains such as memory (e.g., Schacter & Graf, 1986), vision (Weiskrantz, Warrington, Sanders, & Marshall, 1974), and language (Ellis, 2005). Implicit timing has also been shown to be resistent to an interfering task (e.g., an auditory working memory task; Cutanda, Correa, & Sanabria, 2015). Note that this distinction between implicit and explicit processing has also been investigated for pitch in patients with brain damage (Tillmann, Peretz, Bigand, & Gosselin, 2007), or in congenital amusia (Omigie, Pearce, & Stewart, 2012; Tillmann, Gosselin, Bigand, & Peretz, 2012). For example, congenital amusics respond faster to notes with high probability than with low probability in the context of a melody (Omigie, Pearce & Stewart, 2012). This dissociation between explicit and implicit pitch processing in congenital amusia is supported by psychophysiological evidence. Individuals with congenital amusia, in spite of their severe deficits in treating pitch information in explicit tasks, show normal brain responses to small pitch changes (Peretz, Brattico, Järvenpää, & Tervaniemi, 2009). It was concluded that in congenital amusia the neuronal circuitries needed to perceive fine-grained pitch differences are likely to be spared; yet, lack of awareness prevents them from accessing these differences in an explicit task. A similar explanation may apply to the rhythm dissociation described in the present study. This dissociation awaits further confirmation in a larger group of beat-deaf participants, and by comparing their performance in explicit and implicit tasks to that of the same control group.

Explicit and implicit timing mechanisms have been linked to separate neural substrates. A cortico-striato-cortical network has been associated with explicit timing (Coull & Nobre, 2008) while an inferior parietal-premotor network, linked to the cerebellum, was associated with implicit timing and temporal prediction (Coull & Nobre, 2008; Nobre & Coull, 2010; Coull, Warren & Meck, 2011; Zelaznik, Spencer, & Ivry, 2002; Kotz & Schwartze, 2010; Schwartze & Kotz, 2013). It is possible that beat-deaf individuals recruit additional or spared neural pathways to compensate for impaired explicit timing. Consequently, impaired performance in explicit timing tasks may be associated with a malfunctioning network involving the pre-Supplementary Motor Area (pre-SMA) and the Basal Ganglia (BG) (Schwartze, Rothermich & Kotz, 2012). Spared synchronization in L.A. and L.C. may be supported by motor areas (dorsolateral striatum, SMA proper) in addition to regions involved in implicit timing such as the cerebellum and left inferior parietal regions (Coull, Warren and Meck., 2011; Kotz & Schwartze, 2010; Schwartze & Kotz, 2013). These possibilities should be addressed in future studies examining brain responses and neural connectivity in beat-deaf individuals in both explicit and implicit timing tasks.

FOOTNOTES

[1]In order to confirm that L.A. and L.C.'s deficits in perceptual tasks were not due to an effect of practice, these participants were tested a second time on these tasks. All the results were confirmed except the deficit in Duration discrimination for L.C.

[2] Controls were submitted to the BAASTA to ensure that their explicit timing skills were unimpaired. Their results were comparable to those of the control group in the first Experiment.

6. **Chapter 6**. Training of rhythm skills. Study 4: *Rhythm Workers*: A music-based serious game for training rhythm skills

Study 4: *Rhythm Workers*: A music-based serious game for training rhythm skills[5]

Abstract: Most people, musicians and non-musicians alike, can naturally and precociously perceive or produce rhythmic sounds. These skills can be disrupted by developmental or neurological disease (e.g., Parkinson's disease, dyslexia). Poor rhythmic skills have been linked to impoverished cognitive functioning in areas such as language, attention and working memory. Re-training rhythmic skills may provide a promising avenue for improving the associated cognitive domains. To date, there is no tool for training selectively rhythmic skills. To this end, here we present a new protocol implemented in a serious game named *Rhythm Workers* on a tablet device. Experiment 1 served to select the musical material. A set of 54 musical excerpts with increasing rhythmic complexity was selected. Selection was based on the tapping performance of 18 non-musicians who tapped to the beat of music. The excerpts were sorted in terms of the difficulty to track their beat, and assigned to different difficulty levels in the training protocol. In Experiment 2, the Rhythm Workers protocol was devised and tested in a proof-of-concept study, including two versions of the game. One version (*tapping version*) required a synchronized motor response (via tapping), while the other (*perceptual version*) was a perceptual task. Ten participants were trained with one version and 10 with the other version of Rhythm Workers, for 2 weeks. A control group (n = 10) did not receive any training. Participants in the experimental groups showed high compliance and motivation in playing the game. The effect of the training on rhythm skills yielded encouraging results with both versions of the game. *Rhythm Workers* thus appears as a motivating and potentially efficient way to train rhythmic abilities in healthy young adults, with possible applications for (re-)training these skills in individuals with rhythm disorders.

Keywords: Rhythm; Training; Sensorimotor synchronization; Rhythm perception; Music cognition

[5] This study was submitted to *Music & Science.*
Bégel, V., Seilles, A., & Dalla Bella, S. (submitted). Study 4: *Rhythm Workers*: A music-based serious game for training rhythm skills. *Music & Science*.

Introduction

Most of us can easily track the beat of rhythmic auditory events, such as music, and move along with it. This can be seen when we synchronize our movement to the rhythm of music while dancing, marching, doing sport activities (e.g., jogging to the beat of music). This ability is widespread in the general healthy population (Repp, 2010; Sowiński & Dalla Bella, 2013), with just a few exceptions (e.g., beat deafness, Bégel et al., 2017; Launay, Grube, & Stewart, 2014; Palmer, Lidji, & Peretz, 2014; Phillips-Silver et al, 2011; Sowiński & Dalla Bella, 2013). Moving to musical rhythm implies that listeners can extract the beat from an auditory sequence. The beat is defined as a perceived pulse that marks equally spaced points in time (Large & Jones, 1999; London, 2012), to which we usually move when we tap our finger/foot or in dance. Beat tracking can be tested in purely perceptual tasks (e.g., detecting a deviation from isochrony in a sequence of tones, Ehrlé & Samson, 2005) or in sensorimotor tasks (e.g., paced tapping to the sounds of a metronome or to music, Repp, 2005; Repp & Su, 2013). In the past few years, batteries including both perceptual and sensorimotor tasks have been developed for the evaluation of rhythmic and timing abilities, such as the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA, Dalla Bella et al., 2017a) and the Harvard Beat Alignment Test (H-BAT, Fuji & Schlaug, 2013). These batteries are highly valuable as they allow to characterize the timing capacities of distinct populations and to highlight inter-individual differences (Bégel et al., 2017; Benoit et al., 2014; Dalla Bella et al., 2017a; Falk, Müller, & Dalla Bella, 2015).

Rhythmic skills are sustained by a complex neuronal network. Notably, even in the absence of a motor response, mere extraction of the beat from an auditory signal recruits motor regions of the brain, such as the basal ganglia, premotor cortex, pre-SMA, and the cerebellum (Chen, Penhune, & Zatorre, 2008a; Coull, Cheng, & Meck, 2011; Grahn & Brett, 2007; Grahn & Rowe, 2009) on top of perceptual regions (superior temporal gyrus; Chen, Penhune, & Zatorre, 2008b; Schwartze & Kotz, 2013; Thaut, 2003). When a motor response is coupled to an auditory rhythm this network extends to sensorimotor integration areas (e.g. dorsal premotor cortex Chen, Zatorre, & Penhune, 2006; Coull, Cheng, & Meck, 2011; Zatorre, Chen, & Penhune, 2007). Structural and functional damage in these regions typically affects rhythmic skills in neurodegenerative disorders (e.g., Parkinson's disease; Jones & Jahanshahi, 2014; Benoit et al., 2014; Grahn & Brett, 2009; Pastor, Jahanshahi, Artieda, & Obeso, 1992; Spencer & Ivry, 2005) or neurodevelopmental deficits (ADHD, Noreika, Falter, & Rubia, 2013; Puyjarinet et al., under revision. See Annex; stuttering, Falk, Müller, & Dalla

Bella, 2015; Autism Spectrum Disorder, Allman, Pelphrey, & Meck, 2012; speech and language impairments, Corriveau & Goswami, 2011; Corriveau, Pasquini & Goswami, 2007; Goswami, 2011; Huss et al., 2011). Timing and rhythmic skills can be also be selectively deficient in healthy adults (beat deafness, Bégel et al., 2017; Launay, Grube, & Stewart, 2014; Palmer, Lidji, & Peretz, 2014; Phillips-Silver et al., 2011; Sowiński & Dalla Bella, 2013; tone deafness, Dalla Bella & Peretz, 2003; Dalla Bella, Berkowska, & Sowiński, 2015). Interestingly, the ability to track the beat has been associated with other cognitive abilities such as working memory, sustained attention or language and reading skills in children (Tierney & Kraus, 2013; Woodruff Carr et al., 2014).

Altogether these studies indicate that there is a tight link between rhythmic skills, motor, and cognitive functions. Because of that link, one may expect that an improvement in rhythmic skills may positively affect both motor and cognitive functioning. Rhythmic training may provide a viable strategy to improve other functions above and beyond rhythm. This possibility finds some confirmation in studies showing the beneficial effect of rhythmic stimulation on motor functions and cognition. For example, rhythmic training in which patients with movement disorders such as patients with Parkinson's disease walk together with a metronome or music improves their gait, by increasing speed and stride length (Dalla Bella et al., 2017a; de Dreu et al., 2012; Thaut et al., 1996; Spaulding et al., 2013) and reduces their deficits in rhythm perception and production (Benoit et al., 2014; Dalla Bella et al., 2017b). In addition, rhythmic stimulation (e.g., rhythmic priming) can be used for improving speech perception in children with dyslexia, and with Specific Language Impairment (e.g., Przybylski et al., 2013; Schön & Tillmann, 2015).

In sum, training rhythmic skills appears as a promising avenue for improving movement and cognition in a variety of populations. To the best of our knowledge, no systematic protocol for training selectively rhythmic skills was proposed so far. The goal of this study was to devise and test a new rhythm training protocol which is implemented as a serious game exploiting new mobile technologies. A serious game is a game designed specifically for training and education purposes, such as providing a dedicated training for rehabilitation/remediation, in an entertaining and motivating fashion, while being widely accessible to the targeted public and remaining low-cost (Annetta, 2010; Kato, 2010). Over the past two decades, serious games have been extensively used in therapy (for a review, see Rego, Moreira, & Reis, 2010). Several studies proved that serious games involving motor exercises have beneficial effects on movement capacities in stroke (Friedmann et al., 2014; Webster & Celik, 2014), in Parkinson's disease (Barry, Galna, & Rochester, 2014; Harris et al., 2015; Mendes et al., 2012), and in healthy older adults (Sun & Lee, 2013). Dedicated cognitive training, such as working memory or executive function training via serious games has also yielded encouraging results over the past ten years (e.g., Anguera et al., 2010; for review, see Lumsden et al., 2016; However, for a discussion on the limit of computerized cognitive training, see Owen et al., 2010).

There are a few examples of rhythmic games in the market, such as Guitar Hero® or Rhythm Heaven Fever®. Unfortunately, none of these games is specifically dedicated to rhythmic training, and comply with the measurement standards needed for experimental work, as we highlighted in a recent survey (Bégel, Di Loreto, Seilles, & Dalla Bella, 2017). First, measures of rhythmic motor performance lack temporal precision in the presentation of stimuli and/or data acquisition. The output data is insufficient since there is no measure of rhythm performance recorded. Second, there is usually no progression in the games based on the rhythmic features of the musical stimuli. Therefore, these games do not train selectively rhythmic skills. These drawbacks make the use of off-the-shelf rhythm games impossible.

Here we devised a new serious game for training perceptual and sensorimotor rhythmic skills, named *Rhythm Workers*. The game uses rhythmic patterns and musical stimuli with different degrees of beat saliency, assessed in a first experiment. As rhythmic skills pertains to both perception and action (e.g., Grahn & Brett, 2009; Hyde & Peretz, 2004; Iversen, Repp, & Patel, 2009; Repp, 2005; Repp & Su, 2013), we devised two versions of the game. In the *perception* version of Rhythm Workers, the training is performed with an adapted version of the Beat Alignment Test (BAT, Iversen & Patel, 2008). The player detects if a sequence of percussion sounds (a metronome) is aligned to the beat of the stimulus or not. In the *tapping* version, the goal is to tap to the beat of the stimulus as accurately as possible. Having two different versions of the game is particularly useful, as perceptual training alone may be sufficient for improving rhythmic skills. Indeed, beat perception in the absence of associated movement is sufficient for activating motor regions of the brain (Grahn & Brett, 2007; Grahn & Rowe, 2009).

The study consists of two experiments. The goal of the first experiment is to select and validate the musical material. In particular, the experiment served to rank the musical stimuli from high to low beat saliency, tested with a tapping task. Beat saliency is critical for creating difficulty levels in the game. Players in both the perception and the tapping versions of the game need to extract the beat in order to complete the tasks with success. This will be more difficult when the beat has low saliency than when the beat is very salient. When the beat is less salient, beat extraction will particularly recruit mechanisms devoted to the internal generation of the beat (Grahn & Rowe, 2009). The second experiment is a proof-of-concept pilot study, with the goal of testing usability of Rhythm Workers and compliance with a training protocol using this serious game. Healthy young adults played the game on a tablet device at home for two weeks. Usability of the serious game and motivation all along the training protocol were tested. Moreover, in order to obtain first evidence on the effect of Rhythm Workers on rhythm skills, participants were submitted to a version of the BAT taken from BAASTA (Dalla Bella et al., 2017a), before and after the training. This task was chosen as it is a good indicator of beat perception skills, and has been proven to be very sensitive to inter-individual differences (e.g., Bégel et al., 2017; Falk, Müller, & Dalla Bella, 2015). The BAT was successfully used in the past to show changes in rhythm skills following training of gait with rhythmic auditory stimulation (in Parkinson's disease; Benoit et al., 2014).

Experiment 1

The goal of Experiment 1 is to select the musical excerpts for *Rhythm Workers* and to rank them from high beat saliency (low rhythmic difficulty) to low beat saliency (high rhythmic difficulty). The selection of the other stimuli included in the game (metronome and metrical sequences) was not part of this experiment, but is reported in Experiment 2 (Material and Procedure).

Participants

Eighteen participants (5 females, mean age = 26, *SD* = 3.4) without musical training volunteered to participate in the experiment.

Material and Procedure

An initial set of 90 musical excerpts available in MIDI format in an online music repository (http://www.midiworld.com) was selected from three musical genres, 30 from classical music, 30 from jazz, and 30 from pop music. The choice of musical stimuli across different genres affords variety among the excerpts in terms of beat saliency. In addition, it has the advantage to make the game less monotonous and more attractive for players regardless of their musical preferences. For stimuli in which vocal performance was part of the excerpt, the voice was replaced by a melody with a piano timbre. All excerpts were rated by four members of the laboratory (two musicians), experts in timing and rhythm research, in terms of beat saliency, pleasantness, and familiarity. Beat saliency was rated on a seven-point scale (1 = the beat can be hardly perceived, 7 = the beat can be easily perceived). Similar scales were used to rate stimulus pleasantness (1 = not pleasant, 7 = very pleasant) and familiarity (1 = not familiar, 7 = very familiar). The stimuli were ranked based on the ratings of beat saliency, and assigned to three categories including 30 excerpts each: with 1) a highly salient beat (ratings between 5.75 and 6.75), 2) an averagely salient beat (ratings between 4.5 and 5.5), and 3), and a beat with low saliency (ratings between 1.5 and 4). Within each category the five least pleasant excerpts were discarded, leading to 75 excerpts, 25 in each category. Rating scores for pleasantness, familiarity and beat saliency of the excerpts in the three categories were compared with a one-way repeated measures Analysis of Variance (ANOVA). The three stimulus categories significantly differed in terms of average beat saliency (= 2.76 for stimuli with low beat saliency, 5 for stimuli with average beat saliency, and 6.31 for stimuli with high beat saliency; $F(2,48) = 969.23$, $p < .001$). Note that excerpts with a highly salient beat were also the most familiar ones (mean familiarity for high beat saliency = 5.68, average beat saliency = 4.91, and low beat saliency = 4.45; $F(2,48) = 5.68$, $p < .01$). The three stimulus categories did not differ in terms of pleasantness (mean pleasantness for high beat saliency = 4.69, average beat saliency = 5.03, and low beat saliency = 5.06; $F(2,48) = 2.06$, $p = .14$). In this experiment, we wanted to confirm that the excerpts with the most salient beat as rated by the four experts, were those for which the beat was the easiest to track. To do so the 75 excerpts were further tested with a tapping task on a group of non-musicians (see Participants above). Participants were asked to tap with their index finger to the beat of the excerpts, presented in a random order. We recorded their tapping performances via a Roland SPD-6 MIDI percussion pad controlled by Sonar software (LE version). In addition, participants rated the excerpts in terms of beat saliency, pleasantness and familiarity.

Analysis

Motor synchronization to the beat was analyzed with circular statistics (Fisher, 1993; for examples with tapping, Kirschner & Tomasello, 2009; Dalla Bella & Sowinski, 2015). This method consists in representing the Inter-Beat Interval (IBI) of the stimuli on a 360° polar scale. The timing of each finger tap relative to the beat is represented by an angle by comparing the time of the tap to the time of the nearest beat (Figure 6.1). Angles, treated as unitary vectors, are used to compute the resultant vector *R*. The length of vector R, between 0 and 1, represents synchronization *consistency*, namely how variable is the interval between the taps and the beat in a trial (for example, see Dalla Bella et al., 2017a; Sowiński & Dalla Bella, 2013; Kirschner & Tomasello, 2009). Consistency is treated here as an indicator of rhythmic difficulty: the lower the consistency, the more difficult it is for the participants to synchronize to the beat of music. The angle of vector *R* (θ or relative phase, in degrees) represents synchronization *accuracy* (negative angle = the participant taps before the beat, positive angle = the participant taps after the beat). Performances with tapping rates twice as fast than the expected beat, usually corresponding to the quarter note, were discarded because they artificially lead to reduced vector length, even if the tapping performance is good. The percentage of participants who tapped at the rate of the beat was calculated.

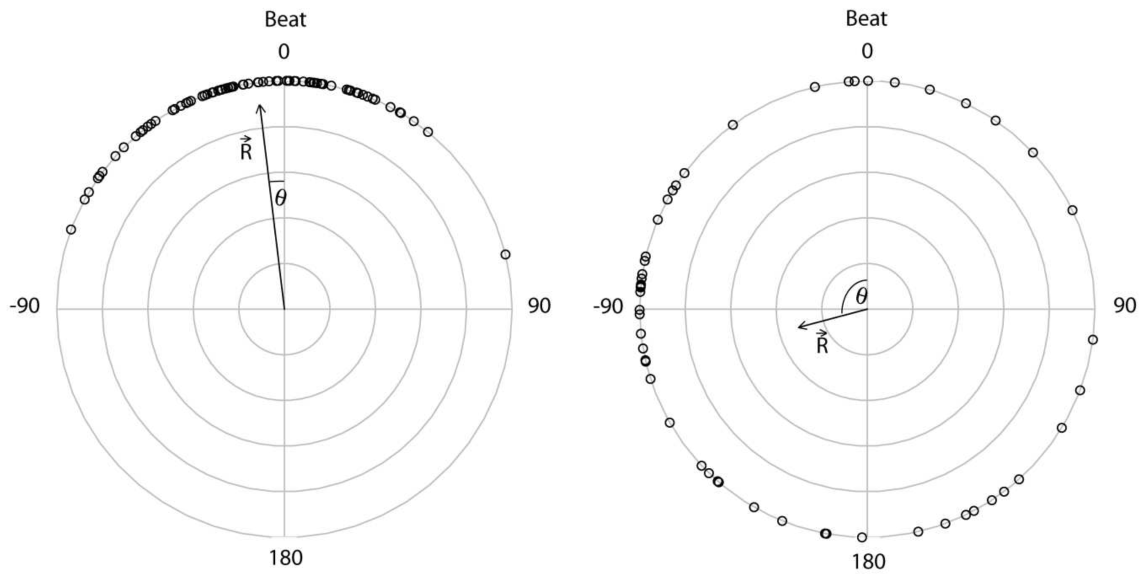

Figure 6.1. Examples of two distributions of taps corresponding to two musical excerpts. The dots represent the distributions of the timing of the taps relative to the beat (= 0 degrees) for one participant. On the left, the dots occur in the vicinity of the beat, indicating high synchronization consistency (length of vector *R* = .90). On the right, the taps are scattered around the circle, showing poor *synchronization consistency* (vector length = .31). The angle (θ) represents *synchronization accuracy*. An angle of 0° means that the taps occurred exactly on the beat. An angle of 180° indicates that the taps occurred in between the beats (i.e., in antiphase).

Finally, in order to obtain an objective measure of beat saliency, for each excerpt we computed pulse clarity, based on the acoustic signal using the "pulse clarity" function in the MIR toolbox in Matlab (Lartillot & Toiviainen, 2007; Lartillot et al., 2008). Large values in terms of pulse clarity indicate that the beat is particularly salient.

Results and Discussion

Twenty-two musical excerpts were rated below 4 in terms of pleasantness, and were thereby discarded. The final set of 53 musical excerpts[1] were ranked from the easiest to the most difficult to synchronize with based on synchronization consistency.

Table 6.1. Description of musical excerpts. Vector length (between 0 and 1) represents synchronization *consistency*. Pulse clarity (between 0 and 1), computed based on the acoustic signal, is an index of beat saliency. Metrical level indicates the percentage of participants who tapped at the expected metrical level (e.g., at the quarter note). Participants' ratings of familiarity, pleasantness, and beat saliency, provided on a 7-point scale, are also reported.

Excerpt #	Name	Composer/Band	Metrical level (%)^2	Vector length	Pulse clarity	Familiarity	Pleasantness	Beat saliency rating
1	Tutu	Davis	88.9	0.97	0.61	4.1	4.8	5.39
2	Take me out	Franz Ferdinand	100.0	0.96	0.92	3.5	4.8	4.83
3	Seven nation army	White Stripes	94.4	0.95	0.94	2.5	3.9	4.72
4	Pokerface	Lady gaga	88.9	0.95	0.68	3.8	4.8	5.22
5	Get lucky	Daft punk	88.9	0.94	0.83	6.7	6.2	6.39
6	Isn't she lovely	Wonder	55.7	0.94	0.8	2.8	4.3	3.06
7	Music	Madonna	66.7	0.94	0.55	6.0	5.6	5.78
8	Billie Jean	Jackson	83.3	0.94	0.87	5.5	5.4	4.89
9	Pavane	Fauré	55.6	0.92	0.35	5.7	5.5	5.39
10	Yellow submarine	The Beattles	77.8	0.92	0.79	6.6	5.9	6.33
11	Footprints	Shorter	77.8	0.9	0.92	3.8	4.8	4.94
12	L'Arlésienne (prelude)	Bizet	66.7	0.89	0.36	5.7	5.3	5.61
13	Peter and the wolf	Prokofiev	38.9	0.89	0.44	4.6	4.8	3.28
14	All shook up	Presley	88.9	0.89	0.71	5.2	5.3	4.5
15	Happy	Williams	66.7	0.88	0.5	3.2	4.2	3.56
16	Come as you are	Nirvana	61.1	0.87	0.9	6.2	5.6	5.72
17	Nutcraker (Arab dance)	Tchaikowsky	61.1	0.86	0.82	2.9	4.6	4.22
18	How blue	King	88.9	0.85	0.79	5.6	5.4	5.83
19	55dive	Stern	94.4	0.85	0.79	3.0	3.9	5.06
20	Round midnight	Monk	50.0	0.85	0.43	3.5	5.1	4.17
21	Walk this way	Run DMC & Aerosmith	66.7	0.84	0.9	3.1	4.4	4.11
22	Corcovado	Jobim	44.4	0.83	0.72	6.3	5.8	6.33
23	Layla	Clapton	77.8	0.82	0.89	4.5	5.0	5.33
24	Giant steps	Coltrane	72.2	0.82	0.78	5.8	5.3	3.83
25	Cumparsita	Traditional Argentina song	77.8	0.82	0.68	3.7	5.1	5.06
26	Rich girl	Stefani	88.9	0.78	0.91	2.8	4.4	2.6
27	Suite for flute in A flat	Telemann	55.6	0.78	0.34	4.4	4.9	5.0
28	Donna lee	Parker	83.3	0.78	0.7	2.5	3.4	3.1
29	Georgia on my mind	Charles	55.6	0.73	0.92	6.9	6.1	6.3
30	Sunday Bloody Sunday	U2	83.3	0.71	0.87	3.4	5.1	5.9
31	Saint Thomas	Rollins	72.2	0.68	0.66	3.8	4.7	2.9
32	Aida Overture	Verdi	83.3	0.68	0.11	4.2	4.9	4.5
33	In a sentimental mood	Ellington	61.1	0.68	0.2	5.8	5.0	6.1
34	Started	Black eyed peas	77.8	0.67	0.7	4.8	5.2	4.6
35	Symphony of psalms 1st movement	Stravinsiky	61.1	0.66	0.72	5.8	5.1	5.8
36	Balletto	Monteverdi	61.1	0.66	0.49	4.9	5.3	5.8
37	I shot the sheriff	Marley	77.8	0.66	0.82	4.7	4.8	6.2

38	My funny Valentine	Rogers & Hart	66.7	0.65	0.37	4.4	4.9	4.9
39	Meistersinger Prelude	Wagner	44.4	0.65	0.36	3.1	5.1	3.0
40	Seven steps to Heaven	Davis	72.2	0.64	0.74	4.9	5.1	5.2
41	Trout	Schubert	44.4	0.63	0.44	2.8	4.5	2.9
42	Body and soul	Hammerstein	77.8	0.61	0.17	5.3	5.6	5.6
43	Song for my father	Silver	55.6	0.59	0.88	3.8	4.7	5.2
44	Take five	Brubeck	27.8	0.56	0.66	3.1	4.8	4.2
45	Spain	Correa	55.6	0.55	0.44	3.9	5.2	4.9
46	The Magic Flute overture	Mozart	66.7	0.49	0.69	5.2	5.5	5.4
47	Anthropology	Parker	50	0.45	0.77	6	5.8	5.8
48	Black narcissus	Henderson	38.9	0.44	0.62	5.6	5.6	6.0
49	Symphony n°9 (Scherzo)	Dvorak	0[2]	0.42	0.88	6.8	4.9	6.4
50	New-York New-York	Sinatra	38.9	0.39	0.48	3.8	4.5	3.9
51	Auprivave	Parker	77.8	0.32	0.17	4.4	4.8	4.4
52	Fantaisie- Impromptu	Chopin	38.9	0.26	0.88	3.3	5.1	5.4
53	Symphony N°3 1st movement	Beethoven	0[2]	0.03	0.28	5.4	5.0	5.7

Musical excerpts ranked based on synchronization consistency, treated as an indicator of rhythmic difficulty, are presented in Table 6.1. It is worth noting that synchronization consistency is positively correlated with pulse clarity ($r = .27$, $p < .05$) and with metrical level ($r = .40$, $p < .01$). This shows that participants' ability to tap to the beat is linked to the presence of a clear pulse in the acoustic signal, and to the tendency to consistently identify the beat at a given metrical level. Highly familiar excerpts were also the most pleasant ones ($r = .85$, $p < .01$), and those for which the beat was judged as the more salient ($r = .68$, $p < .01$).

This set of 53 musical excerpts ranked for rhythmic difficulty was taken as the musical database to design a rhythm training protocol implemented in a serious game (*Rhythm Workers*). The ranking of the excerpts in Table 6.1 was used in the game to assign the excerpts to levels of increasing difficulty. The game is devised and tested in Experiment 2.

Experiment 2

This experiment is a proof-of-concept pilot study of the game *Rhythm Workers*. A small group of young adults underwent a 2-week training protocol with the game; rhythmic skills were assessed before and after the training period. The goal of this experiment is to prove the usability of the game and the compliance with the protocol. Additionally, it will provide first evidence about the effects of this training protocol on rhythmic skills.

Participants

Thirty healthy young adults participated in the experiment (8 females, mean age = 24.67, *SD* = 3.04). Participants considered themselves as non-musicians (average musical training = 1.63 years, *SD* = 2.14). The participants were randomly assigned to one of three groups: *control* (*n* = 10), *tapping* (*n* = 10), and *perception* (*n* = 10). Participants were remunerated for participating in the experiment.

Experimental design

Training protocol: *Rhythm Workers*

Stimulus material

In addition to the musical excerpts selected in Experiment 1, nine metronome sequences (isochronous sequences of tones) and thirty-seven rhythmic sequences were created. The metronome sequences are formed by 80 isochronously presented tones. Rhythmic sequences are temporal patterns of tones with different durations and with an underlying beat. There were 18 strongly metrical sequences and 19[1] weakly metrical sequences defined based on the classification of Povel and Essens (1985; see also Patel, Iversen, Chen, & Repp, 2005) (see Table 6.2). The beat underlying strongly metrical sequences is typically easier to track than in weakly metrical sequences (Patel et al., 2005). In both metronome and rhythmic sequences the timbre of the tones was a woodblock percussion sound.

To create different levels of rhythmic difficulty, the beat rate of metronome sequences and rhythmic patterns was manipulated. An IBI of 600 ms corresponds to the natural rate at which on average individuals tap in the absence of a pacing stimulus (Repp & Su, 2013; Repp, 2005). Stimuli with this beat rate are thus considered as the easiest to tap along with. Difficulty was manipulated by progressively deviating from this optimal rate. We created sequences with IBIs which are 10, 20, 30 and 40% faster or slower than 600 ms for metronome sequences (IBI range: 360-840ms), and 10, 20, 30 and 40% and +50% faster or slower than 600 ms for rhythmic sequences (range: 360-900 ms). Two strongly and weakly metrical sequences were created for each tempo[1]. In order to make the game less monotonous, faster and slower stimuli were interleaved.

Table 6.2. Metrical sequences. Tempos of the sequences were manipulated as follows: the first two sequences were presented with a tempo of 100 Beats Per Minute (BPM ; IBI = 600 ms). The following sequences' tempos were either progressively reduced or increased by 10% of the original BPM value with steps of 10%.

<table>
<tr><th>Tempo (BPM)</th><th>Sequence #</th><th>Strongly Metrical</th><th>Weakly metrical</th></tr>
<tr><td>100</td><td>1</td><td>xxxx | x . .x | x .x . | x</td><td>xxxx | x .xx | .x . . | x</td></tr>
<tr><td>100</td><td>2</td><td>xxx . | x .xx | x . .x | x</td><td>xxxx | .x . . | xxx . | x</td></tr>
<tr><td>90</td><td>3</td><td>x .xx | x .xx | x . .x | x</td><td>xxx . | .xx . | xxx . | x</td></tr>
<tr><td>90</td><td>4</td><td>x .x . | xxxx | x . .x | x</td><td>x .xx | x . .x | .xxx | x</td></tr>
<tr><td>110</td><td>5</td><td>x .x . | x .x . | xxxx | x</td><td>x .x . | .xxx | x .xx | x</td></tr>
<tr><td>110</td><td>6</td><td>xxx . | xxx . | xx . . | x</td><td>xxxx | .x .x | . .xx | x</td></tr>
<tr><td>80</td><td>7</td><td>x .xx | xx .x | x . .x | x</td><td>xx .x | xx .x | . .xx | x</td></tr>
<tr><td>80</td><td>8</td><td>xx . . | xxxx | x .x . |x</td><td>xx .x | . .xx | x .xx | x</td></tr>
<tr><td>120</td><td>9</td><td>xx . . | x .xx | x .xx |x</td><td>x .xx | xx .x | . .xx | x</td></tr>
<tr><td>120</td><td>10</td><td>x .xx | x .xx | xx . . | x</td><td>x . .x | xxxx | .xx . | x</td></tr>
<tr><td>70</td><td>11</td><td>xxx . | xx . . | xx .x | x</td><td>xxxx | .xxx | . .x . | x</td></tr>
<tr><td>70</td><td>12</td><td>xx .x | xxx . | x . .x | x</td><td>xxxx | . .xx | .xx . | x</td></tr>
<tr><td>130</td><td>13</td><td>xx .x | x .xx | xx . . | x</td><td>xx .x | xxx . | .xx . | x</td></tr>
<tr><td>130</td><td>14</td><td>xx . . | xx .x | x .xx | x</td><td>xx .x | . .xx | xxx . | x</td></tr>
<tr><td>60</td><td>15</td><td>x . .x | xx .x | xx .x | x</td><td>x .x . | .xxx | .xxx | x</td></tr>
<tr><td>60</td><td>16</td><td>x . .x | x . .x | xxxx | x</td><td>x . .x | xxxx | .x .x | x</td></tr>
<tr><td>40</td><td>17</td><td>x .x . | xxx . | xx .x | x</td><td>x .x . | .x .x | xxxx | x</td></tr>
<tr><td>40</td><td>18</td><td>x .x . | xxxx | xx . . | x</td><td>x .xx | .xx . | xxx . | x</td></tr>
<tr><td>30[1]</td><td>19</td><td>--</td><td>x . .x | .xxx | x .xx | x</td></tr>
</table>

x = event onset
. = silent position
| = indicates that the following event or silent position is associated with a beat

Rhythm Workers

The goal of the game is to construct buildings. The construction of a building is associated to one of the stimuli presented above (metronome, rhythmic sequence, or music; each stimulus includes eighty beats) and corresponds to one level of the game. Ninety-nine levels were designed. These levels were divided into nine levels of difficulty, referred to as “worlds” (eleven levels per world), as illustrated in Table 6.3. Ninety-nine stimuli were selected (53 musical excerpts, 9 metronome sequences and 37 rhythmic sequences) and assigned to the different worlds, as can be seen in Table 6.3. To make the game interesting, thus potentially motivating, the 3 types of stimuli were alternated within the same world as follows: the game starts with a metronome sequence and other metronome sequences were inserted every 10 of the other stimuli. The other 10 stimuli (i.e., music and rhythmic sequences) were presented after each metronome sequence according to the following fixed order: 2 musical excerpts - 2 strongly-metrical sequences - 2 musical excerpts - 2 weakly-metrical sequences - 2 musical excerpts. This structure of the rhythmic training protocol was implemented in two versions of the game. In the *perceptual* version, the task is an adaptation of the Beat Alignment Test (BAT, Iversen & Patel, 2008) in which the player is asked to detect if a sequence of percussion sounds (a metronome) is aligned or not to the beat of the stimulus. In the *tapping* version, the goal of the task is to tap to the beat of the stimulus as accurately as possible.

Table 6.3. Structure of the rhythmic training protocol implemented in *Rhythm Workers*. Stimuli corresponding to the levels of the game are indicated. For simplicity, we indicate tempo changes only for metronome sequences; tempo changes for metrical sequences are the same as for the metronome (see Table 6.2)

			Stimuli									
		Metronome BPM	Music		Strongly Metrical Sequences		Music		Weakly Metrical Sequences		Music	
Worlds	1	100	M1	M2	SM1	SM2	M3	M4	WM1	WM2	M5	M6
	2	90	M7	M8	SM3	SM4	M9	M10	WM3	WM4	M11	M12
	3	110	M13	M14	SM5	SM6	M15	M16	WM5	WM6	M17	M18
	4	80	M19	M20	SM7	SM8	M21	M22	WM7	WM8	M23	M24
	5	120	M25	M26	SM9	SM10	M27	M28	WM9	WM10	M29	M30
	6	70	M31	M32	SM11	SM12	M33	M34	WM11	WM12	M35	M36
	7	130	M37	M38	SM13	SM14	M39	M40	WM13	WM14	M41	M42
	8	60	M43	M44	SM15	SM16	M45	M46	WM15	WM16	M47	M48
	9	140	M49	M50	SM17	SM18	M51	M52	WM17	WM18	M53	WM19[2]

M = music excerpt

SM = strongly-metrical sequence

WM = weakly-metrical sequence

The aesthetic quality of the building depended on the player's performance (see Figure 6.2). When the player tapped accurately to the beat (*tapping* version) or detected correctly whether the percussion sounds were aligned to the beat (*perception* version) the building appeared as better structured (e.g., more symmetrical), richer, and more aesthetically appealing than when the player's performance was not good.

At the end of each level, a score between 5 and 100 points was calculated and converted into a number of stars, from one star (score below 70) to five (score above 95). A performance leading to at least two stars was needed to unblock the next level within the same world. To unblock (and move to) the next world, the player had to gather at least twenty stars in the current world. Note that if the player could not obtain two stars after five trials at the same level, the next level was automatically unblocked. This process allowed a player who had particular difficulties with one level to move to the next level, with the possibility to train the previous level within the same world later. Finally, if the participant completed all the worlds before the end of the two weeks, the game restarted from world 1, but with a slightly more difficult version of the game, in which a number of three stars, instead of two, was needed to unblock the next level.

Figure 6.2. Three examples of buildings generated by one player, corresponding to a bad (score = 50 points, 1 stars), a good (80, 2 stars), and a very good performance (100, 5 stars), from left to right. The buildings appear progressively in four steps during the performance of a level, from bottom to top. The appearance of the building at each step depends on the performance of the player**.**

Perception version

In the *perception* version of the game, five sequences of isochronously presented tones with a triangle timbre were superimposed on each stimulus at five different moments during the presentation of the stimulus. The first sequence of tones lasted five beats and is an example of an aligned sequence (i.e., the tones are aligned to the beat); in this case the participant was not expected to provide an answer. The following four sequences, with tones aligned or misaligned to the beat, included ten beats. Aligned and misaligned sequences of tones were separated by four beats without superimposed tones.

The task of the player was to judge after each tone sequence whether the tones were aligned or not with the stimulus beat. The player responded by touching one of two buttons ("Yes" and "No") presented in the middle of the screen. The buttons appeared for 2.5 sec in correspondence of the eighth tone of each sequence. A wrong answer led to the appearance of a segment of the building which was less aesthetically appealing and 25 points were subtracted from the final score. A correct answer and the player's reaction time (the faster, the better) determined the final score and whether the section of the building appearing was more or less aesthetically appealing. If the correct response was given in the first half of the response time window (i.e., within 1.25 seconds), the best version of the building was displayed, and no points were subtracted from the final score. If the correct response was provided later, but within the second half of the response time window (i.e., between 1.25 and 2.5 seconds), a less appealing version of the building was displayed; moreover, five points were subtracted from the final score. Finally, if the player provided a wrong response for all the four tone sequences, a minimum score of 5 points, corresponding to one star, was assigned, to avoid a null score that would be very demotivating for the player. Altogether, 396 triangle tone sequences were judged in the game. Half of them (198) were aligned to the beat of the stimulus. The other half (198) were misaligned. When misaligned, the sequence IBIs presented either a change in period (100 sequences) or in phase (98 sequences) relative to the stimulus IBI. Fifty sequences were presented at 10% slower tempo, and the other 50 sequences at a tempo 10% faster, than the stimulus IBI. Moreover, 49 sequences occurred later than the stimulus beat by 30% of the IBI, and 49 occurred earlier by 30% of the IBI, while keeping the same tempo as in the stimulus.

Tapping version

As in the *perception* version, a stimulus at a given level included 80 beats. After four beats, a sequence of ten isochronously presented triangle tones (metronome) aligned to the beat was presented. The goal of this superimposed metronome was to show the time at which the beat occurred in the stimulus. The task of the player was to finger tap on the screen to the beat of the stimulus after the metronome was presented. A section of the building was built every 15 beats, based on the performance of the player.

Circular statistics computed from the last 15 taps before a section of the building appeared were used to assess tapping performance in real time. Synchronization *consistency* (vector length) and *accuracy* (vector angle)[3] were used to calculate the score. The score at each level was computed as follows. Synchronization consistency (a value between 0 and 1) was multiplied by 100 to obtain a score between 0 and 100. Note, however, that maximum consistency (= 1) is impossible to achieve in human performance. Thus, to reward a very good performance, three points were automatically added, leading eventually to a score of 100 points for an excellent player. Points were subtracted from this score depending on synchronization accuracy. When the vector angle was higher than 60 degrees, 5 points were subtracted every 10 degrees with decreasing accuracy, so that between 60 and 70, 5 points were subtracted from the final score, between 70 and 80, 10 points were subtracted, and so on. Finally, in some cases the player may tap right in between the beats (i.e. in antiphase). This situation was treated as an erroneous performance, and was detected during the performance of a level, namely when the player obtained synchronization accuracy which departed by at least 120 degrees from the beat, knowing that the antiphase corresponds to 180 degrees. In this case, a warning message at the end of level appeared with the information that the player tapped in between beats and that the level had to be repeated.

A score was computed for each stage of the building (every 15 beats). If the score was lower than 70, the worst version of the building was displayed. A good version was presented if the score was between 70 and 90, and a very good one if the score was higher than 90. The versions of the buildings were the same as in the *perception* version. The final score was computed on the overall performance. As for the *perception* version of the game, the minimal score was set to 5 instead of 0.

Assessment of rhythmic skills before and after training

Participants' beat perception was tested before and after the training protocol with BAT version of BAASTA (Dalla Bella et al., 2017a). In the BAT, seventy two musical fragments lasting 20 beats from Bach's "Badinerie" and Rossini's "William Tell Overture" were presented at the three different tempos, with 450-, 600- and 750-ms IBIs. From the 7th beat, an isochronous sequence (percussion sound) is superimposed onto the music. The sequence was either aligned with the beat of the music or non-aligned (in terms of phase or period). The participant judged whether the percussion sounds were aligned or not with the beat.

Procedure

The participants were randomly assigned to one of the three groups, *control* (n = 10), *tapping* (n = 10), and *perception* (n = 10). Each participant of the *tapping* and *perception* groups received a tablet (LG G Pad 8.0 model) with the application dedicated to the specific version of the game for the training period. Instructions about the game were provided during the pre-training meeting with participants followed by a short practice session. Participants were instructed to play five times a week for thirty minutes at home, and to rate their motivation to play the game on a seven-point scale at the end of each session (1 = very low motivation, 7 = very high motivation). Before and after the training period, the participants were submitted to the BAT task to assess potential improvement of their rhythmic skills.

Results

Usability and compliance

The total time played was 205.9 minutes (*SD* = 57.6) in the *perception* group and 208 minutes (*SD* = 44.9) in the *tapping* group[4]. The two experimental groups did not differ in the amount of time played ($t < 1$). Only one player in the *tapping* group did not manage to complete the game, probably because he was the one who played the least (118 minutes). Note also that this player omitted to rate motivation. Participants were able to finish the game in approximately one week. Three participants in the *perception* group managed to finish the game a second time. On average, the participants attained the eighth level of the third world in the *tapping* group, and the sixth level of the seventh world in the *perception* group, in both cases at the second repetition of the game. In general, it took more time to complete the *tapping* version (on average, 191.0 minutes; *SD* = 61.57) than the *perception* version (121.9 minutes, *SD* = 17.53) ($t(7.1) = 2.94$, $p < .05$). Average scores for each of the 9 worlds and for the two versions of Rhythm Workers are presented in Figure 6.3. The performance of the *perception* and the *tapping* groups did not differ at the beginning of the game (world 1, $t(13.04) = 1.10$, $p = .29$). The scores in the 9 worlds for the two groups were entered in a 9 x 2 mixed-design Analysis of Variance (ANOVA). World (1 through 9) was the within-subject factor and Group (*tapping* vs. *perception*) the between-subject factor. The effect of the group was close to significance ($F(1, 8) = 4.08$, $p < .058$). This suggests that the tapping version may be slightly more difficult than the perception version. The average performance in the 9 worlds differed as a function of the group, as shown by a significant World x Group interaction ($F(8, 144) = 3.1$, $p < .01$) [4]. Post-hoc tests (Tukey HSD) comparing the two groups at each of the Worlds showed a significant difference only in World 8 ($p < .05$). In sum, the protocol using the *tapping* version of the game was slightly more difficult than the one using the *perception* version, an effect which became visible as the game progressed.

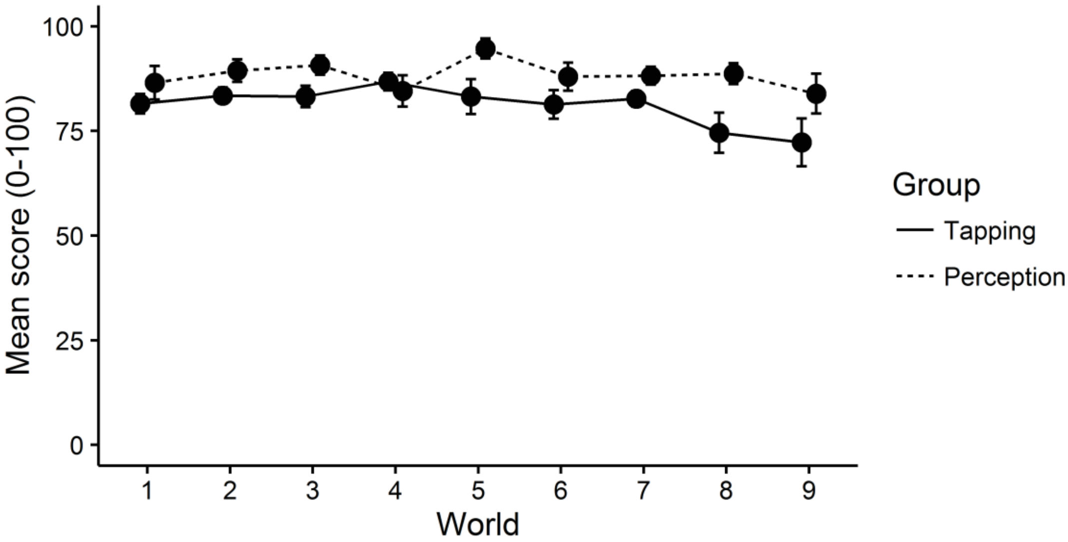

Figure 6.3. Mean scores obtained in the nine worlds for the *tapping* and the *perception* groups. Error bars indicate Standard Error of the Mean.

Motivation

Mean motivation ratings for each session in the two groups are shown in Figure 6.4. In all the sessions, motivation was much higher than the average value of the scale (3.5), irrespective of the version of the game. We compared the motivation in the 10 sessions for the two groups with a 10 x 2 ANOVA. Session (1 through 10) was the within-subject factor and Group (*tapping* vs. *perception*) the between-subject factor. Neither the main effects of Group ($F(1,17) = 0.01$, $p = .76$) and of Session ($F(9,153) = 1.16$, $p = .32$), nor the Group x Session interaction ($F(9, 153) = 0.92$, $p = .51$) reached significance. Thus, motivation to play the game was high and constant all along the protocol in both groups.

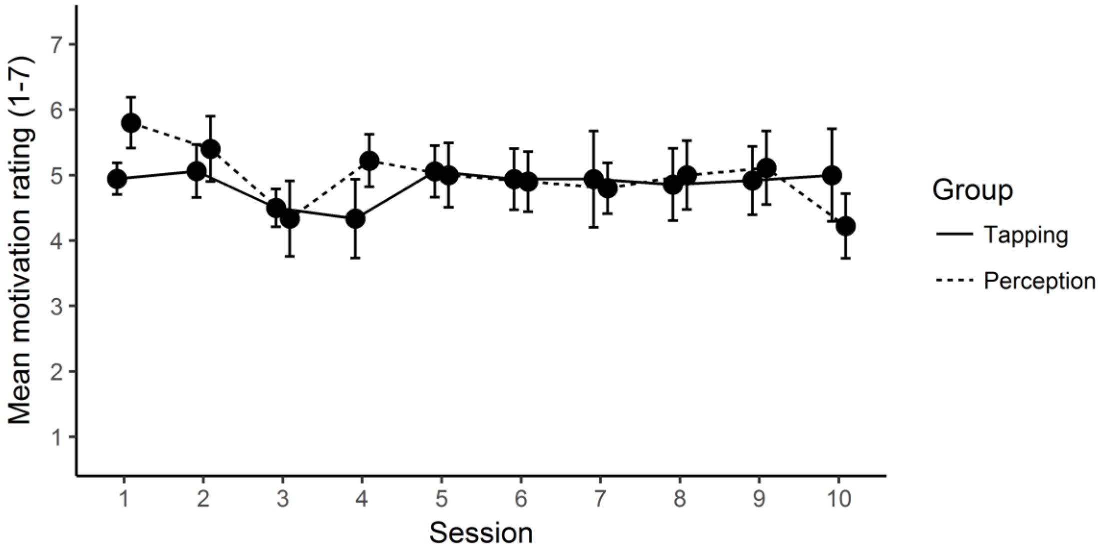

Figure 6.4. Motivation scores across the ten testing sessions. Error bars indicate Standard Error of the Mean.

Beat perception

For the BAT, a sensitivity index (*d'*) was calculated on the basis of the number of Hits (i.e., when a misaligned metronome was correctly detected) and False alarms (i.e., when a misalignment was erroneously reported). No change in the performance of the control group was observed between the two sessions (before, mean = 2.96, SD = .92; after, mean = 3.13, SD = 1.06; $t(9) = 1.05$, $p = .32$). As differences in the effect of the training protocol can be expected from one individual to the other in the experimental groups, the difference between the two sessions in percentage was calculated separately for each individual. Improvement and worsening of the performance post-training between 10% and 25% relative to the performance before the training were considered as small, between 25 and 50% as average, and above 50% as large. Mean and individual results for the *perception* and the *tapping* groups are presented in Table 6.4[5].

A significant improvement was found only for the *perception* group ($t(9)$=3.21, p<.01) but not for the *tapping* group ($t(8) = 0.23$, $p = .41$). In spite of these results at the group level, we observed important individual differences within the two experiments groups, which can be seen in Table 6.4. Most of the participants in the *perception* group (7 out of 10) displayed an improvement of their performance after the training greater than 10%. Two showed a large improvement, two an average improvement, and three had only a small improvement. Note that three subjects did not reveal any improvement. This is not very surprising, though, as two of them already reached the maximum score (*d'* = 4.37), and the third obtained a score very close to the maximum (3.93) before the training. Thus, lack of training effect in these cases can be ascribed to a ceiling effect.

The effects of the training were less visible in the *tapping* group. More than half of the participants (5 out of 9) improved their performance as a result of the training, by more than 10%. Two showed an average improvement and three had a small improvement. In contrast, surprisingly, three participants revealed worse performance after the training than before the training, two of them with an average to large decrease in the detection of beat alignment.

Table 6.4. Individual performances (*d'*) for participants in the *perception* and in the *tapping* groups obtained in the BAT.[5] Grey shades indicate the level of improvement.

Participant #	Session 1 (*d'*)	Session 2 (*d'*)	Session 2 - Session 1 (Delta *d'*)	Change (%)
Perception group				
3	4.37	4.37	0	0.00
5	3.93	3.93	0	0.00
8	4.37	4.37	0	0.00
1*	3.52	3.93	0.41	11.65
6 *	2.71	3.19	0.48	17.71
4 *	3.52	4.37	0.85	24.15
10 **	2.77	3.6	0.83	29.96
2 **	2.61	3.87	1.26	48.28
9 ***	0.67	1.33	0.66	98.51
7 ***	1.9	3.93	2.03	106.84
Mean (*SD*)	3.04 (1.16)	3.69 (0.91)	0.65 (0.64)	
Tapping group				
9 †††	1.98	0.56	-1.41	-71.21
7 ††	2.53	1.38	-1.15	-45.45
10 †	3.08	2.58	-0.5	-16.23
2	1.51	1.63	0.12	7.95
8 *	1.08	1.24	0.16	14.81
5 *	1.94	2.31	0.37	19.07
6 *	3.52	4.37	0.85	24.15
4 **	2.88	3.87	0.99	34.38
1 **	3.15	4.37	1.22	38.73
Mean (*SD*)	2.41 (0.78)	2.48 (1.43)	0.07 (0.93)	

Improvement: *small, **average, ***large
Worsening: † small, †† average, ††† large.

Discussion

The goal of this experiment was to pilot a training protocol based on *Rhythm Workers* in a small group of healthy young adults in order to assess the usability of the game and the compliance with the protocol. Moreover, first evidence was gathered about the effects of the protocol on rhythmic skills using the BAT. In general, the protocol was very well received by the participants. All of them completed the study and played a significant amount of time (on average 69 % of the maximum time). Participants were highly motivated to play the game across the different training sessions. None of them misunderstood the goals of the game or the instructions, or had issues with operating the tablet interface. Despite the fact that rhythmic difficulty increased with the worlds in the game, all participants but one (i.e., who spent the least of time playing) could complete the game in approximately 1 week. The *tapping* version, although very well performed, appeared slightly more difficult than the *perception* version, as seen in the performance at some difficulty levels of the game. Overall, these findings show excellent usability and compliance with both versions of *Rhythm Workers* in young adults.

This protocol creates optimal conditions fostering an improvement of rhythmic skills. First evidence was provided that beat perception tested with the BAT was clearly improved by the *perception* training. All the participants in the *perception* group improved their performance (up to 100% relative to their performance before the training), except those who performed at ceiling before the training. More than half of the participants in the *tapping* group also improved beat perception by more than 10%.

General discussion

Rhythm Workers, a music-based serious game, is a new tool targeted to the training of rhythmic skills. In the first experiment, we selected the musical material used in the serious game. Measures based on expert ratings and on a tapping study served to sort the excerpts from the easiest to the most difficult in terms of beat saliency. In the second experiment the structure of *Rhythm Workers* was presented, including 99 audio stimuli (music, rhythmic sequences and metronome sequences), and a dedicated training protocol was devised. Two training protocols implementing two versions of the game (*tapping* and *perception*) were tested in a small sample of 20 healthy young adults. Usability of the game and compliance with the protocol were tested. In addition, first pilot data with the goal of testing the effect of the training on rhythmic skills were collected.

The results of this proof-of-concept pilot study show high motivation of the participants when playing the game, which is sustained for the two weeks of the training protocol. This finding is very encouraging because players' motivation attests that the game is equally engaging across the different worlds, in both the *perception* and in the *tapping* versions. Thus, the protocol with *Rhythm Workers* is not likely to be hampered by motivational factors, at least over a period of two weeks, and thereby creates optimal training conditions. Moreover, because all the participants but one managed to finish the game in approximately one week, the serious game shows good usability and compliance with both versions.

All the players managed to play and to obtain satisfying scores, in spite of the notable variability in the players' performances. The serious game and the protocol are sufficiently flexible to adapt to initial individual differences in rhythmic skills, without hindering players' motivation. Variability in rhythmic skills in individuals without musical training is expected since it reflects the various profiles of rhythmic abilities in the general population (Bégel et al., 2017; Launay, Grube & Stewart, 2014; Sowiński & Dalla Bella, 2013; Tranchant, Vuvan, & Peretz, 2016).Participants' scores in the *tapping* version of the game, although generally comparable with the scores in the *perception* version, differed at least at one of the difficulty levels of the game. Thus, in its current form, the game may be slightly more challenging in the *tapping* version than in the *perception* version. This is confirmed by the fact that it took more time to complete the *tapping* version than the *perception* version of *Rhythm Workers*. The discrepancy between the two versions can be explained by task factors such as the type of response, and by the temporal processes engaged during the performance the game. In the *tapping* version, the player produces a continuous performance (i.e., up to 60 taps) for a given stimulus (i.e., level in the game), with little possibility of achieving a good score by chance. In the *perception* version, the player has a smaller set of possible responses, with a binary choice ("yes"/"no") for each judgment (50% of chance to answer correctly), and 4 judgments to be provided at a given level. Due to the more limited number of responses in the *perception* than in the *tapping* version of the game, it is easier for the player to provide a performance above chance (i.e., 3 out of 4 correct answers will suffice).

We provided first evidence that a training protocol using a serious game such as *Rhythm Workers* can have a positive effect on rhythm skills. All individuals who received the *perception* training improved their performance in detecting whether a metronome is aligned or not with music (BAT), except those who were at ceiling before training. This was not observed in the control group. When submitted to the *tapping* training, most of the participants also improved, but three of them showed worsening of the performance as a result of the training. This unexpected finding deserves further inquiry in future studies with a larger sample size. Yet, these differences in the response to our rhythmic training protocol are reminiscent of the results obtained with other protocols for rhythmic training such as rhythmic auditory stimulation (RAS; Benoit et al., 2014; Dalla Bella et al., 2017b; de Dreu et al., 2012; Thaut et al., 1996; Spaulding et al., 2013). This is a method consisting in presenting auditory rhythmic stimuli to patients with movement disorders, such as Parkinson's disease (Benoit et al., 2014; Dalla Bella et al., 2015; Dalla Bella et al., 2017b; de Dreu et al., 2012; Lim et al., 2005; Spaulding et al., 2013; Thaut & Abiru, 2010; Thaut et al., 1996) and stroke (Thaut, McIntosh, & Rice, 1997; Thaut et al., 2002, 2007). For example, some patients with Parkinson's disease trained with RAS for several weeks positively respond to the training (i.e., by increasing their walking speed) while others either do not react or respond negatively to the auditory cues (Dalla Bella et al., 2017b; Dalla Bella et al., 2015). Importantly, individuals who respond positively to the training are those who have the best rhythmic abilities (Dalla Bella et al., 2017b). Therefore, by improving rhythmic skills with *Rhythm Workers* it may be possible to increase patients' response to such rehabilitation programs.

In summary, we devised *Rhythm Workers*, a serious game for training rhythm skills, and tested it in a proof-of-concept pilot study in healthy young adults. This step was mandatory to ensure that the game can be used by individuals without neurological or neuro-developmental disorders. Usability and game compliance were excellent. Encouraging results of the effect of the training on rhythm skills were also found. Further studies are needed to test whether the game can be used by individuals with neuro-degenerative (e.g., Parkinson's disease), neurological (e.g., stroke) or neuro-developmental disease (e.g., ADHD, dyslexia or stuttering). Finally, testing the effect of training rhythm skills with *Rhythm Workers* on associated functions such as movement and cognition in these disorders would be highly relevant for rehabilitation.

Notes

[1]Fifty-four excerpts were initially selected. However, one excerpt was discarded because of technical issues during data acquisition. In the game, this excerpt was replaced with a metrical sequence with similar characteristics.

[2]The metrical level value is an estimation of the percentage of participants who tapped at the expected metrical level (e.g., at the quarter note). If all the participants struggled to find the beat or they tapped at the half note, the value is set to 0.

[3]To ensure that synchronization accuracy was properly computed the latency between the touch of the pad and the time recorded by the tablet (133 ms) was subtracted from tapping times.

[4]For one participant in the *tapping* group, a technical problem in calculating the delay aroused. The time played and the scores obtained were therefore limited to the sessions played after the problem was solved. This prevented the participant from finishing the game.

[5]One of the participants of the tapping group was discarded due to missing data.

Discussion and Conclusion

7. **Chapter 7.** Discussion

During the last two decades, several studies have shown that the capacity to process rhythm in humans is tightly linked to other functions such as cognition and motor skills. When rhythmic skills are challenged by brain damage or neuro-developmental disorders, remediation strategies based on rhythm can be considered as valuable alternatives to standard treatment. For example, rhythmic training can be used to improve motor performance (e.g., gait) as well as cognitive and language skills. Therefore, studying rhythmic processing in patient populations is a promising avenue to shed light on the brain circuitry underpinning these disorders and to provide guidelines for successful remediation strategies. However, research on timing and rhythm is quite heterogeneous. Generalization of these results is challenging since paradigms and group samples vary across studies.

In this dissertation, I raised several research questions that were addressed in four separate studies. First, I wanted to know if it was possible to evaluate timing and rhythm skills with a systematic, reliable battery comprising a standardized set of measures that would be used to uncover individuals with spared or impaired rhythmic skills in healthy populations (i.e., beat deaf) and in clinical populations. In particular, my focus was on using BAASTA to characterize rhythm and timing behavior with the goal of revealing new dissociations in the mechanisms sustaining timing and rhythm. The final goal was to create a rhythm training protocol implemented in a serious game. As this was not done before, my main goal was to assess whether this kind of game is usable and motivating for healthy young adults. Moreover, I collected pilot data to provide the first preliminary evidence on the effectiveness of this kind of training for improving rhythmic skills.

A series of experiments presented in this dissertation (Studies 1, 2, and 3) tested the capacities of individuals to perceive timing and rhythm and to produce rhythm. A systematic tool for the evaluation of timing and rhythm skills has been optimized, tested, and validated (BAASTA) in a test-retest study over a period of two weeks, proving its efficiency in highlighting inter-individual differences. In addition, in order to test the possibility of training rhythmic skills with a serious game, a new rhythm training protocol was devised using a serious game (*Rhythm Workers*) and tested in a pilot group (Study 4).

7.1. Overview of results

The BAASTA battery of perceptual and sensorimotor timing tests consists of a set of tasks adapted from previous studies and that provides a quite thorough profile of participants' individual timing and rhythm skills. I tested it in a proof-of-concept study on 20 healthy young individuals (Experiment 1). In general, data obtained with BAASTA fall within the range of the results reported in previous studies. Small discrepancies found in psychophysical tasks (duration discrimination, anisochrony detection) probably pertain to the material or the procedure used in BAASTA.

Most importantly, BAASTA proved sensitive to inter-individual differences. Some participants showed particularly poor performances in certain tasks (i.e., they deviated from the group average by at least two Standard Deviations). I also found that the results of some tasks were highly correlated with the ones of other tasks (e.g., the BAT and paced tapping), and that, on the contrary, some tasks were totally independent from each other (e.g., duration discrimination and all the other tasks). This reveals that the battery can discriminate between tasks involving different and common mechanisms. For instance, the fact that duration discrimination is not related to the BAT implies that processes underlying duration-based and beat-based timing are at least partially independent. In sum, our first study supports that BAASTA is a good tool to identify individuals with difficulties in timing and rhythm processing. BAASTA also shows good promise for the identification of the mechanisms sustaining these inter-individual differences. In Experiment 2, threshold estimations with two different methods (MLP and staircase) were compared. The results obtained with standard staircase methods were proved 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 due to estimates of threshold corresponding to a lower percentage of the psychometric function in MLP (63.1 %) than in staircase methods (75.0 % on average).

In Study 2, 20 healthy adults were tested twice with BAASTA at an interval of two weeks in a test-retest protocol. The ICC index, a commonly used measure of relative reliability, namely, the consistency of the relative position of one individual in a group (Vaz et al., 2013), was good to excellent (.45 to .96) for most of the measures. Yet, a significant change was found from test to retest for synchronization consistency (+ 4.05%) in paced tapping with music. This improvement is likely to reflect a learning effect as the same music excerpts were used to assess synchronization with music at both times of testing. Apart from synchronization with music, the mean of all the other tasks remained stable at the second time of testing. Thus, the performance in these tasks was not affected by a learning effect or annoyance brought about by repeating the tasks.

In Study 3, BAASTA was used to examine the profile in timing and rhythm tasks of beat-deaf individuals. First, the results replicated previous findings by Phillips-Silver and collaborators (2011) by showing that some individuals had poor rhythm perception and synchronization to the beat. In particular, one participant (L.V.) had deficits in perceiving whether a sequence of sounds was regular or not, in identifying whether a metronome was aligned to the beat of music, as well as in synchronization with music. She was also unable to tap consistently with a metronome at a slow and at a fast tempo. Most interestingly, I showed that two individuals (L.A. and L.C.) performed poorly on rhythm perception tasks, such as detecting time shifts in a regular sequence or estimating whether a metronome is aligned to the beat of the music or not. Yet, they could tap to the beat of the same stimuli. The fact that synchronization to a beat can occur in the presence of poor perception is reported for the first time in this study. On top of that, the three beat-deaf participants benefited as well as controls from a regular temporal pattern in an implicit timing task in which they had to respond as fast as possible to a different target pitch after a sequence of standard tones.

Finally, in Study 4, I presented *Rhythm Workers*, a music game that aims at training rhythm skills. In a first experiment, a set of 53 musical excerpts with increasing rhythmic complexity to be used in the game was successfully selected and sorted. Selection was based on the tapping performance (synchronization *consistency*) of 18 non-musicians who tapped to the beat of music. This musical material was then used, along with metronome and rhythmic sequences also varying in terms of rhythm difficulty, to create the rhythm training protocol. The method to implement the protocol of the training in a serious game was presented. One version (*tapping version*) required a synchronized motor response (via tapping), while the other (*perceptual version*) was a perceptual task. At the end, I presented a proof-of-concept pilot study with 20 healthy young adults who played the game for 15 days. Participants in the experimental groups showed high compliance and motivation in playing the game. I tested whether beat tracking skills changed before and after the training with the Beat Alignment Test taken from BAASTA. As compared to a control group, who did not receive any training between the two testing, the training of rhythm skills yielded encouraging results. In the group who received the perceptual training, all the participants displayed an improvement of their performance in the BAT greater than 10%, except those participants who already reached maximum performance in this task before the training. In the *tapping* group, more than half of the participants (5 out of 9) improved their performance as a result of the training by more than 10%.

7.2. Theoretical implications for sensorimotor synchronization models

In the introduction, I presented a perception-action loop model to account for sensorimotor synchronization developed in the context of an information processing framework (Mates, 1994; Repp, 2005, 2006; Repp & Su, 2013; Wing, 2002). According to this model, synchronization to a beat is possible thanks to perceptual processes that convey information about the stimulus timing characteristics (e.g., period and phase relative to a motor event) to a central timekeeper. A motor response is then implemented and adjusted thanks to linear error correction processes that aim to minimize the difference between the time of occurrence of the movement and the time of the stimulus beats. In this section, I will discuss the results obtained in our different studies in the context of this model. The goal is to examine to what extent our results are in keeping with this model and to shed light on some limitations of this model.

7.2.1. Correlations between perception and action in rhythm processing

In our first study, I found correlations between measures from perceptual and motor tasks of BAASTA (e.g., BAT d-prime and synchronization consistency in tapping with tones, anisochrony detection with tones, and synchronization consistency in tapping with a metronome). These correlations suggest that purely perceptual processes, such as those engaged in the perception of the alignment of a metronome to a musical beat or the detection of shifts in the regularity of a sequence of tones are related to synchronization and thus are likely to reflect similar underlying beat-based mechanisms. Neuronal underpinnings of beat-based timing support these correlations as perception and synchronization are sustained by common brain areas. Indeed, motor regions (the basal ganglia; Chen, Penhune, & Zatorre, 2008b; Grahn & Brett, 2007; Grahn & Rowe 2009), and sensorimotor integration areas (e.g., dorsal premotor cortex; Chen, Zatorre, & Penhune, 2006; Zatorre, Chen, & Penhune, 2007) are involved in synchronization with, as well as in mere perception of, the beat. Ultimately, the aforementioned relations between perceptual and sensorimotor tasks confirm the tight coupling between perception and action in beat-based timing.

These results, interpreted within the frame of the perception-action model, allow to make predictions on the co-variation of rhythmic skills in the general population. For example, it is expected that individuals with good beat perception will also show good abilities to synchronize to the beat. This is consistent with the hypothesis that synchronization relies on perceptual processes that allow the system to adjust the period and the phase of the movement based on the timing of a central timekeeper. In this context, a strong dependency is expected between synchronization and beat perception.

This conclusion is strengthened by the fact that correlations between perception and production tasks are also found when the material is not the same. For instance, anisochrony detection with tones is correlated to synchronization with music, and the BAT is correlated to synchronization with tones. This suggests that the correlations found between perception and production tasks do not merely reflect the ability to process the features of the same stimuli (rhythm, pitch, tonality) either in a perceptual task or in a sensorimotor task.

Altogether, the correlations between perceptual and sensorimotor tasks, including tasks with different stimuli, point toward a general mechanism that sustains sensorimotor synchronization and beat tracking. This mechanism postulates a linear relation between the perception of a rhythmic stimulus, which allows processing of its timing characteristics by a central timekeeper, and the motor implementation.

7.2.2. Inter-individual differences

It is worth noting that a tight relation between perception and action in rhythmic tasks was found in healthy individuals, who represent the majority. However, this situation may fall apart as a result of brain dysfunctions or neuro-developmental disorders whereby a disconnection between perception and action may occur. Study 3 on beat deafness showed that a linear relation between perception and action in sensorimotor synchronization can be violated. I showed that perception in an explicit timing task can be affected without affecting synchronization. To the best of our knowledge, this dissociation is reported here for the first time. The opposite dissociation was described in previous studies in individuals whose synchronization is poor despite unimpaired beat perception (Sowiński & Dalla Bella, 2013). It is important to note that these individuals had normal performance in self-paced motor tapping, ruling out a pure motor deficit that would explain poor synchronization. Our results complement this study and confirm the existence of different phenotypes of rhythm disorders, resulting from either poor perception and/or deficient auditory-motor integration.

Overall, this double dissociation between perception and action in the processing of rhythm supports the idea that a linear model of perception-action might be incomplete. Indeed, as some individuals who have poor beat perception can still synchronize with the beat, other perceptual processes that can affect the activity of a timekeeper can be recruited. Beat-deaf participants, in spite of their poor performance in explicitly perceiving the beat, can still benefit from the periodic temporal structure of a sequence of sounds. Therefore, some form of covert extraction of the beat is likely to afford synchronization in beat deaf with poor beat perception who are able to synchronize.

These results imply that different mechanisms may be affected in beat deafness. The core deficit in beat-deaf individuals may not necessarily be in the extraction of the beat. In individuals who can perceive overtly the beat but who cannot synchronize accurately with it (Sowiński & Dalla Bella, 2013), a deficit in the auditory-motor is likely. Individuals who can synchronize but who have difficulties in perceiving the beat may have difficulties in the conscious access to an internal representation of the beat. Their synchronization capacities are likely it to be sustained by covert beat extraction processes. This hypothesis corroborates with some recent EEG evidence indicating attentional deficits in some cases of beat deafness. Mathias and collaborators (Mathias et al., 2016) showed a normal mismatch negativity to beat irregularities in beat-deaf participants, indicating unimpaired pre-attentive processing, and therefore, spared covert mechanisms of beat extraction. However, one beat-deaf individual (Mathieu) revealed abnormalities in later attentional processes (reduced P3b response to deviant tones). This finding suggests that attentional deficits relate to beat deafness, regardless of the fact that individuals can synchronize or not.

7.2.3. Rhythmic skills training

One way to further unravel the relation between perception and motor action in synchronization tasks is to train rhythmic skills. In the Introduction, I reviewed studies in which rhythm skills were trained as a part of more general musical training. Even if these studies did not focus on evaluation and training rhythm skills *per se*, they reported promising results suggesting that rhythmic skills can be trained. Timing and rhythm skills are enhanced in musicians as compared to non-musicians (Chen, Penhune, & Zatorre, 2008; Matthews, Thibodeau, Gunther, & Penhune, 2016; Repp, 2010; van Vugt & Tillmann, 2014). Thus, it turns out that rhythmic skills may change over time as a result of musical training. However, little is known about the effects of a dedicated rhythmic training.

In Study 4, I presented *Rhythm Workers*, a serious game for training rhythmic skills. This study is the first to suggest that a dedicated perceptual rhythmic training may improve perceptual rhythmic skills. This improvement is less visible when sensorimotor training is used. In this study, the task used to assess perceptual rhythm skills is the same as the one that served for the perceptual training. The effect of training on the trained capacity was expected, as previous studies reported convincing improvement on the tests that were actually trained in the cognitive domain. For example, Owen and collaborators (Owen et al., 2010) showed that in a group of individuals who were trained with tasks that emphasized reasoning, planning, and problem-solving abilities, these specifics tasks were improved after the training. In contrast, in this study, no improvements were found in other cognitive functions such as short-term memory, attention, visuospatial processing, and mathematics.

Interestingly, more than half of the individuals in the sensorimotor training group improved their perceptual skills (up to 38% of the initial performance). However, three of them revealed worse performance after the training. It is possible that the unexpected negative effect of the training in some participants is not due to the training itself, but is caused by a factor such as a lack of motivation in doing the task for the second time. These differences in the response to a sensorimotor training protocol are not unusual, though. They are reminiscent of the results obtained with other forms of rhythmic training protocols such as RAS (e.g., Benoit et al., 2014; Dalla Bella et al., 2015; Dalla Bella et al., 2017b). In RAS, some patients (responders) respond positively to the rhythmic training (i.e., they walk better after the training) while other (non-responders) do not respond or respond negatively to the training. In the same manner, in our study, individuals who had a sensorimotor training may be classified as responders and non-responders on the basis of the effect of the training on beat tracking.

Because of these inter-individual differences, I did not find a group effect of the sensorimotor training on perceptual skills. There was no group difference in the BAT before and after the training in the *tapping* group. However, this may be due to the small sample size. Considering the inter-individual differences in the response to the sensorimotor training (i.e., responders versus non-responders), it is possible that an effect would be visible with more subjects, as observed in RAS (Dalla Bella et al., 2017b).

The effect of transfer from motor learning to perceptual judgment has already been described (Hecht, Vogt, & Prinz, 2001). These authors showed that a sensorimotor training with cyclical arm movement had a beneficial effect on visual judgments of similar patterns. Even if this task was not a rhythmic task, participants had to realize it with a certain relative timing specified by verbal command. In the speech domain, it has been shown that there is a beneficial effect of a sensorimotor learning on speech perception (Darainy, Vahdat, & Ostry, 2013; Ito, Coppola, & Ostry, 2016; Lametti et al., 2014) and that a perceptual training can boost sensorimotor learning (Lametti, Krol, Shiller, & Ostry, 2014). Further studies on rhythmic training with more participants are needed to evaluate whether a sensorimotor training has an effect on rhythm perception.

One important question that also needs to be addressed in further studies is to what extent it is possible to train sensorimotor rhythmic skills. In young adults, most of the participants are too good at baseline in synchronization, leaving little room for improvement. Therefore, studies on patients with rhythmic disorders, children or older adults are needed in order to test whether sensorimotor skills may be improved by a rhythmic training. In Study 2, I showed that with older adults, mere exposure to the same musical stimuli at a two-week interval was sufficient to improve their synchronization skills.

In summary**, a perceptual rhythmic training seems to systematically improve perceptual rhythm skills.** This proves that, in general, rhythm skills can be enhanced even in healthy young adults after a dedicated training. A sensorimotor rhythmic training has effects that seem to vary significantly from one individual to the other. The fact that a sensorimotor rhythmic training can improve rhythm perception would confirm that perception and motor processes are highly coupled in the processing of rhythm at least for healthy young adults (Chen, Penhune, & Zatorre, 2008; Grahn & Rowe, 2009; Keele, Pokorny, Corcos, & Ivry, 1985). This would be consistent with linear models of sensorimotor synchronization that postulates a linear relation between perception and motor response (Mates, 1994; Repp, 2005, 2006; Repp & Su, 2013; Wing, 2002). The sensorimotor training implies sensorimotor integration mechanisms which engage both perceptual processes and motor response whereas in the perceptual training, only perceptual processing of the temporal information is required (Coull, Cheng, & Meck, 2011; Dalla Bella et al., 2015). Hence, from a computational point of view, tapping to the beat is likely to improve perception since it also involves a perceptual component.

7.2.4. Links between different timing processes

Duration-based versus beat-based timing. BAASTA is a battery that focuses on the evaluation of rhythmic skills (i.e., beat-based timing). Nevertheless, a perceptual duration-based timing task (duration discrimination) has been added to the set of tasks in order to control for duration-based timing skills in individuals tested with the battery. Beat-based and duration-based timing supposedly engage different processes (Zelaznik, Spencer, & Ivry, 2002) and partially different brain areas (Coull & Nobre, 2008; Coull, Cheng, & Meck, 2011). Our results tend to confirm the independence between these two forms of timing (Study 1).

Results obtained by the 20 participants in duration discrimination do not correlate with any other measures of BAASTA.

However, it is intriguing to note that L.C., one of the beat-deaf individuals with impaired perception but spared synchronization presented in Study 3, had difficulties in duration discrimination as well as in beat-based timing tasks (anisochrony detection with a metronome, BAT). For L.A., another beat-deaf individual, thresholds could not be reliably computed due to the inconsistency of her responses in all the perceptual tasks implemented with the MLP procedure, including beat-based and duration-based tasks. She was unable to distinguish between the examples during the practice trials in duration discrimination as well as in anisochrony detection. Finally, for L.V., the last beat-deaf individual who showed impairments in both beat perception and tapping, all three blocks were discarded in the duration discrimination task due to an excess of FAs. Even if we cannot draw conclusion about her capacities in duration-based timing, this suggests that she has difficulties with the processing of duration-based stimuli.

Taken together, the results obtained in Study 3 suggest that beat-deaf individuals, whose difficulties were initially described in the context of beat-based timing (Launay, Grube, & Stewart, 2014; Palmer et al., 2014; Phillips-Silver et al., 2011; Sowiński & Dalla Bella, 2013), also have impairments in duration-based timing. Therefore, beat-based timing and duration-based timing may have mechanisms in common that are disrupted in beat-deafness, resulting in a deficit in both forms of timing. In spite of the fact that beat deafness was first described in the context of beat-based timing, it seems that the deficits displayed by beat-deaf individuals are not limited to rhythm. The capacities of beat-deaf individuals in duration-based timing need to be tested in further studies.

Implicit versus explicit timing. The results obtained in Study 3 tend to confirm the independence of implicit and explicit timing in beat deafness (Coull, Cheng, & Meck, 2011; Coull & Nobre, 2008; Zelaznik, Spencer, & Ivry, 2002). Indeed, even subjects who had the most severe difficulties in explicit timing tasks, such as L.V., who revealed very poor performance in both perceptual and sensorimotor explicit timing, benefited similarly to controls from a regular temporal pattern detecting the pitch target. This functional dissociation between spared implicit timing and impaired explicit timing is reported for the first time in this study.

In spite of the observed dissociation between implicit and explicit timing, there is evidence suggesting that implicit and explicit timing may rely on the same internal representation of duration (Piras & Coull, 2011). Therefore, it is possible that the representational mechanism engaged in overt extraction of a beat (explicit timing) is the same as in covert extraction (implicit timing). If this is the case, deficits observed in beat deafness would be explained by the fact that the conscious access to the internal representation of the beat is impossible.

In summary, these studies showed evidence in favor of the classical distinctions made between duration-based and beat-based timing, and between implicit and explicit timing. However, it is important to take into consideration the relations that may appear between traditionally separated processes, in particular in the cases of dysfunction of timing skills such as beat deafness. Indeed, duration-based timing seems to also be affected by beat deafness. On top of that, implicit timing, or a common internal representation of the beat in implicit and explicit timing, may serve to sustain synchronization in individuals who have poor beat perception.

7.3. Perspectives

The final goal of this dissertation was to develop *Rhythm Workers,* a serious game for training rhythm skills, and to conduct a first proof-of concept study with the game. In Study 4, the game was devised and tested in a population of healthy young adults. The preliminary results obtained in this proof-of-concept study are encouraging, since an improvement of beat tracking capacities was found in most of the participant who were trained with the game, especially the ones who had a perceptual training.

In a population of healthy young adults like the one tested in Study 4, synchronization skills are typically very good before training. Therefore, a lack of training effect on synchronization skills can be ascribed to a ceiling effect in synchronization as expected in young adults. However, as I have shown in the Introduction and in Study 3 of this dissertation, synchronization skills may be disrupted as a result of brain dysfunctions (e.g., cerebellar damage—Provasi et al., 2014; Schwartze, Keller, & Kotz, 2016; developmental disorder—Bégel et al., 2017; Sowiński & Dalla Bella, 2013). This may be due to impaired perceptual rhythm skills or to a weakening of the link between perception and action. Therefore, training with *Rhythm Workers* has the potential to reinforce the link between perception and action in patients, ultimately leading to an improvement of general rhythm skills. Improvement of rhythm skills may positively affect the motor and cognitive functions that are supposedly associated to rhythm.

The potential effect of the training of rhythm skills should notably be tested in PD. Benoit et al. (2014) showed that a training with RAS in PD that engages sensorimotor synchronization of the steps with musical stimuli positively affected time perception (duration discrimination and the BAT) in addition to benefits on gait capacities and sensorimotor timing skills. The authors proposed that this generalization of rhythm benefits is mediated by a domain-general system that governs perceptual and motor timing beyond gait. The benefit on perceptual skills found in Study 4 is particularly encouraging since, if reproduced in PD patients, the training of the perceptual rhythmic system may have a positive effect on movement parameters such as gait. Neurophysiological explanations of the effect of RAS are proposed, engaging either spared compensatory neuronal mechanisms or partly restoring the functioning of impaired brain circuitries (Dalla Bella et al., 2015). Areas of the brain involved in rhythmic processing are shared with regions involved in movement (especially the basal ganglia, the premotor cortex, and the cerebellum). Thus, it is likely that a rhythmic training protocol, such as the one I propose with *Rhythm Workers*, would have positive effects on rhythm skills and on motor control (e.g., gait) that are associated to PD.

Rhythmic skills are selectively impaired in Parkinson's disease, as well as in a variety of other neurological conditions (for a review, see Allman & Meck, 2012) such as ADHD (Puyjarinet et al., under revision. See Annex) or neuro-developmental diseases such as dyslexia (Huss et al., 2011), autism (Allman, 2011), or stuttering (Falk, Müller, & Dalla Bella, 2015). Thus, other examples of promising applications of a rhythmic training with *Rhythm Workers* can be found in the treatment of neuro-developmental disorders such as dyslexia or ADHD. Rhythmic skills also correlate with other cognitive functions in children (attention and working memory—Tierney & Kraus, 2013; literacy and reading skills—Gordon et al., 2015; Huss et al., 2011; Woodruff Carr et al., 2014). Thus, training rhythmic skills with a serious game, which may be particularly motivating for a developmental population, may bring about benefits that could extend to these cognitive functions.

In summary, **Study 4 paves the way for future investigations on the effect of a rhythmic training in a variety of patient populations including neuro-degenerative, neurological, as well as neuro-developmental diseases**. Ultimately, these beneficial effects of rhythmic training are likely to have positive consequences for health and well-being, such as promoting an active lifestyle by reducing motor and cognitive decline in patient populations or reducing the need for healthcare services.

7.4. Conclusion

This dissertation contributed to the development of tools for the assessment and training of rhythm skills. In a first set of experiments, I present BAASTA, a new battery for the systematic assessment of rhythm and timing abilities. I proved its reliability in a test-retest study and its sensibility to individual differences in rhythmic skills by identifying individual profiles in healthy participants and in individuals with rhythm disorders. This represents an important step for gaining a better understanding of the mechanism underlying rhythm processing. In the second part of the dissertation, *Rhythm Workers*, a new game for training rhythm skills, was developed and tested. The results of a pilot study on healthy adults who were trained for 2 weeks are very encouraging, showing good reception of the game and compliance to the training protocol. Moreover, I provide the first evidence that the game can improve some rhythmic skills (e.g., the ability to perceive the musical beat). This study paves the way to the design of experiments using rhythm training protocols for rehabilitation in patients with rhythm disorders. Ultimately, it is expected that training rhythm skills would have a beneficial effect on the associated cognitive and motor functions of language, attention, and gait.

Résumé substantiel de la thèse en français

1. Introduction

Les capacités de rythme chez l'humain

L'être humain est doté de capacités à traiter l'information temporelle particulièrement développées. Cette capacité est liée à la variété d'évènements temporels que nous rencontrons dans notre environnement (Grondin, 2008). Plus spécifiquement, nous avons un sens du rythme qui se manifeste à travers la façon dont nous bougeons à l'écoute de la musique. Délibérément ou spontanément, nous frappons des mains, tapons du pied ou dansons avec la musique (Repp, 2005; Repp & Su, 2013; Sowiński & Dalla Bella, 2013), et ce, dans toutes les cultures (Nettl, 2000). La synchronisation du mouvement à la musique nécessite qu'il y ait une pulsation marquant des points réguliers dans le stimulus. Cette pulsation est appelé *beat* (Grahn & Rowe, 2009; London, 2012). Nous pouvons, pour la majorité d'entre nous, ressentir le *beat* d'évènements rythmiques comme un métronome ou de la musique et nous synchroniser avec ce *beat* (Repp, 2005; Repp & Su, 2013; Sowiński & Dalla Bella, 2013).

Il est probable que les capacités de rythme soient biologiquement ancrées chez l'homme, puisqu'elles apparaissent spontanément et précocement dans le développement (Drake, Jones, & Baruch, 2000; Hannon & Trehub, 2005), résultat de centaine de milliers d'années d'évolution durant lesquelles les comportements rythmiques ont été utiles à l'être humain (Wallin, Merker, & Brown, 1999). Par exemple, il a été proposé que la danse et la musique ont évolué ensemble en raison de leur rôle dans les comportements de cour, jouant certainement un rôle dans la sélection sexuelle (Dean, Byron, & Bailes, 2009).

L'hétérogénéité des mécanismes de *timing* et de rythme chez l'homme rend difficile l'étude du traitement temporel comme une capacité cognitive générale. Différents paradigmes, méthodes et stimuli ont été utilisés. Une première catégorisation concerne la distinction entre le *timing* explicite et le *timing* explicite. En général, le *timing* explicite est impliqué dans des tâches qui requièrent une production motrice volontaire (par ex., reproduction de durée, kagerer et al., 2002; synchronisation avec un stimulus rythmique ; Repp, 2005) ou une discrimination perceptive (par ex., discrimination de durées ; Allan & Kristofferson, 1974, détection d'irrégularités dans des séquences rythmiques, Ehrlé & Samson, 2005; Hyde & Peretz, 2004) de durée ou de rythme. En parallèle, le *timing* implicite est associé à des tâches qui ne testent pas explicitement le *timing* (par ex., des tâches de temps de réaction, Sanabria, Capizzi, & Correa, 2011), mais dans lesquelles la prédiction temporelle influence la performance (Coull, 2009; Coull & Nobre, 2008; Lee, 1976; Nobre, Correa, & Coull, 2007; Piras & Coull, 2011; Sanabria, Capizzi, & Correa, 2011).

Une autre distinction importante concerne le *timing* basé sur les durées ou sur les intervalles (anglais « duration or interval-based » *timing*, Allan & Kristofferson, 1974; Grondin, 1993; Ivry & Schlerf, 2008; Merchant & De Lafuente, 2014; Wittmann, 2013) et le *timing* basé sur le rhythme (anglais « Beat-based » *timing*, Grahn & Rowe, 2009; Lewis & Miall, 2003; Repp, 2005; Repp & Su, 2013; Dalla Bella et al., 2016). Le *timing* basé sur les durées concerne des tâches impliquant l'estimation, la comparaison ou la production d'intervalles simples (Block & Grondin, 2014; Grondin, 2008; Grube, Cooper, Chinnery, & Griffiths, 2010; Teki, Grube, Kumar, & Griffiths, 2011). Le *timing* basé sur le rythme consiste en des tâches telles que la synchronisation à des stimuli avec un *beat* sous-jacent (Dalla Bella et al., 2017a; Repp, 2005; Repp & Su, 2013; Wing & Kristofferson, 1977), la détection de changements dans une séquence de sons réguliers (Dalla Bella et al., 2017a; Ehrlé & Samson, 2005), ou estimer si un métronome est aligné au rythme de la musique ou non (Beat Alignment Test (BAT), Dalla Bella et al., 2017a; Iversen & Patel, 2008). Il est important de noter que ces deux formes de *timing* impliquent chacune un traitement temporel purement perceptif (par ex., l'estimation de durées, la détection d'irrégularités dans une séquence) et une réponse motrice (par ex., la production d'une durée ou le *tapping* digital au rythme d'une séquence) qui peuvent être étudiés séparément.

Différents modèles ont été développés pour rendre compte des différentes formes de *timing*. Par exemple, les approches traditionnelles tendent à considérer le traitement temporel comme une représentation linéaire du temps par un système de « pacemaker », ou horloge interne, représenté par une aire cérébrale spécifique ou un réseau distribué dans le cerveau (Buhusi & Meck, 2005; Gibbon, 1977, 1991; Petter & Merchant, 2016). En parallèle, la théorie des systèmes dynamiques modélise le traitement de l'information temporelle par des oscillateurs internes qui focalisent l'attention sur des points précis dans le temps (Large & Jones, 1999).

Les capacités de rythme sont sous-tendues par un réseau neuronal complexe qui inclut les régions motrices du cerveau (par ex., les ganglions de la base, les cortex moteur et pré-moteur, Grahn & Brett, 2007; Grahn & Rowe, 2009; Zatorre, Chen, & Penhune, 2007), les régions associées à l'intégration sensori-motrice (par ex., le cervelet, Coull, Cheng, & Meck, 2011; Grube, Cooper, Chinnery, & Griffiths, 2010; Schwartze & Kotz, 2013; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003) en plus des régions associées à l'audition (le cortex auditif primaire, le gyrus temporal supérieur, Grahn & Brett, 2007; Zatorre, Chen, & Penhune, 2007).

Le but final de cette thèse est de proposer une méthode d'entrainement aux capacités de rythme en améliorant les capacités des participants à percevoir et à se synchroniser avec un *beat* (c.-à-d., *timing* explicite). Par conséquent, le *timing* basé sur le rythme est central dans cette thèse.

Les liens entre rythme, mouvement et capacités cognitives

Il existe un lien étroit entre le rythme et le mouvement qui se manifeste dans la façon dont réagissons à l'écoute de la musique. Spontanément ou intentionnellement, nous bougeons, tapons des pieds ou frappons dans nos mains au rythme de la musique. Cette réaction naturelle suggère que nous sommes pré-disposés à fournir une réponse motrice à l'écoute du rythme. L'observation selon laquelle la simple perception du rythme engage les régions motrices du cerveau (Chen, Penhune, & Zatorre, 2008; Grahn & Brett, 2007; Grahn & Rowe, 2009) confirme ce lien et laisse penser que le rythme et le mouvement ont des origines communes. Ce lien est également observé dans la pathologie. Les études sur les patients atteints de troubles du mouvement (par ex., la maladie de Parkinson) ont montré qu'ils étaient, en général, également atteints de troubles rythmiques perceptifs et sensorimoteurs (Benoit et al., 2014; Grahn & Brett, 2009; Pastor, Artieda, Jahanshahi, & Obeso, 1992).

De plus en plus de travaux mettent en évidence l'importance du rythme dans le langage et les capacités cognitives. Par exemple, le langage est organisé avec des règles séquentielles précises et, par conséquent, les capacités de langages reposent sur la prédiction et le codage temporel des évènements (Goswami, 2011; Kotz & Schwartze, 2010; Tallal, 2004). Ainsi, les capacités rythmiques sont positivement corrélées aux capacités de lecture (Bekius, Cope, & Grube, 2016; Huss et al., 2011; Tierney, White-Schwoch, MacLean, & Kraus, 2017 ; Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014), de grammaire (Gordon et al., 2014), de phonologie et de langage (Corriveau, Pasquini, & Goswami, 2007; Grube, Cooper, & Griffiths, 2013; Huss et al., 2011) et d'attention soutenue (Tierney & Kraus, 2013) chez l'enfant et l'adulte.

Les déficits rythmiques chez l'homme

Malgré le fait que la majorité puisse percevoir et se synchroniser avec un *beat*, cette capacité peut être entravée chez certaines populations atteintes de troubles neuro-développementaux ou de maladie neuro-dégénérative. C'est le cas notamment des mauvais synchroniseurs (anglais « poor synchronizers », appelés également « beat deaf »). Les mauvais synchroniseurs sont des individus sans troubles neurologiques mais qui ont des déficits dans le traitement du rythme, au niveau perceptif et/ou sensorimotor (Palmer et al., 2014; Sowiński & Dalla Bella, 2013), qui les empêchent de se synchroniser avec des stimuli rythmiques.

Les patients atteints de maladie de Parkinson présentent des déficits dans les capacités de rythmes. Typiquement, les patients atteints de la maladie de Parkinson ont des déficits de perception et de production de durées (Artieda, Pastor, Lacruz, & Obeso, 1992; Pastor, Artieda, Jahanshahi, & Obeso, 1992) ainsi que dans la discrimination de séquences rythmiques et dans l'extraction du *beat* (Grahn & Brett, 2009; Benoit et al., 2014). Des études ont également rapporté une tendance à se synchroniser avec moins de précision que les sujets sains (Benoit et al., 2014), et une plus grande variabilité lorsqu'il s'agit de produire spontanément un rythme régulier (O'Boyle, Freeman, & Cody, 1996).

D'autres exemples de troubles des capacités de rythme sont trouvés chez les enfants et les adultes atteints de dyslexie développementale (Huss et al., 2011; Thomson, Fryer, Maltby, & Goswami, 2006; Wolff, 2002), de troubles du langage (anglais « Specific Language Impairment », SLI, Corriveau, Pasquini, & Goswami, 2007; Corriveau, & Goswami, 2009) et de bégaiement (Falk, Müller, & Dalla Bella, 2015 ; Wieland, Mcauley, Dilley, & Chang, 2015).

Enfin, les troubles dysfonctionnels de l'attention avec ou sans hyperactivité (TDAH) entraînent également des troubles rythmiques (Toplak & Tannock, 2005; Rubia et al., 2003) ; Dans une étude récente (Puyjarinet et al., en révision), nous avons testé les capacités de rythme dans le TDAH à l'aide de la « Battery For the Assessment of Auditory and Sensorimotor Timing Abilities » (BAASTA, Dalla Bella et al., 2017a. Cette batterie est présentée dans l'étude 1 de cette thèse). Nous avons montré que les enfants et les adultes atteints de TDAH avaient des difficultés à extraire la pulsation et à se synchroniser notamment avec du matériel musical.

En résumé, de nombreux travaux ont montré que les capacités de rythme étaient liées aux fonctions cognitives et à la motricité. Il a été démontré que les troubles rythmiques étaient fréquemment associés à des troubles cognitifs et moteurs. Dans ce contexte, il est nécessaire de caractériser précisément les capacités rythmiques chez les individus sains et chez les patients. Dans cette optique, **le premier but de cette thèse est d'étudier en profondeur les capacités de rythme à l'aide d'un outil systématique (BAASTA) composé d'un ensemble de tâches et de mesures pour mieux comprendre les différences interindividuelles dans le traitement de l'information rythmique.**

Les méthodes de réhabilitation utilisant le rythme

Il existe quelques exemples montrant l'effet bénéfique de protocoles de stimulations rythmiques pour entraîner le mouvement et les fonctions cognitives chez le patient. La stimulation auditive rythmique (anglais « Auditory Rhythmic Stimulation », RAS) a été utilisée avec succès pour ré-entraîner la marche chez le patient parkinsonien (Benoit et al., 2014; Dalla Bella et al., 2015; Dalla Bella et al., 2017b ; Lim et al., 2005; Thaut et al., 1996). Cette méthode consiste à présenter un stimulus avec un *beat* (un métronome ou de la musique) lorsqu'il marche pour lui fournir une indication sur le moment où un mouvement doit être exécuté. Cette méthode permet d'augmenter la vitesse de la marche et la longueur du pas chez la plupart des patients (Howe et al., 2003; McIntosh, Brown, Rice, & Thaut, 1997; Rubinstein, Giladi, & Hausdorff, 2002; Spaulding et al., 2013) et de réduire la variabilité de la marche (Hausdorff et al., 2007; van Wegen et al., 2006). Il est important de noter que l'effet d'un protocole de stimulation rythmique est maintenu jusqu'à plusieurs semaines (Benoit et al., 2014; McIntosh, Brown, Rice, & Thaut, 1997).

L'entraînement à la marche par stimulation rythmique a également un effet sur les capacités de rythmes. Benoit et al. (2014) ont testé les capacités de rythme aux niveaux perceptif et sensorimoteur avant et après un protocole de stimulation rythmique avec BAASTA. Ils ont montré une amélioration des capacités de rythme non seulement au niveau sensorimoteur mais également au niveau purement perceptif, en plus de l'amélioration de la marche.

La stimulation auditive rythmique a également été utilisée avec succès dans la rééducation de la parole chez le patient parkinsonien ou les patients ayant subi un traumatisme crânien (Mainka & Mallien, 2014; Thaut, McIntosh, McIntosh, & Hoemberg, 2001) ou dans la rééducation du mouvement chez le patient post-AVC (Ford, Wagenaar, & Newell, 2007), dans la paralysie cérébrale (Kim et al., 2011; Kwak & Kim, 2013) et dans la sclérose en plaques (Conklyn et al., 2010).

En résumé, plusieurs études ont montré qu'il était possible d'entraîner la cognition et la motricité par stimulation rythmique. Il a aussi été montré que les capacités de rythme de patients atteints de la maladie de Parkinson pouvaient être améliorées par un protocole d'entraînement à la marche par stimulation rythmique. Cependant, à notre connaissance, aucune étude visant à tester s'il est possible d'entraîner directement les capacités rythmiques n'a été conduite jusqu'à présent. **Le second but de cette thèse est donc et de présenter un protocole d'entraînement des capacités de rythme sous forme de jeu sérieux.**

L'entraînement rythmique à l'aide de jeux sérieux

Les jeux sérieux permettent de divertir le joueur tout en visant un autre but, par exemple l'entraînement ou la réhabilitation de certaines fonctions. Ainsi, au cours des dernières décennies, beaucoup de travaux ont permis le développement de jeux pour l'entraînement des capacités de mouvement utilisant des technologies de capture du mouvement peu coûteuses (par ex., Hammer and Planks, Di Loreto et al., 2013) ou pour l'entraînement des capacités cognitives (par ex., RehaCom, Fernández et al., 2012).

Nous avons mené une étude afin d'examiner si les jeux de rythme disponibles sur le marché pouvaient potentiellement être utilisés comme outil d'entraînement des capacités de rythme (Bégel, Di Loreto, Seilles, & Dalla Bella, 2017). Parmi les 27 jeux évalués, nous avons constaté qu'aucun ne fournissait une précision suffisante dans les informations sur la performance (la plupart fournissent uniquement un score final). De plus, les jeux n'entraînent pas spécifiquement les capacités de rythme mais également la synchronisation visuo-spatiale, le temps de réaction, etc. Nous avons conclu qu'aucun jeu de rythme disponible sur le marché n'était satisfaisant pour la réalisation d'un protocole d'entraînement des capacités de rythme bien contrôlé. Nous proposons que pour être satisfaisant pour un protocole d'entraînement, les jeux devaient implémenter les méthodes d'analyse de la performance de synchronisation utilisées en neuroscience du rythme (Kirschner & Tomasello, 2009; Pecenka & Keller, 2009; Woodruff Carr et al., 2014; Dalla Bella et al., 2017a). De plus, les stimuli utilisés doivent être sélectionnés en fonction de leur difficulté rythmique et classés par difficulté croissante afin d'entraîner les capacités du joueur à la perception et à la synchronisation à une pulsation de plus en plus difficile à extraire.

Finalement, **nous avons estimé qu'il était nécessaire de développer un jeu sérieux d'entraînement aux capacités de rythme** comprenant les critères présentés ci-dessus.

En résumé de cette partie introductive, nous avons mis en évidence deux buts principaux. Le premier est d'améliorer nos connaissances des différences inter-individuelles dans le traitement de l'information rythmique au moyen d'une batterie d'évaluation systématique. Le second est le développement d'un jeu sérieux d'entraînement des capacités de rythme.

2. Partie expérimentale

La partie expérimentale de cette thèse est divisée en deux sous-parties, correspondant aux deux buts présentés dans l'introduction. La première sous-partie concerne **l'évaluation des capacités de rythme** et la deuxième sous-partie porte sur **l'entrainement des capacités de rythme** au moyen d'un jeu sérieux.

Évaluation des capacités de rythme

Étude 1 : BAASTA : Battery for the Assessment of Auditory Sensorimotor and Timing Abilities[6]

La Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA) est un nouvel outil pour l'évaluation systématique des capacités de *timing* perceptif et sensorimoteur. Elle vise à étudier une large gamme de capacités de *timing* afin de mettre en évidence différent profiles individuels. La BAASTA consiste en plusieurs tâches sensitives de perception et de production du temps. Les tâches perceptives sont la discrimination de durées , qui consiste à estimer si deux sons sont de même longueur ou non, la détection d'anisochronies avec métronome et musique, dans laquelle le sujet doit estimer si la séquence est régulière ou non, et une version de la Beat Alignment Task (BAT). Dans la BAT, le participant doit estimer si un métronome est aligné au rythme de la musique ou non. Les seuils de perception pour la discrimination de durées et la détection d'anisochronie sont calculés avec l'algorithme maximum likelihood procedure (MLP). Pour la BAT, un index d-prime (*d'*) est calculé en fonction des bonnes réponses et des fausses alarmes. Les tâches de

[6] Cette étude a été publiée dans le journal *Behavior Research Method.*
Dalla Bella, S., Farrugia, N., Benoit, C. -E., Bégel, V., Verga, L., Harding, E., & Kotz, S. A. (2017). BAASTA: Battery for the Assessment of Auditory Sensorimotor and Timing Abilities. *Behavior Research Methods, 49*, 1128–1145.

production sont des tâches de *tapping* digital et incluent le *tapping* spontané et le *tapping* indicé avec métronome et musique, une tâche de synchronisation-continuation (le sujet doit se synchroniser avec un métronome puis continuer à taper au même rythme lorsque le métronome s'arrête) et une tâche de *tapping* adaptif, équivalent à la synchronisation-continuation mais avec des changements possibles à la fin de la séquence de métronome. La batterie a été testée dans une étude de faisabilité avec 20 adultes non musiciens (Experience 1). Afin de valider les résultats de la procédure MLP, moins fréquemment utilisée que le méthode « staircase » standard, trois tâches perceptives (discrimination de durées, détection d'anisochronies avec métronome et avec musique) on été testées avec des paradigmes « staircase » « 2 down / 1 up » et « 3 down / 1 up » auprès d'un second groupe de 24 non-musiciens (Expérience 2). Les résultats montrent que les profiles individuels au niveau du *timing* mis en évidence par la BAASTA permettent de détecter les cas de déficits de *timing* et de rythme. De plus, les seuils de perceptions calculés par l'algorithme MLP, bien que généralement comparables aux résultats obtenus avec la méthode « staircase », tendent à être légèrement moins élevés. En résumé, la BAASTA est une batterie exhaustive pour tester les capacités de *timing* perceptif et sensorimoteur et pour détecter les déficits de *timing* et de rythme.

Étude 2 : étude de fidélité test-retest de la BAASTA[7]

Les capacités de *timing* perceptif et sensorimoteur peuvent être évaluées de manière exhaustive grâce à la BAASTA. La batterie a été utilisée pour tester les capacités rythmiques chez les adultes sans pathologie (Étude 1) et chez certaines populations de patients (par ex., la maladie de Parkinson, Benoit et al., 2014), montrant une bonne sensibilité aux déficits de rythme et de *timing*. Dans cette étude, nous évaluons la fidélité test-retest de la BAASTA dans un groupe de vingt adultes sans pathologie. Les participants ont été testé deux fois avec une version tablette de la BAASTA, dans un intervalle de deux semaines. Le coefficient de corrélation intraclasse (anglais « Intraclass Correlation Coefficient », ICC) a été utilisé comme mesure de fidélité test-retest. En dépit de la grande variabilité entre les individus, les résultats montrent une bonne fidélité des mesures test-retest dans la plupart des tâches. Une

[7] Cette étude est en révision dans le journal *Annals of Physical and Rehabilitation Medicine.* Bégel, V., Verga, L., Benoit, C. -E., Kotz, S. A., & Dalla Bella, S. (en révision). Test-retest reliability of the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA). *Annals of Physical and Rehabilitation Medicine*

amélioration de la performance en re-test a été observée en *tapping* avec la musique. Ce résultat est susceptible de refléter un effet d'apprentissage. En général, la BAASTA est un outil garantissant une bonne fidélité des mesures test-retest pour l'évaluation des capacités de *timing* et de rythme.

Étude 3 : « ″Lost in time″ but still moving to the beat[8]»

La synchronisation au *beat* d'une séquence auditive (métronome ou musique) est une capacité commune chez l'humain. Cependant, certains individus « *beat* deaf » on des difficultés à se synchroniser. Cette difficulté a été expliquée par une mauvaise perception du *beat*. Dans cette étude, deux cas de personnes (L.A. et L.C.) ayant des difficultés dans la perception du *beat* alors que leur synchronisation est bonne sont présentés. Dans l'Expérience 1, les capacités de rythmes de L.A. et L.C., ainsi que d'un troisième sujet (L.V.) on été testées avec la BAASTA. En comparaison avec un groupe contrôle, L.A. et L.C. ont des difficultés dans les tâches de perception du rythme, comme évaluer si une séquence est régulière ou si un métronome est aligné au rythme de la musique. En revanche, elles peuvent toutes les deux taper en rythme avec les mêmes stimuli. L.V. a des déficits à la fois en perception et en synchronisation. Dans l'Expérience 2, le but était de tester si les déficits perceptifs de L.A., L.C., et L.V. s'étendent à une tâche de *timing* implicite, dans laquelle les sujets devaient répondre le plus rapidement possible à un son différent après une séquence de sons standards. Les trois *beat deafs* bénéficient autant que les contrôles de la régularité de la séquence précédant la cible. Le fait que la synchronisation à un *beat* soit possible alors que la perception est déficitaire montre que la perception et l'action peuvent être dissociées dans des tâches de *timing* explicite. La perception implicite du *beat* permet probablement la synchronisation chez certains sujets *beat-deafs*. Ce résultat suggère que différentes voies cérébrales sous-tendent la perception du *beat* selon la nature explicite ou implicite de la tâche chez certains sujets *beat-deafs*.

[8] Cette étude a été publiée dans le journal *Neuropsychologia.*
Bégel, V., Benoit, C. -E., Correa, A., Cutanda, D., Kotz, S. A., & Dalla Bella, S. (2017). "Lost in time" but still moving to the beat. *Neuropsychologia*, *94*, 129-138.

Entraînement des capacités de rythme.

Étude 4 : *Rhythm Workers*, un jeu sérieux pour l'entrainement des capacités de rythme[9]

La plupart des gens, musiciens comme non-musiciens, peuvent naturellement et de façon précoce percevoir ou produire des rythmes. Cette capacité peut cependant être entravée par des pathologies développementales ou neurologiques (par ex., maladie de Parkinson, dyslexie). Les difficultés rythmiques sont liées à des déficits des fonctions cognitives comme le langage, l'attention et la mémoire de travail. Ré-entraîner les capacités de rythme peut s'avérer être une piste prometteuse pour améliorer les fonctions cognitives associées. À l'heure actuelle, il n'y a pas d'outil pour entraîner spécifiquement les capacités de rythme. Afin de combler ce manque, un nouveau protocole sous forme de jeu sérieux sur tablette tactile, appelé *Rhythm Workers,* a été développé. L'Expérience 1 a servi à sélectionner le matériel musical. 54 extraits musicaux avec une difficulté rythmique croissante ont été sélectionnés. La difficulté rythmique a été évaluée en considérant la performance de 18 non-musiciens qui ont tapé au rythme de la musique. Les extraits de difficulté rythmique croissante ont été assignés à différent niveaux de difficultés dans le jeu. Dans l'Expérience 2, le protocole *Rhythm Workers* a été créé et testé dans une étude de faisabilité avec deux versions du jeu. Une version (*version tapping*) requiert une réponse motrice synchronisée (via le *tapping* digital) alors que la second version (*version perception*) est une tâche purement perceptive, une version adaptée de la BAT. 10 participants ont joué à une version du jeu et 10 à l'autre, pendant deux semaines. Un groupe contrôle n'a pas reçu d'entraînement. Les participants des groupes expérimentaux ont montré une bonne adhésion au jeu et se sont montrés motivés à jouer. L'effet sur les capacités de rythme a été testé avec la version de la BAT issue de la BAASTA, soumise aux participants avant et après l'entraînement. L'entraînement perceptif a mené à une amélioration significative de la performance à la BAT, en comparaison du groupe contrôle. Les performances avant et après l'entraînement sensorimoteur ne sont pas significativement différentes, en raison de fortes différences inter-individuelles. Cinq sujets ont une performance améliorée de plus de 10% alors que trois ont une performance détériorée de plus de 10% en seconde session. En résumé, *Rhythm Workers*

[9] Cette étude a été soumise au journal *Music & Science.*
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est un jeu motivant et potentiellement efficace pour entraîner les capacités de rythmes, avec de possibles applications pour les individus atteints de troubles rythmiques.

3. Discussion & conclusion

Dans cette dissertation, j'ai posé plusieurs questions de recherché qui ont été abordées dans quatre études différentes. Tout d'abord, il était question de savoir s'il était possible d'évaluer les capacités de *timing* et de rythme à l'aide d'un outil systématique, comprenant un ensemble de mesures standards, afin de mettre évidence les capacités déficitaires et les capacités épargnées chez différents groupes d'individus (par ex., *beat deafs* ou patients). En particulier, l'objectif était d'utiliser la BAASTA pour caractériser les comportements de *timing* et de rythme et révéler de nouvelles dissociations dans les mécanismes sous-tendant ces capacités. Dans l'Étude 1, il a été démontré que la batterie était effectivement sensible aux différences inter-individuelles. Certains participants ont notamment obtenu des résultats particulièrement faibles à certaines tâches, déviant de la moyenne du groupe par plus de deux écart-types. Dans l'Étude 2, la fidélité test-retest de la plupart des mesures s'est avérée bonne, confirmant que la BAASTA est un outil fiable pour évaluer les capacités de *timing* et de rythme. Dans l'Étude 3, les capacités rythmiques de sujets *beat deafs* ont été examinées plus en profondeur. Deux dissociations ont été mises en évidence pour la première fois. Tout d'abord, certains sujets ont des difficultés à percevoir le rythme dans des séquences de métronome ou de musique alors qu'ils sont capables de se synchroniser avec les mêmes séquences. Ensuite, les sujets *beat deafs*, malgré leurs difficultés dans des tâches de *timing* explicite, sont capables de percevoir la régularité dans une tâche de *timing* implicite. Ces résultats suggèrent qu'une représentation interne du *beat* est bien présente chez les *beat deafs* mais que l'accès conscient à cette représentation est impossible en raison de déficits attentionnels. Mathias et collaborateurs (Mathias et al., 2016) ont montré que les sujets *beat deafs* avaient une activité neurophysiologique normale dans le traitement pré-attentionnel du *beat* mais que, chez un sujet (Mathieu), des anomalies dans les stades de traitement attentionnels plus tardifs sont observés (réduction de la réponse P3b aux rythmes déviants). Ces résultats tendent à confirmer, d'une part, que différents profils de *beat deafs* peuvent exister et que la source du déficit peut varier (voir aussi Sowiński & Dalla Bella, 2013). D'autre part, il est important de noter que la capacité à se synchroniser de certaines personnes qui ont des difficultés à percevoir le rythme peut reposer sur une représentation implicite du *beat*.

Le second but de la thèse était de créer un protocole d'entraînement des capacités de rythme sous forme de jeu sérieux. Le jeu, *Rhythm Workers,* a été créé et testé dans une étude de faisabilité auprès de 20 adultes non-musiciens. Le jeu s'est avéré motivant et les participants ont suivi le protocole avec implication. Les capacités à percevoir le rythme de la musique ont été testées avant et après l'entraînement avec la BAT. La plupart des participants ont bénéficié de l'entraînement en améliorant leur performance à cette tâche.

Cette étude pilote suggérant un effet bénéfique d'un protocole d'entraînement des capacités rythmiques par jeu sérieux ouvre des perspectives intéressantes pour le futur. En effet, un tel entraînement pourrait s'avérer utile dans les pathologies affectant le rythme (par ex., maladie de Parkinson, dyslexie). De futures études devront être conduites afin d'évaluer si ce type d'entrainement peut avoir un effet bénéfique sur les fonctions cognitives et motrices associées aux capacités de rythme, telles que la marche, la parole etc., dans ces maladies.

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Annex

Annex: Children and adults with Attention-Deficit/Hyperactivity Disorder cannot move to the beat[10]

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[10] This study is under revision in *Scientific Reports*.
Puyjarinet, F., Bégel, V., Lopez, R., Dellacherie, D., Strachowski, O., & Dalla Bella, S. (under revision). Children and adults with ADHD cannot track the beat of music. *Scientific Reports*

Abstract

Children and adults with Attention-Deficit Hyperactivity Disorder (ADHD) fail in simple tasks like telling whether two sounds have different durations, or in reproducing single durations. The deficit is linked to poor reading, attention, and language skills. Here we demonstrate for the first time that these timing distortions emerge also when tracking the beat of rhythmic sounds. This contrasts with the common observation that durations are better perceived and produced when embedded in rhythmic stimuli. Children and adults with ADHD struggled when moving to the beat of rhythmic sounds, and detecting deviations from the beat. Our findings point to failure in generating an internal beat in ADHD while listening to rhythmic sounds, a function typically associated with the basal ganglia. Rhythm-based interventions aimed at reinstating or compensating this malfunctioning circuitry may be particularly valuable in ADHD, as already shown for other neurodevelopmental disorders, such as dyslexia and Specific Language Impairment.

INTRODUCTION

More than 5% of children show poor concentration, impulsivity and visible signs of hyperactivity (1), either alone or in combination. This condition, named Attention Deficit/Hyperactivity Disorder (ADHD), is the most common neurobehavioral disorder of childhood (2). Akin to other neurodevelopmental disorders such as dyslexia and Development Coordination Disorder (1), it comes with poor school success and socioeconomic disadvantages (3). While many children outgrow it, in about 50% of the cases ADHD carries over into adulthood with negative consequences at work and in everyday life (4).

Children and adults with ADHD also struggle in perceiving and reproducing event durations. They have difficulties in telling or reproducing the duration of visual and auditory stimuli and in comparing time intervals (5). Distortions in duration perception and production are also reported in other neurodevelopmental disorders such as autism spectrum disorders and dyslexia (6, 7). Impaired timing is associated with poor reading, attention and language skills, and with impaired executive functions (5, 8). The neural substrates of processing event durations (i.e., *duration-based timing*) include cerebellar-cortical pathways (9). Structural anomalies in these brain regions (e.g., inferior or posterior vermis) and impaired connectivity within fronto-cerebellar networks are found in ADHD (10). Thus, it does not come as a surprise that the processing of event duration is impaired in ADHD.

Owing to these difficulties in encoding and producing single durations, one may conclude that children with ADHD have a poor appraisal of the timing of events altogether. This conclusion may be premature, though. Children with ADHD might still be able to treat durations when embedded in a rhythmic context, by benefitting from its predictable temporal structure (i.e., by tracking the beat). Typically, durations can be processed more easily by the healthy brain when they form a rhythmic structure (11-12). The mechanism underlying beat tracking is based on relative analysis of time intervals, and referred to as *beat-based timing* (9, 12-15). Beat tracking is involved in both perceptual and motor tasks, such as detecting a subtle deviation from a beat (e.g., in music), or moving to the beat. This ability can be selectively spared following brain damage (e.g., spinocerebellar ataxia) in the presence of impaired processing of single durations (16). Beat-based timing has been linked to partly independent neuronal networks, engaging basal-ganglia-cortical circuitries (12, 14, 16, 17).

It is still unknown whether children with ADHD can take advantage of a rhythmic context, in a motor or in a purely perceptual task. This possibility is particularly appealing, as rhythmic auditory stimulation may serve as a remediation strategy in ADHD, as done for other timing disorders, such as Parkinson's disease (18), which displays poor beat tracking skills (15). Interestingly, ADHD has been consistently associated to structural anomalies of the basal ganglia and malfunctioning basal-ganglia-cortical connectivity both in children (19) and in adults (20). For example, structural asymmetries in the caudate (21), and lower activity in the putamen (22) are reported in ADHD. Caudate is known to be preferentially linked to cognitive functioning, while putamen is more closely related to sensorimotor functions (23).

Due to the aforementioned malfunctioning of basal ganglia-cortical circuitries in ADHD, it is expected that children with this condition may have difficulties to track the beat, on top of their poor appraisal of single durations. To test this hypothesis, children with ADHD were asked to track the beat of rhythmic sounds sequences. Metronomes and music were used to test the ability to both track a periodic sound and to internally generate a beat (based on music), a function typically associated with the activity of the basal ganglia (12, 24). Children were asked to detect subtle deviations from the beat of music and metronome sequences. Moreover, they tapped with their finger to the beat of the same stimuli. For comparison, their ability to perceive single durations (duration-based timing) was tested by asking children to compare the duration of pairs of tones.

In addition, half of the tested children in the present study showed Developmental Coordination Disorder (DCD, 1) on top of ADHD. DCD is characterized by impairments in activities that require motor coordination, and co-occurs with ADHD in about 50 % of the cases (25). There is evidence that children with DCD, like children with ADHD, are more variable in rhythmic motor tasks such as tapping than healthy controls (5, 26). Increased abnormalities in motor network connections in children with both DCD and ADHD compared to ADHD alone have been recently described (27). This would negatively impinge on beat tracking for motor tasks. However, DCD is not expected to affect beat tracking in purely perceptual tasks more than ADHD does. Finally, to assess whether the same pattern of timing disorders carries over into adulthood, a group of adults with ADHD was tested with a subset of the same beat tracking tasks.

RESULTS

Duration and beat perception. Children with ADHD showed general difficulties in perceiving durations and in tracking the beat, relative to a group of matched controls (see Fig. 1 *A*, for the results in duration discrimination, and beat perception tasks). Because children with ADHD with and without DCD did not differ on these tasks, we report only data from the pooled group.

Summary statistics for the two groups are presented in Table S1 (*SI Differences between ADHD and ADHD-DCD children performance*). Children with ADHD performed worse than healthy controls when asked to discriminate single durations [$t_{(37.8)} = 4.13$, $P < 0.0001$, $d = 1.31$]. This difference disappeared when children detected a deviant duration in the context of a periodic sequence of tones (Anisochrony detection with tones). However, poor beat tracking in children with ADHD relative to controls was apparent with music (Anisochrony detection with music) [Group x Stimulus interaction; $F_{(1,38)} = 4.91$, $P < 0.05$, $\eta^2 partial = 0.11$; group difference with tones, $t_{(36.3)} = 1.69$, $P = 0.10$, $d = 0.53$; with music, $t_{(38)} = 3.58$, $P < 0.001$, $d = 1.19$]. Finally, children with ADHD had difficulties in judging whether a sound was misaligned or not with a musical beat, as compared to controls [BAT; $t_{(17.6)} = 4.70$, $P < 0.0001$, $d = 1.48$]. This group difference persisted when covarying for duration discrimination performance, hence confirming a genuine impairment in beat tracking irrespective of poor coding of single durations [ANCOVA, $F_{(1,41)} = 25.99$, $P < 0.00001$, $\eta^2_{partial} = 0.39$].

In sum, children with ADHD could detect a deviation from the beat for a simple periodic auditory signal. Yet, they failed to do so with music. This is compelling evidence in favor of a beat-based deficit in ADHD. Beat tracking in music requires extracting periodicities at different embedded time scales from a complex auditory signal. Interestingly, poor beat tracking persisted into adulthood (see Fig. 1 *B*). Adults with ADHD were poorer than age-matched controls in detecting whether a sound and a musical beat were aligned or not [BAT; $t_{(37)} = 3.50$, $P < 0.001$, $d = 12$]. Overall, adults outperformed children on this task [main effect of Age, $F_{(1,85)} = 51.11$, $P < 0.00001$, $\eta^2_{partial} = 0.38$], and all participants, regardless of age and group, showed worst beat tracking performance when music was presented at a fast tempo than at a slow tempo [main effect of Tempo, $F_{(2,170)} = 7.41$, $P <$

0.001, $\eta^2 partial$ = 0.07; for details, see Fig. S1]. No interaction was found between Age group and presence/absence of ADHD.

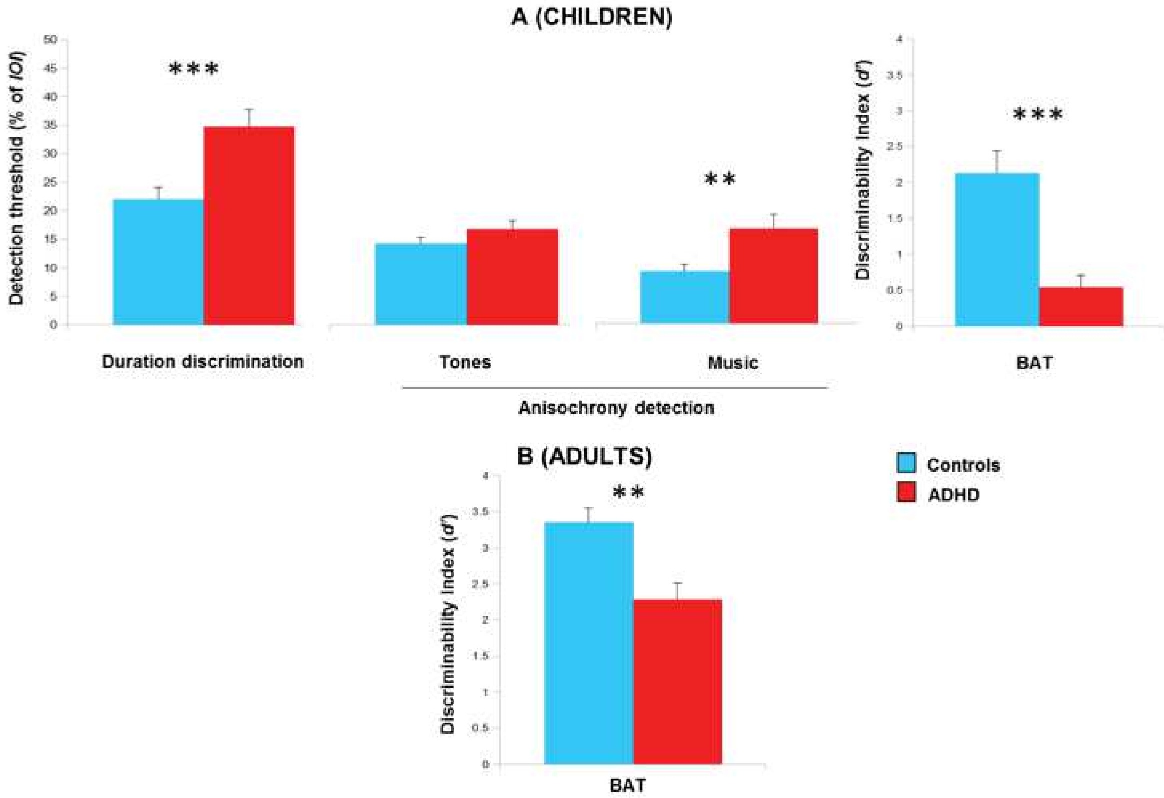

Fig 1. Beat tracking skills measured with perceptual tasks of BAASTA for children and adults with ADHD, and healthy controls. (A) Perception of duration tested in children with ADHD and controls using the Duration discrimination task, and beat tracking skills assessed with Anisochrony detection tasks (with tones and music) and the Beat Alignment Test (BAT). (B) Performance of adults with ADHD and controls tested with the BAT. Error bars are SEM. *** $P < 0.0001$, ** $P < 0.01$.

Tapping to the beat. Poor beat tracking in children with ADHD was also apparent when they tapped their finger to the beat of a metronome and of music (Fig. 2 *A*). In this motor task, a difference was apparent between children with and without DCD. Children with ADHD and DCD exhibited worse synchronization to the beat (i.e., lower synchronization consistency) than children with only ADHD, and even worse than age-matched controls [main effect of Group, $F_{(2,51)} = 37.61$, $P < 0.00001$, $\eta^2_{partial} = 0.60$; ADHD-DCD < ADHD, $t_{(38.8)} = 3.07$, $P < 0.01$, $d = 0.96$]. Moreover, these group differences varied with stimulus complexity

[Group x Stimulus interaction, $F_{(2,51)} = 4.20$, $P < 0.05$, $\eta^2_{partial} = 0.14$]. While controls tapped similarly well to both tones and music [$t_{(13)} = 2.37$, $P = 0.10$, $d = 0.38$], children with ADHD showed more difficulty when tapping to the musical beat than to tones [with DCD, $t_{(18)} = 4.25$, $P < 0.01$, $d = 0.95$; without DCD, $t_{(20)} = 6.17$, $P < 0.0001$, $d = 1.33$]. Notably, these findings were replicated across different tempos (see Fig. S2).

Adults with ADHD showed a similar pattern of results (see Fig. 2 *B*). They synchronized less consistently than controls with all stimuli [$t_{(33.2)} = 4.34$, $P < 0.0001$, $d = 1.39$]. Despite the adults outperformed children on this task [main effect of Age, $F_{(1,70)} = 61.45$, $P < 0.00001$, $\eta^2_{partial} = 0.47$], ADHD participants showed greater difficulties in tracking the beat of music than of tone sequences [Group x Stimulus interaction, $F_{(1,70)} = 24.22$, $P < 0.00001$, $\eta^2_{partial} = 0.26$; stimulus difference for ADHD, $t_{(41)} = 6.22$, $P < 0.0001$, $d = 0.74$; for controls, $t < 1$].

As tapping to the beat involved both a perceptual and a motor component, we tested whether poor motor control alone may account for the aforementioned group differences. Indeed, children and adults with ADHD showed higher motor variability than controls when tapping regularly without sound [vs. controls, $F_{(1,88)} = 11.51$, $P = 0.001$, $\eta^2_{partial} = 0.12$]. Summary statistics for children and adults in unpaced tapping are presented in Figure S3. Yet, when covarying for motor variability, ADHD children and adults still revealed lower synchronization performance than controls [main effect of Group, $F_{(1,67)} = 31.06$, $P < 0.00001$, $\eta^2_{partial} = 0.32$]. This difference was more apparent with music than with tones [Group x Stimulus interaction, $F_{(1,67)} = 17.72$, $P < 0.0001$, $\eta^2_{partial} = 0.21$] (see *SI Comparison of ADHD children and adults tapping performance* for ANCOVA results).

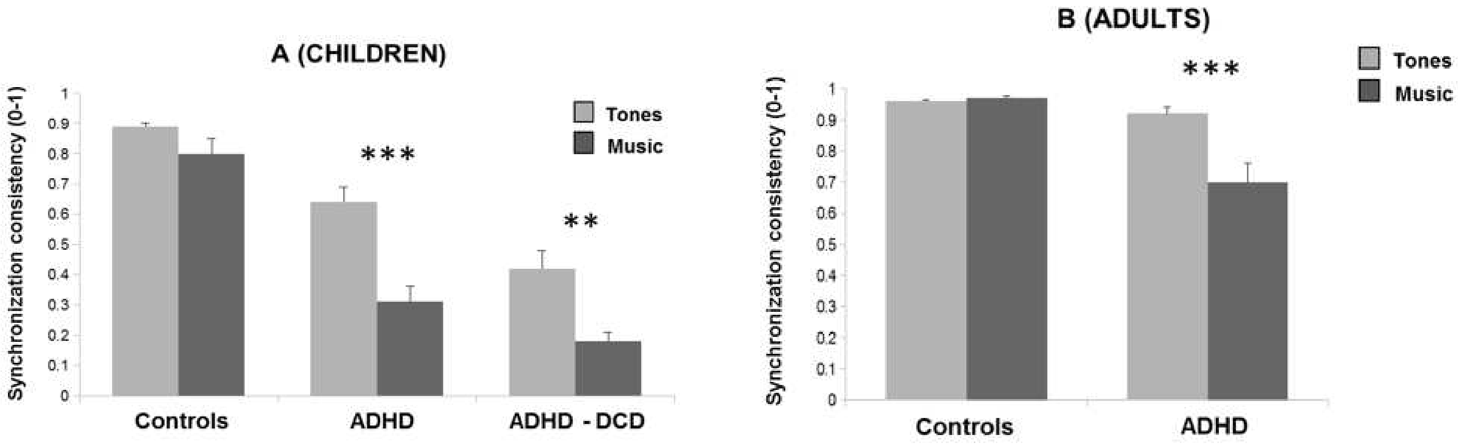

Fig 2. Beat tracking skills measured with motor tasks (finger tapping) of BAASTA for children with ADHD/ADHD-DCD, adults with ADHD, and healthy controls. (A) Performance of children with ADHD and controls when they tapped their finger to the beat of tone sequences and to music. Performance is expressed by the consistency of synchronization, from 0 to 1. Greater values indicate better synchronization to the beat. (B) Performance of adults with ADHD and controls on the same tapping tasks. Error bars are SEM. *** $P < 0.0001$, ** $P < 0.01$.

Individual differences. Despite group results provided compelling evidence of poor beat tracking in ADHD and ADHD-DCD, we observed important individual differences. They can be seen when plotting individual performances in the BAT task against synchronization consistency (Fig. 3 *A* and *B*, for children and adults, respectively). Some ADHD participants (31.4 % of children, and 38 % of adults) still performed within the range of controls, while others showed very poor beat tracking skills. Scores in these two tasks are highly correlated [children, $r = 0.70$, $P < 0.0001$; adults, $r = 0.68$, $P < 0.0001$]; hence, they are likely to pinpoint the same beat tracking skills. Notably, because performance on the BAT does not rely on fine motor control, variability in beat tracking cannot be accounted for by differences in motor control.

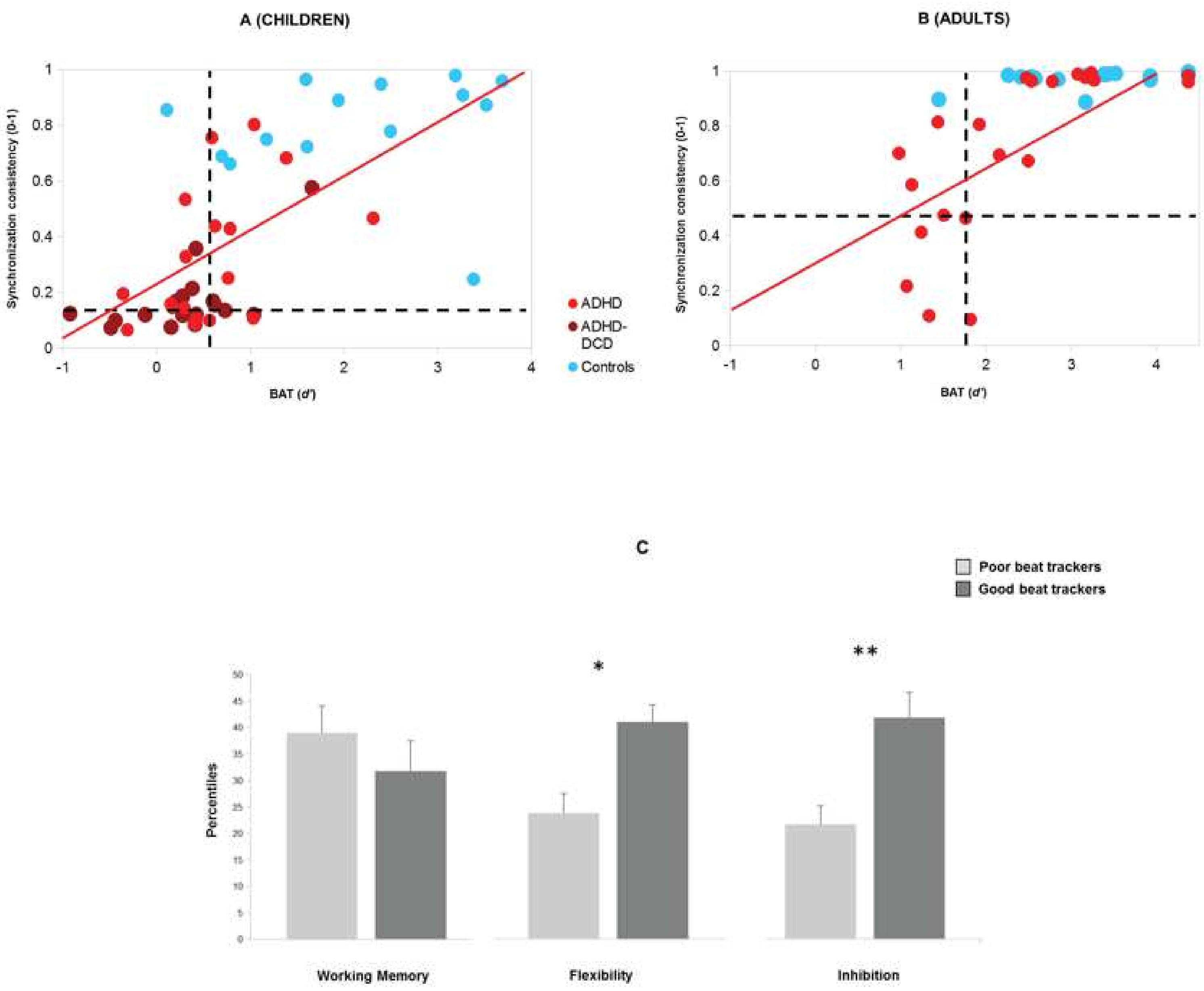

Fig 3. Individual performances in beat tracking as reflected by their results in the BAT (*d'*) and in paced tapping (synchronization consistency). Results from (A) children (ADHD, ADHD-DCD, and controls), and (B) adults (ADHD and controls). In both panels (A) and (B), dotted lines indicate the threshold used to identify participants as poor or good beat trackers, corresponding to -2 *SD* relative to the performance of the respective age-matched control group. (C) Cognitive functioning (short-term memory, flexibility, and inhibition) for children and adults with ADHD, divided into good and poor beat trackers. Error bars are SEM. ** $P < 0.01$, ** $P < 0.05$.

Having shown variable beat tracking skills in ADHD, we tested whether this variability is associated with the severity of cognitive impairment, such as reduced flexibility, poor short-term memory, and poor inhibitory control (28-30). To this aim, children and adults with ADHD were divided into good and poor "beat trackers", based on the calculation of a *Beat Tracking Index* (BTI; see Materials and Methods). The BTI is a composite score based on normalized individual performances in the BAT and in paced tapping tasks of BAASTA, two tasks particularly sensitive to individual differences (11). ADHD participants with a BTI score higher than -2 were classified as *good beat trackers*, and those with a score lower than -2, as *poor beat trackers*. Good beat trackers performed better than poor trackers on the Flexibility task and on the Inhibition task (see Fig. 3 *C*) [$t_{(49.5)} = 2.15$, $P < 0.05$, $d = 0.56$, and $t_{(50.5)} = 3.07$, $P < 0.01$, $d = 0.79$, respectively]. In spite of the association between beat tracking and short-term memory sometimes reported (31), good and poor beat trackers did not differ in that respect [$t < 1$]. In addition, children who were good and poor beat trackers did not differ in I.Q., and on measures of visual-selective, divided, and sustained attention, as well as on a general measure of auditory attention. Summary statistics for these measures are presented in Table S2.

DISCUSSION

Distortions in perceiving and producing single durations are a hallmark of ADHD (5, 32). In this study we demonstrate that ADHD is also associated with rhythmic deficits, thus providing first evidence of impaired beat-based timing in this population. Children with ADHD, albeit they show sensitivity to subtle deviations from the beat in simple sound patterns, do not benefit from the rich rhythmic structure of music. Extracting a beat based on music's peculiar metrical structure (i.e., a system of embedded periodicities) (33) appears as a particularly challenging task. This is visible in both perceptual and motor tasks, when children move to the beat. These difficulties are independent of children's ability to discriminate single durations. Interestingly, poor beat tracking in musical contexts is not confined to childhood. Adults reveal the same pattern of results. Finally, we demonstrate that beat-tracking skills in children and adults are closely linked to inhibition and flexibility, two cognitive functions often impaired in ADHD.

Poor discrimination of durations in children with ADHD confirms impaired duration-based timing already documented in this condition (5, 32). This deficit is associated with brain defects in the cerebellum and fronto-cerebellar pathways (34, 35), usually linked to the processing of single durations (5, 9, 16). The surprising finding that children still perceive durations in the context of a simple rhythm suggests that they may still benefit from a predictable temporal structure (11, 16). However, the beneficial effect of a rhythmic context is not confirmed with music. Children and adults with ADHD struggle in tracking the beat of music. Because poor beat tracking with music is apparent in both perceptual and motor tasks we can conclude that this deficit is not merely the outcome of high motor variability typically found in ADHD (26).

Music is particularly well-suited to test someone's ability to track the beat. Unlike a metronome, the beat of music is not immediately provided by the temporal structure of a sequence of periodic sounds. With music, the beat has to be internally generated based on the complex pattern of durations characteristic of music sequences. This process has been found to engage a cortico-subcortical network, including in particular the basal ganglia (e.g., the putamen) and their connectivity with cortical areas (supplementary motor area and premotor cortex) (13, 24). The possibility of a deficient system for internal generation of a beat is appealing, and consistent with the neuronal substrates of ADHD. There is compelling evidence that the aforementioned brain areas and their connectivity are affected in ADHD. This condition is associated with reduced blood flow in the putamen (22) and lower functional connectivity between motor areas (primary and premotor) and the putamen as compared to controls (27). In sum, poor beat tracking observed in ADHD may results from impaired internal generation of the beat, a function mostly linked to the basal ganglia.

Poor beat tracking in ADHD may also point to deficits in the way children and adults with this condition attend to events dynamically over time. This function, referred to as "dynamic attending" (36) is supported by growing neurophysiological evidence (electro-encephalogram - EEG) that in the healthy brain beat perception is driven by entrainment of neuronal populations which resonate at the beat frequency of an external rhythmic stimulus (37-39). Oscillatory brain activity (e.g., in the beta band) is sensitive to the complexity of the rhythmic patterns (40, 41) and can distinguish well-known metrical structures, such as marches and waltzes (41). Thus, entrainment to an external rhythm as revealed by oscillatory brain behavior may be an additional indicator of beat-based deficits in ADHD. To date, EEG studies in ADHD, conducted in the absence of external stimulation (at rest) showed both increased power in the theta band and decreased power in the beta band (42). Abnormal neural oscillations may pave the way to poor response to an external rhythmic stimulation in ADHD (38, 43, 44). This interesting possibility remains purely speculative at this stage, though, and deserves further investigation.

As expected, tracking the beat in motor tasks was more difficult for children with ADHD and DCD than for children with ADHD. However, ADHD and ADHD-DCD children were similarly poor in tracking the beat in perceptual tasks. Thus, the source of the difference between the two conditions lies in motor processing, rather than generally beat tracking. This is in line with recent work showing specifically impaired sub-cortical/cortical connectivity in motor areas in DCD, relative to ADHD (27). Nevertheless, ADHD and DCD share cerebral abnormalities, notably in the basal ganglia (45), which may represent the neuronal underpinning of a core deficit with beat tracking found in both conditions. Because beat tracking skills in perceptual and motor tasks are highly correlated, performances in these tasks are likely to reflect a common beat-based mechanism which might go awry during development in ADHD (38) and DCD.

To conclude, our findings demonstrate core deficits with tracking the beat of music in ADHD, with and without DCD, in children as well as in adults. These deficits may stem from the ability to generate the beat internally, a function engaging basal ganglia-cortical networks. Nevertheless, it has to be mentioned that beat tracking skills are quite heterogeneous in ADHD. The observed differences between ADHD participants and controls are found at a group level. Yet, it appeared that 35 % of ADHD participants could track the beat as controls did, while the others showed impairment. This variability is not totally surprising, as ADHD is generally characterized by high heterogeneity in terms of cognitive functioning (29, 46). Interestingly, we found that beat tracking skills covary with functions such as flexibility and inhibition, but not short-term memory. Poor beat trackers displayed lower flexibility and inhibition than controls. This finding is highly relevant from a clinical point of view. For example, it is still unknown whether medication (e.g., methylphenidate) affects beat tracking skills, together with the improvement of general cognitive functioning (5). Beneficial effects of medication may indeed generalize to temporal processing.

Moreover, with other populations, there is evidence that variability in rhythmic skills before a dedicated training can be exploited to predict the success of the training (47). For example, individuals with relatively spared rhythmic skills can benefit from a long-term training in which they move together with rhythmic sound (e.g., rhythmic auditory stimulation in patients with Parkinson's disease, 47). Owing to the link between rhythmic and cognitive functions (5, 8, 48), rhythmic training may be a viable tool for remediation of cognitive disorders in ADHD, as done for other neurodevelopmental disorders, like dyslexia (49, 50). Knowing individual rhythmic skills and cognitive functioning in patients with ADHD may similarly allow predicting whether a rhythm-based training can be successful for these populations. This type of musically-based intervention has the advantage of being highly motivating, usable at home, and implementable in low-cost new technologies such as touch screen tablets and smartphones.

MATERIALS AND METHODS

Participants

Children

Fifty five children were recruited from the Montpellier area (France) to participate in the experiment. Forty-on were children with ADHD. Among them, 22 (2 females; 6 left-handed) were children with ADHD only, aged between 6.3 and 12 years (Mean = 8.7 years, *SD* = 1.5) and 19 (3 females; 4 left-handed) were children with ADHD and DCD, aged between 6.8 and 12.6 years (Mean = 8.8 years, *SD* = 1.7). Children in the ADHD group had received a diagnosis of ADHD based on DSM-5 criteria (1) by a multidisciplinary team from the University Regional Hospital (CHRU) of Montpellier. Only children with ADHD of the combined type (with both hyperactiveimpulsive and inattentive symptoms) were recruited. Children in the ADHD-DCD group received a diagnosis by the same hospital team. They performed below the 15th percentile on the French version of the gold-standard M-ABC test (51, 52), a developmental battery assessing motor disturbances. Children in both groups complained at the beginning of attentional, school or motor difficulties. They all scored above 70 on the I.Q. test (53, 54). Other comorbid conditions such as dyslexia, neurological disorders, autistic spectrum disorders, sensory or physical disabilities were excluded. Finally, none of the children with ADHD (with or without DCD) was treated with methylphenidate the day of the experiment. This medication, typically administered to reduce inattention, hyperactivity and impulsive symptoms, has also beneficial effects on timing abilities (5, 55, 56), thus potentially affecting measurement of timing skills. A third group of 14 healthy children (5 females; 1 left-handed) without ADHD, aged between 8.2 and 14.1 years (Mean = 9.4 years, *SD* = 1.6) were recruited for the Control group. Healthy participants did not show intellectual, cognitive, learning or motor disorders.

Adults

Thirty nine adults were recruited from the Montpellier area (France). Twenty-one (11 females; 1 left-handed) aged between 19.1 and 50.1 years (Mean = 31.4 years, *SD* = 10.5) formed the ADHD group. They received a diagnosis of ADHD based on DSM-5 criteria (1), by a psychiatrist (RL) in a specialized outpatient clinic for adult ADHD. Eleven adults with ADHD were of the combined type (with both hyperactive-impulsive and inattentive symptoms), while 10 were of the inattentive type. None of the adults with ADHD was treated with methylphenidate during the week preceding the testing, and the day of the test. The other 18 participants (7 females; 3 left-handed), aged between 19 and 42.2 years (Mean = 32 years, *SD* = 7.2) formed the Control group. Healthy adults did not reveal signs of intellectual, cognitive, learning and motor disorders. The study was approved by the Institutional Review Board (n. 1610D) of the EuroMov research center. All experiments were performed in accordance with relevant guidelines and regulations. Informed consent was obtained from all children's parents and from all adult participants.

Measures of perceptual and sensorimotor timing skills

Perceptual and sensorimotor timing skills were assessed with the Battery for the Assessment of Auditory and Sensorimotor Timing Abilities (11). BAASTA consists of a set of perceptual and motor tasks which proved sensitive to timing and beat tracking deficits in a variety of conditions (e.g., Parkinson's disease, developmental stuttering, beat deafness, and tone deafness) (11, 18, 57- 59). In this study we selected five tasks from BAASTA for assessing beat tracking skills (3 perceptual tasks and 2 sensorimotor tasks), with simple and complex auditory material (sequences of tones and music). Perceptual tasks consisted in detecting deviations from the beat (Anisochrony detection), or in saying whether a superimposed metronome was aligned or not with a musical beat (Beat Alignment Test).

Sensorimotor tasks involved finger tapping to the beat (Paced tapping). Two additional control tasks were performed to assess perception of single durations in the absence of beat tracking (Duration discrimination) and motor variability in the absence of an auditory stimulus (Unpaced tapping). Details for each task are provided below. Children were tested on all the tasks with a computer version of BAASTA. Auditory stimuli were delivered via headphones (Sennheiser HD201) and tapping data was acquired with a Roland SPD-6 MIDI tapping pad. Responses were provided verbally by the participants and entered by the Experimenter via the computer keyboard. Adults were tested on the BAT and on the motor tasks with a tablet version of BAASTA (LG G Pad 8.0 model), while auditory stimuli were delivered via headphones (Sennheiser HD201). The order of the tasks was fixed (Duration discrimination, Anisochrony detection with tones and music, BAT, for perceptual tasks; Unpaced tapping and Paced tapping to tones and music, for motor tasks).

Perceptual tasks

Anisochrony detection with tones

With this task we tested participants' ability to perceive a temporal irregularity (i.e., a time shift) in an isochronous sequence of tones - a metronome (see (60) and (61)). Participants listened to sequences of five tones (tone duration = 150 ms; frequency = 1047 Hz). While some sequences (20% of all trials) were isochronous and presented a constant inter-onset interval (IOI = 600 ms), others contained a deviation from isochrony. This corresponds to a time shift of the fourth tone that occurred earlier than expected based on the previous sounds. The amount of the time shift, up to 30% of the IOI, was changed adaptively depending on the participants' response. This was implemented via a Maximum Likelihood Procedure (61) using the MATLAB MLP toolbox (28, 62). The task was to judge whether the sequence was "regular" or "irregular". Participants performed 3 blocks of 16 trials each.

Anisochrony detection with music

As done in the previous task, participants detected a time shift. However, this time this corresponded to a deviant beat in a short musical excerpt (11, 60). In each trial, a computergenerated musical excerpt from Bach's "Badinerie" (orchestral suite for flute BWV 1067) was played with a piano timbre at a tempo of 100 beats/min (IOI = 100 ms; beat =

quarter note). The excerpt was played in a regular version (with isochronous beats) or in an irregular version with a time shift introduced at the onset of the fifth beat. The magnitude of the time shift, up to 30% relative to the IOI was controlled by the MLP algorithm. The task was to tell whether the rhythm was “regular” or “irregular”. As before, there were 3 blocks of 16 trials each.

Beat Alignment Test (BAT)

With this task we tested listeners’ ability to detect deviations from the beat. The task is an adapted version of the BAT (63). Participants listened to four musical excerpts with a salient beat: two from Bach's « Badinerie » and two from Rossini's « William Tell Overture ». Each excerpt included 20 beats (beat = quarter note). After the seventh beat, a sequence of isochronous tones with a triangle timbre (a metronome) was superimposed onto the music. The tones were either aligned or not to the musical beat. When unaligned, the tones occurred earlier or later than the beat by 33% of the quarter note duration, or the interval between the tones was increased or decreased by 10% of the quarter note duration. The stimuli were presented at three different tempos (IOIs = 450, 600 and 750 ms), for a total of 72 stimuli. Stimuli were presented in randomized order. Participants judged whether the metronome was aligned or not to the beat of music.

Duration discrimination (control task)

In this test we assessed whether participants could perceive single durations, in the absence of an underlying beat. They were presented with two tones (frequency = 1 kHz, interval between tones = 600 ms). The first tone (standard) lasted 600 ms, and the second, between 600 ms to 1000 ms. Participants judged if the second tone lasted longer than the first. The duration of the second tone was controlled by the MLP algorithm. There were 3 blocks, each including 16 trials.

Motor tasks

Paced tapping to tones

We tested whether participants could track the beat by asking them to tap with their finger to sequences of isochronously presented sounds. Each sequence included 60 piano tones (tone frequency = 1319 Hz). The tones were presented at three tempos (IOIs = 450, 600, and 750 ms).

All stimuli were repeated twice.

Paced tapping to music

The same task as above was carried out with musical stimuli. Participants were asked to tap with their finger to the beat of two excerpts taken from Bach's « Badinerie » and from Rossini's « William Tell Overture » (quarter note IOI = 600 ms). Each excerpt included 64 beats and was repeated twice.

Unpaced tapping (control task)

We tested participants' motor variability in a tapping task in which they did not have to track the beat. Their task was to produce regular fingers taps with their dominant hand at a comfortable rate for 60 seconds (e.g. 64). The tasks were carried out twice.

Data analysis

Perceptual tasks: for Duration discrimination and Anisochrony detection tasks, the perceptual thresholds obtained in the three blocks were averaged and expressed in percentage of the stimulus IOI (Weber ratio). Blocks with more than 30 % of false alarms were discarded (11). In the BAT, the sensitivity index (*d'*) was calculated, as an unbiased measure of detection performance, based on the number of Hits (when unaligned tones were correctly detected) and False alarms (when lack of alignement was incorrectly reported). *d'* is the difference between the z-transform of Hits rate and False Alarm rate.

Motor tasks: for both Paced and Unpaced tapping tasks, the first ten taps were discarded. For the Unpaced tapping task, the mean *tapping rate* (the mean inter-tap interval, ITI) and *motor variability* were calculated. Motor variability was the coefficient of variation of the ITI (CV of the ITI), namely the ratio of the *SD* of the ITIs over the mean ITI. For Paced tapping tasks, synchronization of the taps to the stimulus beat was calculated with circular statistics (11, 64, 65). Individual taps were expressed as angles on a polar scale from 0 to 360 deg., considering that the full circle corresponds to the inter-beat interval. Angles were treated as unit vectors and used to calculate the mean resultant vector *R* (64, 65, 66). The length of vector *R*, ranging from 0 to 1, indicates *synchronization consistency* (i.e., the reciprocal of variability) (e.g, 28, 60, 65, 66, 67). A value of 1 means that all the taps occured exactly at the same time interval before or after the pacing stimulus (maximum consistency); 0 means absence of synchronization (the taps are randomly distributed between the beats). For more details, see (11). Before statistical analyses, synchronization consistency was submitted to a logit transformation (11, 59).

Beat Tracking Index (BTI): this is a global measure of beat tracking skills computed by considering the performance of both the BAT and Paced tapping tasks from BAASTA. The source data to compute the BTI was the overall sensitivity index (*d'*) obtained from the BAT, and synchronization consistency in paced tapping averaged across stimuli (tones and music) and tempos. *Z*-scores for values of *d'* and synchronization consistency were independently calculated for children and adults [z-score = (value – $\text{Mean}_{\text{controls}}$) / SD_{controls}], while taking mean and *SD* of their respective control groups. The BTI was calculated by averaging the *z*-scores obtained for the BAT and paced tapping. Participants with BTI scores lower than -2 (i.e., with a performance lower than 2 *SD* relative to their matched control group) were treated as "poor beat trackers", while the others were considered as "good beat trackers".

Neuropsychological measures

Children and adults with ADHD were submitted to neuropsychological tests for assessing their cognitive functioning (general intelligence, memory, attention and executive functions). Different tasks were administered to children and adults. For comparison, raw scores obtained in tests of attentional and executive functions were converted into percentiles.

Children

The neuropsychological tests included measures from the WISC-IV intelligence scale, from which we took into consideration the composite total I.Q. score, and the score from the digit span task, as a measure of short-term memory (53, 54). In the latter task, children repeated numbers in the same order as presented aloud by the examiner. For backward digit span, the children repeated numbers in the reverse order of that presented by the examiner. I.Q. scores were converted into composite scores (Mean = 100, *SD* = 15). Moreover, the digit span score was converted into percentiles based on normative data.

Six attentional and executive functions were assessed with the Test of Everyday Attention for Children (68). They included selective visual attention, auditory attention, flexibility, divided attention, inhibition, and sustained attention. The tests of these functions were administered in the following order.

Selective visual attention : in this timed task, pairs of four different types of spaceship drawings were presented. Most pairs included two different spaceship drawings. Children had to find the pairs of identical spaceship drawings (target items) as quickly as possible. Twenty target items were distributed among 108 pairs with different drawings (i.e., distractors). The performance score takes into account the number of good pairs of drawings circled and the time spent to do it.

Auditory attention : children listened silently to 10 series of tones. Each series included between 5 and 16 tones. Children had to report how many sounds they heard at the end of each series. The score is the number of good responses.

Flexibility : in this attention visual-switching task presented in a booklet the participant had to count the number of "creatures" (i.e., green little monsters) visible all along their burrow. Arrows interspersed among the creatures pointed either upwards or downwards. The children were instructed to begin counting the creatures one by one and to change the direction of their counting when the sense of the next arrow was downwards, until the last creature was presented. The final score took into account the number of good responses and the time spent to complete the task.

Divided attention : children performed simultaneously two tasks, namely a visual-search task and an auditory counting task. The individual tasks are similar to the aforementioned auditory and visual selective attention tasks. The final score took into account the number of good responses both on the visual task and on the auditory task, and the total time spent to complete the test. The test took end when the children thought they found all visual stimuli they could.

Inhibition : in this Go/No go task, children pointed with a felt-tip pen to a series of squares drawn on a sheet as they heard short sequences of tones (from 4 to 16 tones). They were asked to stop pointing when a different timbre occurred. The rate of presentation of the tones increased progressively. The score is the number of good responses.

Sustained attention : this is a test of vigilance in the auditory modality. The children monitored a stream of digits presented at a rate of one/2 sec. They were instructed to detect a particular target sequence (two consecutive "5"), and to report the digit occurring immediately before the sequence. Forty targets were presented over 16 min. The score is the number of good responses.

Adults

Adults were administered the computerized Test of Attentional Performance (69), for the evaluation of three attentional and executive domains: inhibition, flexibility, and short-term memory.

The tests were administered in the following order.

Inhibition : in this Go/No go task, an up-right ("+") cross and a diagonal ("×") cross were presented in an alternating sequence on the screen. Participants were asked to press a button as quickly as possible only when the diagonal cross (i.e., the target) appeared. The score corresponds to the number of wrong responses (i.e., when a participant pressed the button when an up-right cross appeared on the screen).

Flexibility : in this set-shifting task, in each trial a letter and a digit were simultaneously presented on the right or left side of a computer screen. Participants were asked to press the left or right button on the keyboard as fast as possible depending on the side of appearance of the letter, then of the digit. The final score takes into account the number of good responses and the reaction time for each item.

Short-term memory : this task examines the control of information flow and the updating of information in short-term memory. A sequence of digits was presented to the participants on the computer screen. Participants pressed a button when the digit visible on the screen was the same as the penultimate one. The performance score is the number of omissions made by the participant.

Statistical analysis

Independent samples *t*-tests and mixed-design ANOVAs were used to compare ADHD participants (with and without DCD) and controls on BAASTA tests. In ANOVAs, stimulus was the within-subjects factor (tones vs. music) and group (ADHD vs. controls) the between-subjects factor. Further ANOVAs tested the differences between children and adults, by taking age (children vs. adults) as an additional between-subject factor. When differences between children with ADHD and ADHD-DCD did not reach significance, data were pooled. Post-hoc paired and independent samples *t*-tests with Bonferroni correction were performed to define observed effects. Pearson correlations also were performed between variables. Statistics were computed using R software (70).

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FP, SDB, VB, RL and DD contributed to the design of the experiment. FP and DD conducted the experiments. FP and SDB analyzed the results. All authors contributed to writing the manuscript.

COMPETING INTERESTS

The authors have no competing interests as defined by Nature Publishing Group, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Résumé

L'être humain est doté d'une grande capacité à traiter l'information temporelle, particulièrement visible dans notre tendance à bouger avec la pulsation de la musique. Cette pulsation est appelée *beat.* Les capacités rythmiques sont sous-tendues par un réseau neuronal complexe, incluant les régions auditives (cortex auditif, gyrus temporal supérieur), les régions motrices et pré-motrices (les ganglions de la base, les cortex moteur et pré-moteur) et les régions de coordination motrices (par ex., le cervelet). Lorsque ces régions sont affectées par des maladies neurologiques ou développementales, les capacités rythmiques peuvent être atteintes. C'est le cas dans la maladie de Parkinson ou la dyslexie par exemple. Les déficits de rythme sont associés à des déficits moteurs et cognitifs. Une autre forme de troubles du rythme est le cas des mauvais synchroniseurs (anglais « beat deaf »), des sujets sans troubles neurologiques qui ont des difficultés à se synchroniser et/ou à percevoir le rythme.

Dans cette dissertation, deux questions sont posées. Tout d'abord, est-il possible d'étendre nos connaissances des différences inter-individuelles dans les capacités de rythme avec un outil systématique, de manière à mieux comprendre les mécanismes sous-tendant le traitement du rythme ? Ensuite, les capacités de rythme peuvent-elles être entraînées, avec de potentielles applications dans l'entraînement des domaines cognitifs et moteurs associés chez les patients atteints de troubles rythmiques ?

Dans la première partie de la section expérimentale, j'ai utilisé la Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA) pour évaluer systématiquement et caractériser les capacités rythmiques perceptives et sensorimotrices des individus. Les résultats obtenus à certaines tâches corrèlent hautement avec d'autres, alors que certaines tâches sont totallement indépendantes les unes des autres. Cela révèle que la batterie peut distinguer les mécanismes en commun ou différents d'une tâche à l'autre. Dans une autre étude, 20 sujets sains adultes ont été soumis à la BAASTA à deux semaines d'intervalle. La performance dans la plupart des tâches reste stable en phase de re-test. Finalement, la BAASTA a été utilisée auprès de sujets *beat deaf*. J'ai montré que deux individus ont des difficultés dans la perception du rythme, par exemple dans une tâche consistant à estimer si un métronome est aligné au rythme de la musique (Beat Alignment Test, BAT) alors qu'ils peuvent se synchroniser avec les mêmes stimuli. Le fait que la synchronisation au beat puisse être fonctionnelle alors que la perception est déficitaire est reporté pour la première fois. De plus, les sujets beat deaf bénéficient comme les sujets contrôles de la régularité d'une séquence (timing implicite) dans une tâche dans laquelle le but est de répondre le plus rapidement possible à une cible après une séquence de sons standards.

Dans la deuxième partie de la section expérimentale, je présente un jeu sérieux pour l'entraînement des capacités de rythme (*Rhythm Workers*) conçu durant la thèse. J'ai développé un protocole d'entraînement des capacités de rythme progressive et conduit une étude pilote sur 20 sujets qui ont joué pendant deux semaines. Les participants ont montré une bonne adhésion au jeu et une bonne motivation à jouer. Des résultats encourageants sur l'évolution des capacités rythmiques, testés avec la version de la BAT issue de la BAASTA avant et après l'entraînement, sont présentés.

En résumé, dans cette dissertation, j'ai contribué au développement d'outils pour l'évaluation et l'entraînement des capacités de rythme. Cela a permis de conduire des études pour mieux comprendre les mécanismes de traitement du rythme et d'ouvrir la voie à l'utilisation de jeux de rythme dans la réhabilitation et la remédiation cognitive et motrice.

Mots clefs : rythme, jeu sérieux, mouvement, entraînement, musique

Summary

Humans are highly skilled in processing temporal information. This is particularly visible in our compelling sense of rhythm that manifests in our tendency to move to the beat of music. Deliberately or spontaneously, we have a tendency to clap our hands, tap our feet, or dance with music. These skills are sustained by a complex neuronal network involving auditory regions (auditory cortex, superior temporal gyrus), motor and pre-motor areas (basal ganglia, motor and pre-motor cortices), as well as motor coordination regions (e.g., the cerebellum). However, rhythm skills can be disrupted in neurological diseases like Parkinson's disease or in neuro-developmental diseases such as dyslexia. Rhythm deficits are associated with movement and cognitive disorders. Another form of rhythm disability is beat deafness, a specific condition in which healthy individuals encounter particular difficulties in synchronizing to the beat.

In this dissertation, I aim at addressing two questions. First, is it possible to extend our knowledge of inter-individual differences to rhythm skills in order to better understand mechanisms underlying rhythmic processing with a systematic tool? Second, can rhythm skills be trained in order to improve the associated motor and cognitive domains in patient populations revealing rhythm disorders?

In the first part of the experimental section, I used the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA) to systematically test and characterize subjects' perceptual and sensorimotor timing skills. I found that the results of some tasks were highly correlated with the ones of other tasks and that, on the contrary, some tasks were totally independent from each other. This reveals that the battery can discriminate between tasks involving different and common mechanisms. In a further study, 20 healthy adults were submitted twice to BAASTA at a two-week interval. The performance in most of the tasks remained stable at retest. Finally, BAASTA was used in beat-deaf individuals. I showed that two individuals performed poorly on rhythm perception tasks, such as detecting or estimating whether a metronome is aligned to the beat of the music or not (Beat Alignment Test [BAT]). Yet, they could tap to the beat of the same stimuli. The fact that synchronization to a beat can occur in the presence of poor perception is reported for the first time in this study. On top of that, beat-deaf participants benefited similarly to controls from a regular temporal pattern (implicit timing) in a task in which they had to respond as fast as possible to a different target pitch after a sequence of standard tones.

In the second part of the experimental section, I present a serious game for training rhythmic skills (*Rhythm Workers*) designed during the doctorate. I developed a progressive rhythm training protocol with stimuli varying in rhythmic difficulty. I conducted a proof-of-concept pilot study on 20 individuals who played the game for 15 days. Participants in the experimental groups showed high compliance and motivation in playing the game. Encouraging results were found on the evolution of their rhythmic skills, as tested with the BAT taken from BAASTA that was submitted to the participants before and after the training.

In sum, in this dissertation contributed to the development of tools for the assessment and training of rhythmic skills. This enabled us to design studies to better understand rhythm processing mechanisms and to pave the way for the use of rhythm games in cognitive and motor remediation and rehabilitation.

Keywords: rhythm, serious game, movement, training, music