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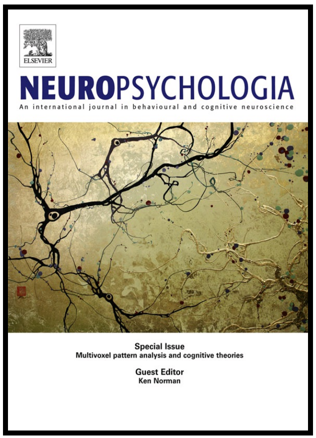

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Rhythmic entrainment as a musical affect induction mechanism

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Abstract

One especially important feature of metrical music is that it contains periodicities that listeners' bodily rhythms can adapt to. Recent psychological frameworks have introduced the notion of rhythmic entrainment, among other mechanisms, as an emotion induction principle. In this review paper, we discuss rhythmic entrainment as an affect induction mechanism by differentiating four levels of entrainment in humans—perceptual, autonomic physiological, motor, and social—all of which could contribute to a subjective feeling component. We review

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[1] Both authors have contributed equally to this article

the theoretical and empirical literature on rhythmic entrainment to music that supports the existence of these different levels of entrainment by describing the phenomena and characterizing the associated underlying brain processes. The goal of this review is to present the theoretical implications and empirical findings about rhythmic entrainment as an important principle at the basis of affect induction via music, since it rests upon the temporal dimension of music, which is a specificity of music as an affective stimulus.

Keywords: entrainment; rhythm; music; affect; psychophysiology; feeling

1. Introduction

Music is a powerful form of art, because it is able to elicit strong affective experiences, which may not only result in a brief emotional episode or change of mood in the listener, but may also induce motoric behavioral changes in the form of rhythmic motion or even rhythmic dance movements in a social context. Because of these phenomena, music may even manifest in long-term therapeutic effects (de Dreu, van der Wilk, Poppe, Kwakkel, & van Wegen, 2012; Loewy, Stewart, Dassler, Telsey, & Homel, 2013; Thaut, McIntosh, & Hoemberg, 2015). In fact, this social aspect is believed to play a major role in music, by bringing people together to enjoy or celebrate important events in the community for example. In this sense, music as a social activity promotes common actions between individuals and helps to communicate and even to synchronize actions in a group. Common phenomena include spontaneous synchronization of hand clapping or dancing with the rhythm of the music. Who has not experienced this urge to move with the music when their favorite song comes up? Dance, which is often based on a rhythmic activity in synchronization to the music, has a long tradition in many cultures and across the evolution of mankind (Clayton, Will & Sager, 2005). Moving to music in dance and music listening are thus popular behaviors that seem to be an integral part of our culture. One potential explanation for why such activities are so popular might be that music induces a pleasant state and helps to regulate moods and emotions. Indeed, according to Todd and Lee (2015), these behaviors are intrinsically rewarding and self-reinforcing partly thanks to their stimulation of the vestibular system and its connections with the limbic system. Taking these roles of music together, music can be understood as a social activity that fosters synchronized behavior and stimulates our reward system. This dual role of music raises the question of whether there is a close link between synchronization processes and the affective experiences that music induces. In this review, we suggest that such entrainment processes play an important role in music performance, as well as in music perception, and that these processes might contribute to the emotional power of music. Specifically, we present four different levels in the music listening context in which such entrainment processes can take place. We describe the subjacent brain mechanisms and discuss the links of these processes to the induction of affective experiences in musical contexts.

1.1. Defining entrainment

Entrainment is the process through which two physical or biological systems become synchronized by virtue of interacting with each other. However, the term entrainment describes not only the case of perfect period and phase synchronization between two oscillators, but also the tendency toward that state that can be observed between two or more systems capable of emitting periodic outputs. Therefore, perfect synchronization is just one specific case of entrainment.

The history of the theory of entrainment can be traced to classical mechanics when Christiaan Huygens first noticed in 1666 that two pendulum clocks set on the same flexible surface would eventually become synchronized (Rosenblum & Pikovsky, 2003). This phenomenon has since been observed between all kinds of devices and organisms exhibiting rhythmic behavior as periodic oscillation. According to Clayton, Sager, and Will (2005), at least two autonomous oscillating systems must be present in order to distinguish entrainment from other concepts. Autonomy means that the oscillators should be able to oscillate, that is, move about an equilibrium position, on their own even when not interacting. In the human body, many physiological processes can be conceptualized as oscillating systems, including cardiac activity, respiration, locomotion, female menstrual cycles, and the periodic firing of neurons. The condition of autonomy is important to differentiate entrainment from resonance, the latter of which is differentiated from the former by its effects being confined to an increase in an object's natural frequency amplitude following exposure to another object with an similar frequency. Moreover, the oscillations of a resonating system cease when the active influence of the original impulse emitting system is removed. However, not all interacting oscillators will entrain, because they need to be relatively close in terms of periodicity for the phenomenon to occur and even then, strict phase and frequency synchronization is not necessarily observed. Entrainment can also occur only at the phase level, that is, phase entrainment or phase-locking; although the frequency may not be modified, we can still talk about frequency coupling or cross-frequency coupling. In cross-frequency coupling, the amplitude of a given frequency (e.g. gamma energy at the cortical level) is coupled to the phase of a lower frequency (e.g. alpha or theta; Canolty & Knight, 2010; Fries, 2005).

1.2. Entrainment with music

Music is a form of art that develops in time. This development is organized into several periodicities for most musical styles. Thus, music constitutes an acoustic signal that often contains different periodicities and therefore can have the properties of an oscillating system at several frequencies. The idea that music can be regarded as an entraining oscillator comes from ethnomusicology, where the effect of especially repetitive music on ritual dancing, including the synchronization of movements and communication between members of a group, has often been studied (Merker, Madison, & Eckerdal, 2009). The most obvious situation of entrainment with music is therefore the adaptation of movements and the production of musical rhythm with the body, such as hand clapping or swaying. If a musician is playing and producing rhythmical sequences, the musician can both adapt the music to his or her bodily rhythms, for example, to breathing cycles, and, in turn, his or her bodily rhythms can adapt to a chosen musical rhythm, for example, by accelerating breathing. In this case, proper entrainment can take place, since the interaction can work mutually between the musician's body and the music. In the case of music listening, the bodily rhythms of the listener can entrain to the music, but the rhythms of the music are not necessarily influenced. Regarding the definition of entrainment, in this condition, the two oscillators interact only in one direction, that is, asymmetrically. However, this phenomenon is still considered a form of entrainment and is described as such in the literature (Large, 2008), since the rhythms of the body of the listener can adapt their phase and/or periodicities to those of the musical rhythms.

1.3. Investigating rhythmic entrainment as an affect induction mechanism

Rhythmic entrainment has only recently been recognized to play a potential role in affect induction in music listening (Juslin, 2013; Juslin, Liljeström, Västfjäll, & Lundqvist, 2010; Scherer & Coutinho, 2013; Scherer & Zentner, 2001; Trost & Vuilleumier, 2013). The BRECVEMA (brain stem reflexes, rhythmic entrainment, evaluative conditioning, emotional contagion, visual imagery, episodic memory, musical expectancy, aesthetic judgment) framework consists of eight psychological mechanisms that explain how music induces emotions in listeners, citing rhythmic entrainment as one of these mechanisms (Juslin, 2013; Juslin et al., 2010). In this context, the authors claim that “the powerful, external rhythm of the music interacts with an internal body rhythm of the listener such as heart rate, such that the latter rhythm adjusts towards and eventually ‘locks in’ to a common periodicity” (Juslin et al., 2010, p. 621). This adjusted rhythm is then proposed to trigger an emotional response much in the same way that smiling could trigger amusement via proprioceptive feedback mechanisms (Strack, Martin, & Stepper, 1988). However, this definition does not clearly state which kind of entrainment the authors are referring to. Their main focus seems to be on entrainment of physiological processes, but they also appear to suggest a mixed concept in which processes of entrainment at the motor and the social levels are elicited via physiological entrainment. A similar process was also proposed by Scherer and colleagues (Scherer & Coutinho, 2013; Scherer & Zentner, 2001) through their peripheral “proprioceptive feedback” route of emotion production (Scherer & Zentner, 2001), later renamed “entrainment and proprioceptive feedback” route in a revised version of the framework (Scherer & Coutinho, 2013).

The close link between rhythm and emotions is also illustrated by the central role of prediction and anticipation. By its very nature, rhythmic entrainment generates expectations, explicitly or implicitly, and it is known that dopamine release is indeed related to musical expectations (Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011). It could be proposed, then, that entrainment is experienced as a desirable and pleasant state, which would explain our attraction toward activities that require entrainment or why we choose to organize some everyday activities and behavior in a rhythmical way. Musical expectancies are punctual anticipations of musical events to take place. It has been suggested that the confirmation or the disappointment of these anticipated musical events produces an emotion (Meyer, 1956). Rhythmic entrainment is also based on temporal expectancies in time and is therefore a specific kind of musical expectancy. These expectancies can appear in different musical contexts, from the listener's anticipation of the next drumbeat, to the first violinist's expectation of the director's subtle hand signal.

When considering the potential links between rhythmical entrainment and affect, a crucial question is, what kinds of affect rhythmic entrainment could induce. Indeed, affect can be understood as an overarching term that encompasses experiences such as preferences, attitudes, affective dispositions, interpersonal stances, moods, and emotions (Scherer, 2005). According to authors like Russell (Russell, 1980, 2003), all affective experiences may be described in terms of two basic dimensions: "valence" (or "pleasure"), ranging from negative to positive (or unpleasant to pleasant), and "arousal" (or "activation"), ranging from calm to excited (or deactivated to activated). In the context of their framework, Juslin and colleagues (2010) do not specify other affects beyond "general arousal" or "pleasant feelings of communion." However, given the evolutionary origins of synchronous activities (Merker et al., 2009) and their suggested function for the community, it seems reasonable to limit the affective experiences induced by rhythmic entrainment to those that have positive valence, strengthen the feeling of unity with others and promote prosocial behaviors within a group, such as communication, cooperation and coordination (Koelsch, 2010). More specifically, using the emotional dimensions of the Geneva Emotional Music Scale (Zentner, Grandjean, & Scherer, 2008), which was specifically developed to measure emotions induced by music, this could include experiences of wonder, transcendence, tenderness, or joyful activation.

In the following section, we will examine the different ways in which entrainment may induce emotions in listeners by expanding upon a framework developed by Trost and Vuilleumier (2013) where entrainment is proposed to occur at four different levels, even simultaneously.

2. Levels of entrainment and their role in affect induction

Trost and Vuilleumier (2013) have pointed out that in humans, entrainment behavior can be observed and distinguished on four levels: perceptual, autonomic physiological, motor, and social (see Figure 1). These levels may in fact become integrated and contribute to the emergence of a subjective feeling of entrainment (Labbé & Grandjean, 2014). Although rhythmic entrainment phenomena can be seen as a hierarchical process, the exact form in which these different levels coexist or interact is still being researched. Furthermore, there are many aspects of the link between rhythmic entrainment and affect induction that remain unclear. Using the framework presented by Trost and Vuilleumier (2013) as our basis, we will review the different levels, provide empirical evidence for them from the literature in music psychology and auditory neuroscience, discuss the underlying brain mechanisms involved, and the link with affective experiences. The present review thus aims to describe the different levels in more detail and to present rhythmic entrainment in a more comprehensive manner. First, however, we will discuss the principle of neural entrainment and distinguish it from the other four levels. We make this distinction because neural entrainment is proposed as a general principle of neural communication (Fries, 2005) that is unspecific to music or affect (see Figure 1). Because the main focus of this review is the link between entrainment processes and affect, however, we will mention neural entrainment only briefly. For more information concerning the specific field of neural entrainment and synchronization, we refer the reader to Buzsáki (2006).

2.1. Neural entrainment

Entrainment is a major principle in neurophysiology as a form of communication between organized and connected neurons (Womelsdorf & Fries, 2007). Indeed, cells can communicate not only through the firing of neurons, but also through “communication-through-coherence” (Fries, 2005). The idea is that it is only when neuronal populations are synchronously firing at the same rate and with the same *phase*, (in-phase synchronization), that communication can take place because of the systematic variation of neuronal excitability within a cycle. This is achieved through coupling, which “allows one oscillator to perturb another by altering its phase, its intrinsic period, or both” (Large & Kolen, 1994, p. 10). However, apart from the role of entrainment in neural communication, entrainment is also a mechanism involved in perception , which can take place at a relatively low level of processing. It is known from single cell recordings in animal studies that neurons can pick up the periodicities of perceived oscillations in a stimulating signal. For example, it has been shown in the tectum of zebrafish larva that neural ensembles can entrain their rhythmic activity to the periodicity of a repetitive sensory stimulation (Sumbre, Muto, Baier, & Poo, 2008). In the auditory domain, studies using LFPs from the primary auditory cortex of primates have provided evidence that neurons can entrain their activities to the periodicity of an auditory stimulation, for example, in the form of clicks presented in the gamma-band range, i.e. 30 Hz and above (Brosch, Budinger, & Scheich, 2002).

For humans, one of the most basic levels at which acoustical stimulations can be observed is at the level of the brain stem. Auditory brain stem responses are neural responses that occur within the first 10 milliseconds following the onset of an auditory stimulus. These responses can be measured by using surface electrodes and have been used, among other things, in audiology to detect hearing thresholds since the intensity of simple sounds can be tracked (Mason, Mccormick, & Wood, 1988). Evidence that is consistent with neural entrainment has also been found at higher levels of auditory processing in the form of the auditory steady-state response. This describes the phenomenon whereby an increase in the power amplitude of neural responses of neural ensembles is observed at the frequency of the auditory stimulation. Using intracranial electroencephalography (iEEG) recordings, researchers have shown that auditory steady-state responses can be found at different frequencies (4-16 Hz) in different areas of the primary auditory cortex (Liégeois-Chauvel, Lorenzi, Trébuchon, Régis, & Chauvel, 2004). Similar findings were also reported by using surface electroencephalography (EEG), for example, in a study with children listening to vocal syllables presented at 2 Hz (Power, Mead, Barnes, & Goswami, 2012). Moreover, a study by Will and Berg (2007) on neural synchronization demonstrated how entrainment to regular auditory stimuli could be reflected in the electroencephalogram within the range of human behavior and incidentally, the preferred tempo range in music (60-480 beats per minute; bpm). Intertrial coherence measures showed phase coherence to increase in all frequency bands under periodic stimulation and an entrainment response to occur in repetition rates between 60 and 300 bpm in the corresponding EEG frequency bands (i.e. 1 and 5 Hz). Furthermore, neural entrainment processes can also take place at multiple timescales. For example, when people listen to speech, which is also a rhythmic sequence (in the theta band range, 5 to 7 Hz), theta-modulated gamma oscillations can be observed (Giraud & Poeppel, 2012), indicating so-called cross-frequency coupling.

Neural oscillations and thus also neural entrainment processes have been proposed to be at the basis of all brain activity, including behavior, cognition, and emotional processing (Fries, 2005; Melloni et al., 2007). For instance, concerning emotional processing, Grandjean, Sander, and Scherer (2008) have suggested that it is the neural synchronization between populations of neurons that code for the states of different emotion components that actually results in the emergence of emotional feelings. Elsewhere, evidence suggests that entrainment of the spike timing of neural populations in the basolateral amygdala, a crucial structure in emotion processing (Murray, Brosch, & Sander, 2014), to hippocampal theta rhythms might mediate emotional memory formation (Bienvenu, Busti, Magill, Ferraguti, & Capogna, 2012). However, defining the exact relation between the lowest level of neural entraining activity and affective experiences is a challenge and is still an issue for research.

2.2. Perceptual entrainment

Perceptual entrainment is defined as the process whereby auditory signals are integrated into a percept of the periodicities in an auditory input. Perceptual entrainment can be regarded as the process that is necessary to perceive periodic information, such as the musical *beat*. Being entrained on the perceptual level creates a conscious or unconscious representation of a periodic rhythmical pattern, which should be distinguished from neural entrainment with regard to the level of processing, even if perceptual representations are rooted in neuronal entrainment. Perceptual entrainment requires an integration of sensory information and top-down influences (e.g. expectations) to form a cognitive representation of the auditory signal, which can be either accessible or inaccessible to consciousness. For perceptual entrainment, a kind of temporal pattern recognition has to take place in order to extract the periodic information contained in the auditory signal, which can happen very fast, as soon as the first couple of beats of the music are heard (Krumhansl, 2000). It is a general principle that when events happen in time with certain periodicities, temporal expectancies are engendered about when the next events are going to happen (for a review see Nobre & Rohenkohl, 2014). The same mechanism is at work in musical rhythms, and thus temporal expectancies are also at the basis of perceptual entrainment. In perceptual entrainment temporal expectancies play an important role as attention is permanently oriented and reoriented in time along the rhythmical structure and in particular along the musical beat.

The *beat* in music, which is sometimes also called the *pulse*, is a psychological construct that is perceived because of repeatedly recurring musical events in a specific time interval. The beat can be understood as the basic unit of measurement of evenly spaced events, while the meter "involves our initial perception as well as subsequent anticipation of a series of beats that we abstract from the rhythmic surface of the music as it unfolds in time" (London, 2004, p. 4). The meter in music refers to the temporal organization of beats; it assigns a hierarchy between the beats belonging to one metrical unit by defining a metric for these beats (Lerdahl & Jackendoff, 1983). This defined metrical hierarchy allows the distinction between beats that occupy different levels in the hierarchy, which are perceived as being more or less salient. More salient beats are higher in the hierarchy and are often called "strong beats" (i.e. the first beat of a 4/4 time signature), and less salient beats, at lower levels of the hierarchy are called "weak beats" (i.e. off-beat positions, like the second and fourth beat of a 4/4 time signature). A psychological theory that tries to explain the perception of the musical meter in terms of entrainment processes is the Theory of Dynamic Attending (Jones & Boltz, 1989). This theory suggests that the periodicities in a musical rhythm can only be perceived because of entrainment of attentional processes to the different periodicities of the musical meter (Jones & Boltz, 1989). Therefore, the recognition of a periodic pattern and even a metrical hierarchy between the beats presented in metrical music requires cognitive processing and thus constitutes a form of perceptual entrainment, even when it is implicit (Bolger, Trost, & Schön, 2013; Grube & Griffiths, 2009). This implicit perceptual entrainment of attentional processes can be tested in reaction time paradigms. In keeping with the theory of dynamic attending, selective attention is increased in moments of the musical beat, and even more during metrically salient beats, which can lead to increased accuracy and faster processing during these moments. Accordingly, it has been shown that reaction times to visual and auditory targets are significantly reduced when these targets are presented during metrically strong positions with both simple metrical sequences and classical music excerpts (Bolger, Coull, & Schön, 2014; Bolger et al., 2013; Trost et al., 2014).

Perceptual entrainment effects can also be explained by predictive coding and predictive timing theories of perception that suggest that our predictions *are* the internal representation of the stimulus (Arnal & Giraud, 2012; Friston, 2005; Giraud & Poeppel, 2012), which is consistent with models of meter perception and particularly with the Theory of Dynamic Attending. These theories suggest that, when a pattern of beats is heard one forms a metrical representation of the rhythm allowing one to anticipate future beats. This representation is then constantly updated as the physical input (rhythm) is compared with the internal prediction (meter), which is corrected as needed, the difference between the two (the “prediction error”) being the only thing that is actually processed by the brain for maximum efficiency (Vuust & Witek, 2014).

One example of perceptual entrainment is the phenomenon of *subjective accenting*. Subjective accenting demonstrates that the perception of rhythm is, to some extent, subjectively driven (Bolton, 1894). This phenomenon can be observed when a person is listening to identical isochronous clicks, but perceives a rhythmical pattern or grouping of these clicks instead of identical events, as in the tick tock of a clock, for example. This can even be reflected in greater amplitudes of event related potentials to subjectively “strong” beats in a series of equally spaced and equally loud tones (Brochard, Abecasis, Potter, Ragot, & Drake, 2003; Potter, Fenwick, Abecasis, & Brochard, 2009). Subjective accenting could be explained by resonance theories of rhythm perception (Large, 2008; Large & Jones, 1999; Large & Kolen, 1994), which propose that both the beat and the metrical structure of a piece of music (or any auditory stimulus) emerge in the mind of listeners as internal oscillators with a similar frequency resonate and entrain to the frequencies in the auditory signal. As these oscillators resonate, their amplitudes increase and it is the sum of these amplitudes that then gives rise to an impression of a hierarchical structure. When the auditory stream is an isochronous sequence, it has been proposed that internal oscillators at frequencies close to that of the isochronous sequence but also close to subharmonics of this frequency resonate and entrain, causing a hierarchical structure to be perceived (Bååth, 2015). We also know that a strong sense of both the beat and the meter can be induced through temporal accenting, that is, not necessarily by playing a note louder or softer or even changing its pitch, but simply by manipulating the length of the silences preceding and following a note (London, 2004). In one study, Grube and Griffiths (2009) manipulated both the strength of metrical sequences and the clarity of their endings. Participants reported feeling the pulse most strongly on sequences with more notes during the downbeat (strong sequences), and they accented the last downbeat of a sequence (compact ending) as though it were still playing during the rests until the end.

Perceptual entrainment could also be regarded as the underlying mechanism of altered states of consciousness like trance that is induced via listening to repetitive sounds. These trance states can be compared to the experience of flow and are usually evoked to gain insight and are therefore states of high concentration (Hove et al., 2016).

A number of studies, using a range of techniques from intracranial and cortical EEG to MEG, have shown evidence for perceptual entrainment and demonstrated how neuronal activity can become entrained to cognitively perceived periodicities in simple rhythms (Fujioka, Fidali, & Ross, 2014; Fujioka, Trainor, Large, & Ross, 2009, 2012; Fujioka, Trainor, & Ross, 2013; Fujioka, Zendel, & Ross, 2010; Nozaradan, Peretz, Missal, & Mouraux, 2011; Nozaradan, Peretz, & Mouraux, 2012; Nozaradan, Zerouali, Peretz, & Mouraux, 2015; Snyder & Large, 2005; Will & Berg, 2007). Empirical research in newborn babies in which the researchers used EEG suggests that detecting regularities in auditory rhythmic sequences seems to be innate or learned during the pregnancy (Winkler, Haden, Ladinig, Sziller, & Honing, 2009). This may indeed be the case since the fetus is already exposed to rhythmic auditory stimulations in the womb primarily in the form of the mother’s heartbeat. Perceptual rhythmic entrainment is therefore already trained at this early developmental stage, for example, in the context of rhythmic motor actions produced by the mother.

2.2.1. Brain regions involved in perceptual entrainment

Perceiving a rhythm requires aspects of time processing and temporal grouping and it is therefore obvious that brain networks involved in time perception are also solicited in rhythm perception (Geiser, Walker, & Bendor, 2014). These networks have been suggested to include the cerebellum, the parietal and sensorimotor regions (supplementary motor area [SMA], premotor cortex [PMC], and motor cortex), and the basal ganglia (BG; (Grahn & Rowe, 2012; Grondin, 2010). Furthermore, it seems likely that the brain processes for perceiving a rhythm without producing any movements would involve brain structures similar to those involved in motor synchronization to music, since the production of a rhythmic movement in synchrony to an external rhythm is supposedly preceded by an internal perceptual analysis. These kinds of tasks refer to the perceptual entrainment level. For example, in a study by Grahn and Brett (2007), the authors found that when participants listened to rhythms without tapping, compared with a rest condition, activations in the SMA, PMC, BG, and cerebellum could be observed. Similarly, Bengtsson and colleagues (2009) demonstrated that passive listening to metrical rhythms, in comparison to random sequences, activated more dorsal PMC, SMA, and pre-SMA, as well as the lateral cerebellum. Furthermore, when considering whether the focus is on rhythm perception independent of the influence of any motor preparation process, one has to distinguish the studies that include a motor task in any form from those that do not. In a study by Chen and colleagues

(2008a), this question was addressed. These authors suggested a distinction in the PMC: the ventral part is involved only in the perceptual task when a subsequent motor response is required. However, a later study reported ventral premotor activations when no tapping was required; in this case, premotor activity increased during the preferred tempo (Kornysheva, von Cramon, Jacobsen, & Schubotz, 2010). In a MEG study on rhythm perception where no motor task was involved, spatial-filtering source analysis also found modulations in the hippocampus, the BG, the PMC, the auditory cortex, the association cortex, and the insula (Fujioka et al., 2010).

2.2.2. Links between perceptual entrainment and affect

A link between perceptual entrainment and affective experiences could imply that sensitivity to the metrical structure increases when an individual listens to music that induces a certain level of arousal or pleasantness. However, thus far, the literature on this relation is limited. One study suggested that consonant music that has been evaluated as pleasant and arousing increased the sensitivity to the metrical structure to a finer-grained level than did dissonant music, which was evaluated as less pleasant and less arousing (Trost et al., 2014).

Furthermore, apart from this first evidence of the link between perceptual entrainment and emotions, a body of work links tempo and pulse clarity with the strength of either perceived or felt emotions and mood in music listening. Tempo and pulse clarity can be regarded as indices of perceptual entrainment: temporal processing is required for both musical features, since it engenders mental representations of the auditory presentation. It seems an accepted fact that music with a higher tempo induces higher arousal in the listener (Husain, Thompson, & Schellenberg, 2002; McConnell & Shore, 2011). Gabrielson (2009) notes that in emotion recognition studies, fast tempo has also been associated with mostly positive and arousing emotions, such as perceived “activity/excitement, happiness/joy/pleasantness, potency, surprise, flippancy/whimsicality, anger, uneasiness and fear," whereas slow tempo has been associated with low arousal or even negative emotions such as "calmness/serenity, peace, sadness, dignity/solemnity, tenderness, longing, boredom, and disgust." However, tempo is determined not just by the speed at which a piece or song is played, but rather by the perceived rate, which is based on the implied pulse, another subjective or at least implied feature. Furthermore, the association of a specific musical tempo with arousal does not imply an association between the strength of perceptual entrainment and the induced affect. Thus, another feature to take into account when considering perceptual entrainment is *pulse clarity* (Lartillot, Eerola, Toiviainen, & Fornari, 2008), which is related to the ease with which listeners can pick up an underlying pulse and thus implies the matching of an internal temporal percept with an external rhythm. Indeed, greater pulse clarity has been shown to be associated with increased "activity" (Luck et al., 2008), that is, arousal, and decreased experienced anger (Eerola, Lartillot, & Toiviainen, 2009). Moreover, a study using continuous emotion evaluations has shown that pulse clarity can also contribute to the prediction of the affective experiences on the arousal but also the valence, i.e. the pleasantness dimension (Trost, Fruhholz, Cochrane, Cojan, & Vuilleumier, 2015). The early sound environment of the womb might be one of the reasons that clear and stable beats are experienced as pleasant. Salk (1962) has suggested that the individual frequency of the mother's heartbeat would act as a calming influence on the baby. He suggested that the individual heart rate of the mother at rest would lead to an adaptation of the baby's heart beats and that this effect would consequently calm the baby. However, Smith and Steinschneider (1975) demonstrated that generally, only a stable rhythmic acoustic stimulation had a soothing effect on babies. One could argue that this is because rhythmic patterns are more predictable and therefore more easily processed by our central nervous system than arrhythmic patterns, inducing, comparatively, more pleasant states (Winkielman & Berridge, 2003).

2.3. Autonomic physiological entrainment

Autonomic physiological entrainment is the tendencies for biological rhythms, which are under the control of the sympathetic and parasympathetic branches of the autonomic nervous system, to entrain to externally perceived rhythms. This form of entrainment includes mainly respiratory and cardiac activity, which are often correlated with each other, but this specification might be due to the difficulty in measuring other visceral activities (e.g. gastric activity). It is obvious that in the case of autonomic entrainment processes, the frequency of autonomic oscillations will not be synchronized to the external rhythm at high frequencies, but that only an approximation can take place, for example, adapting the frequency toward the target tempo or potentially resetting the phase of the autonomic system. Physiological adaptation of respiration and heart rate toward the tempo of the music has often been described in the literature (Etzel, Johnsen, Dickerson, Tranel, & Adolphs, 2006; Khalfa, Roy, Rainville, Dalla Bella, & Peretz, 2008; Nyklicek, Thayer, & van Doornen, 1997). Experiments with a simple rhythmical pattern have shown that respiration frequency is adapted in an unconscious manner toward the tempo of the metronome (Haas, Distenfeld, & Axen, 1986). A review by Ellis and Thayer (2010) showed the effective role of slow tempo, especially in dynamically flat and legato music, on reducing the heart rate, respiration rate, and blood pressure. Moreover, several authors have recently suggested that the tempo of the music can have an important impact and that it is even able to predict most physiological reactions in the listener (Etzel et al., 2006; Gomez & Danuser, 2007). Entrainment processes at this level are likely to be relatively slow compared with other levels of entrainment, due to the natural constraints of the cardiovascular system. An example of this can be seen in Bernardi et al.'s (2009) study in which slow endogenous circadian rhythms of about 6 cycles per minute were entrained to phrases of similar length in pieces ranging between 2.5 and 5 minutes, which induced calmness. Because the average respiration rate to pulse rate is 1:4, with the normal respiration rate varying between 12 and 20 respirations per minute and the normal pulse rate varying between 60 and 80 bpm (Lindh, Pooler, & Tampa, 2006), it would take several seconds for entrainment to occur at this level.

A potential explanation for autonomic physiological entrainment to the tempo of the music (period entrainment) comes from sports sciences and performing musician studies. Here it has been shown that common and coordinated movements can have a similar entraining effect on physiological rhythms. For example, in choral singing, researchers have shown that cardiac and respiratory efforts become synchronized between the members of the choir and the choir director (Müller & Lindenberger, 2011; Vickhoff et al., 2013). In addition, when individuals do physical exercises, their breathing frequency adapts and thus entrains naturally to the rhythm of the exercise (Bechbache & Duffin, 1977; Paterson, Wood, Morton, & Henstridge, 1986). Moreover, increased locomotion-respiration coupling has also been reported to decrease oxygen consumption, showing that adapting the respiration to movements is a more efficient way to perform (Bardy, Hoffmann, Moens, Leman, & Dalla Bella, 2015). Autonomic physiological entrainment does not necessarily involve the synchronization of movements, but may affect music listeners who sit perfectly still. The non-overt adaptation of the bodily rhythms to the tempo of the music might stem from processes of empathy that make the listener sympathize with the performer of the music and thus synchronize to the imagined or actual movements of the musicians, although these movements might not even be visible (Scherer & Coutinho, 2013). Effects like this are known from studies on sports or rituals (Konvalinka et al., 2011; Paccalin & Jeannerod, 2000).

Nonetheless, the power of the musical tempo to have an impact on autonomic physiological processes has been questioned by others. Regarding heart rate, some studies did not find evidence for an adaptation of the heart beat toward the tempo of the music (Dousty, Daneshvar, & Haghjoo, 2011; Koelsch & Jäncke, 2015; Krabs, Enk, Teich, & Koelsch, 2015). However, in these studies, the stimuli included relatively limited tempo variation, tempo range and stimulus duration, which may have biased the results. More research that controls for these issues is needed.

2.3.1. Brain regions involved in autonomic physiological entrainment

Concerning the integration and regulation of autonomic physiological changes in the body, several authors have reported the role of a network of regions, including the insula, cingulate cortex, amygdala, hypothalamus, prefrontal and orbitofrontal cortices, and reticular formation (Benarroch, 1997; Craig, 2009; Karageorghis & Jones, 2013; Thayer & Lane, 2000). Thayer and Lane (2000) have proposed a "central autonomic network," whose primary output indirectly innervates the heart and the seat of which is the anterior cingulate cortex for the integration of visceral, attentional, and affective information because it receives feedback from peripheral end organs. Moreover, the insula, anterior cingulate cortex, and orbitofrontal cortex are all involved in processes of interoception (Critchley, 2004); thus, they are also involved in the representation and interpretation of the bodily states and the attribution of an emotional reaction (Critchley, 2005). The insula, anterior cingulate cortex, and orbitofrontal cortex are also known to be involved in the processing of musical emotions (Blood & Zatorre, 2001; Brattico et al., 2016; Koelsch, 2014; Salimpoor et al., 2013; Trost, Ethofer, Zentner, & Vuilleumier, 2012). This double involvement of these regions in the regulation of physiological processes and of emotion processing corroborates the close connection of these processes. It also suggests that these brain regions play a role in autonomic physiological entrainment, which indicates its connections to emotional reactions.

2.3.2. Links between autonomic physiological entrainment and affect

The possible link between autonomic physiological entrainment and affect may stem from the fact that changes in autonomic physiology already form an integral part of the emotion response, and entrainment of autonomic physiological rhythms to the music could therefore trigger an affective response via proprioceptive feedback processes (Scherer & Coutinho, 2013; Scherer & Zentner, 2001). Indeed, researchers have proposed that bodily feelings are essential in emotional feelings (Berntson, Sarter, & Cacioppo, 2003; Damasio, 1996; Friedman, 2010; Grandjean et al., 2008). Feelings are phenomena characterized by the integration of different kinds of representations (appraisals, autonomic reactions, motivations, and motor expression; Scherer, 2005). While the rhythm of the music induces changes in respiration and cardiac activity, these changes might subsequently be interpreted consciously or unconsciously as a felt affective reaction or as being part of the induced feeling (Fancourt, Ockelford, & Belai, 2014). In fact, the notion of rhythmic entrainment as an emotion induction mechanism, as suggested by Juslin and colleagues (2010), probably stems from this possible link between physiological arousal and emotion, which suggests that there might be a causal relation. On the one hand, one might interpret this as indicating that a slower tempo induces slower respiration or heart rate and that this in turn would induce low arousing emotions, whereas a fast tempo would in the same way induce high arousal emotions. On the other hand, it is known from the literature on chill experiences, which are moments of high musically induced pleasantness (Panksepp, 1995), that physiological reactions are rising in general during the experience of chills, independently of the musical tempo (Salimpoor, Benovoy, Longo, Cooperstock, & Zatorre, 2009). This result seems to contradict the notion of autonomic entrainment as an induction mechanism in the sense that stronger entrainment would be associated with stronger affective experiences. However, this seeming contradiction can be put into perspective if it is assumed that these are two independent processes. It might well be that the chill reaction is a specific kind of affective reaction with no return beyond a certain point, whereas affect induction via rhythmic autonomic entrainment might set in before or after the chill, or might simply be masked by the chill response. Moreover, it has been shown that chill responses to music occur most frequently to familiar and preferred music, and expectations are probably essential in the genesis of such phenomena (Grewe, Nagel, Kopiez, & Altenmüller, 2007; Guhn, Hamm, & Zentner, 2007). Autonomic entrainment has also been shown to be influenced by the level of musical expertise (Bernardi et al., 2009). Autonomic entrainment, in this case, might therefore be associated with a more analytical style of listening, which might be used in the case of listening to rather new and unfamiliar music, which is also less likely to induce chills. Furthermore, autonomic entrainment might serve as an affect induction mechanism such that it adapts the peripheral physiological processes of the listener to the tempo presented in the music and helps to put the listener into the arousal state expressed by the music. In this way, autonomic entrainment influences the peripheral physiological component of the affective response and might therefore be called an induction mechanism.

2.4. Motor entrainment

The phenomenon of motor entrainment to music is the most commonly mentioned example of musical entrainment, for example, in dancing or bouncing, where the musical rhythm is used to synchronize movements. In an evolutionary context, music has been closely linked with dancing behavior or rhythmically synchronized movements as a means of communication and bonding within a group (Merker et al., 2009). Some authors have suggested that it might be an evolutionary advantage to entrain motor actions in time to auditory rhythms, for example to facilitate work (Thaut, Kenyon, Schauer, & McIntosh, 1999) and coordinate movements in a group (Cummins, 2009). Motor entrainment in the form of musical synchronization of movements might therefore be considered a natural human phenomenon, which has recently also been proposed to distinguish humans from other primates (Honing, Merchant, Haden, Prado, & Bartolo, 2012) and which has until recently been thought to be shared only with other kinds of species for whom rhythmic entrainment is a by-product of vocal mimicking learning mechanisms (Fitch, 2009; Patel, Iversen, Bregman, & Schulz, 2009; Schachner, Brady, Pepperberg, & Hauser, 2009); this view has, however, recently been contested since evidence for entrainment has been found in at least one nonvocal mimic (Cook, Rouse, Wilson, & Reichmuth, 2013). In contrast to autonomic physiological entrainment, entrainment at the motor level can happen a lot faster, presumably as soon as a clear beat is perceived.

In experimental settings, motor entrainment is usually studied as the synchronization of movements in the form of finger tapping to a presented auditory stimulus (for a review, see Repp & Su, 2013; Ross & Balasubramaniam, 2014), that is, asking participants to tap along with an auditory rhythm or music in order to measure the level of synchronization. This task is usually termed sensorimotor synchronization (SMS; Repp, 2005). There are also studies that code more general bodily movements, using video recordings or motion capture systems in order to evaluate the level of motor synchronization with an auditory rhythm or music (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2014; Kirschner & Tomasello, 2009; Zentner & Eerola, 2010). Furthermore, motor entrainment can be tested more implicitly in a working memory setting in which participants have to reproduce a previously heard rhythmical sequence after a short time interval (Konoike et al., 2012).

2.4.1. Brain regions involved in motor entrainment

To produce a rhythmical sequence, one has to perform actual movements and it is therefore obvious that the entire motor system is involved, including subcortical and cortical motor regions. Functional neuroimaging studies have investigated motor entrainment by using synchronized tapping or rhythm reproduction paradigms to identify the brain regions that are involved: the premotor cortex (PMC), supplementary motor area (SMA), cerebellum, and basal ganglia (BG; Chen et al., 2008a; Chen, Penhune, & Zatorre, 2008b; Grahn & Brett, 2007; Konoike et al., 2012). Studies on SMS that used functional magnetic resonance imaging (fMRI) or MEG techniques showed that a cerebello-thalamo-cortical network is involved in the synchronized beat tapping task that included the sensorimotor cortices, SMA and PMC, as well as the thalamus, posterior parietal regions, and cerebellum (Chen et al., 2008b; Krause, Schnitzler, & Pollok, 2010; Kung, Chen, Zatorre, & Penhune, 2013). In a study that investigated dance movements to music, participants were asked to make dancing steps while lying in the fMRI scanner, either in synchrony to tango music or to nonrhythmical versions of the same music (Brown, Martinez, & Parsons, 2006); the putamen was found to be significantly more activated during the synchrony condition. Furthermore, the cerebellum has also been suggested to be involved in SMS (Molinari, Leggio, De Martin, Cerasa, & Thaut, 2003; Molinari, Leggio, & Thaut, 2007), because lesions in the cerebellum have been shown to impair precise timing tasks (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002). A meta-analysis on the functional neuroimaging literature of audiomotor entrainment suggested a dissociation between externally paced and self-paced tapping (Chauvigné, Gitau, & Brown, 2014); although the cerebellum plays a role in externally paced tapping, probably related to a timing comparison between the external clock and motor actions (Ivry et al., 2002; Molinari et al., 2007), the BG are both involved in externally and internally paced SMS. In other studies, working memory paradigms were used to study how rhythmical information is processed and retrieved in the brain (Grahn & Brett, 2007; Konoike et al., 2012). In a study by Konoike and colleagues (2012), participants had to retain either a rhythmical sequence or a number sequence. The contrast between these two conditions in the retrieval phase shows that for rhythmical reproduction SMA, the inferior frontal gyrus and inferior parietal lobule were specifically involved. Another approach is not to ask participants to tap the beat, but to tap exactly the same rhythm as heard, that is, to reproduce the rhythmical pattern in synchrony (Chen et al., 2008b). Chen and colleagues (2008b) correlated the temporal complexity of the rhythmical sequences and found that the pre-SMA, SMA, dorsal premotor cortex (dPMC), inferior parietal lobule, cerebellum, and dorsolateral prefrontal cortex modulated the activity in terms of the temporal complexity of the presented rhythmical pattern. As was described in section 2.2 (Perceptual Entrainment), the literature seems to suggest that a similar network is involved in the perception and production of rhythms. Some studies have tried to disentangle the roles of the individual brain structures involved in these tasks (Chen et al., 2008a; Grahn & Brett, 2007; Kung et al., 2013). Chen and colleagues (2008a) performed a study in which some participants listened to rhythms without knowing that they would have to reproduce them afterward, whereas others were informed about the tapping task. These authors found that during naïve listening without probable motor preparation, the network recruited was similar to that recruited when the tapping task was announced, which includes the SMA, PMC, and cerebellum. Furthermore, Chen and colleagues suggest that the ventral PMC (vPMC) was involved only when the tapping condition was announced.

Several studies have also considered the functional connectivity between the individual brain areas known to be involved in rhythm processing. For example, Chen and colleagues found evidence for functional connectivity between the dPMC and secondary auditory regions (Chen et al., 2008a; Chen, Zatorre, & Penhune, 2006). Moreover, the close interaction of movements, especially to music, might be based on the dorsal stream of auditory processing through which the auditory cortex is closely linked to the motor cortex (Rauschecker, 2011; Zatorre, Chen, & Penhune, 2007). The dorsal pathway of auditory processing projects the signal via the planum temporale and the inferior parietal lobule to the primary and premotor regions (Erickson, Rauschecker, & Turkeltaub, 2016; Rauschecker, 2011; Rauschecker & Tian, 2000). This pathway has also been called the “where” pathway, because it has been demonstrated to be involved in the localization of a sound (Ahveninen et al., 2006; Alain, Arnott, Hevenor, Graham, & Grady, 2001; Kaiser & Lutzenberger, 2003; Kuśmierek & Rauschecker, 2014) and more recently in sensorimotor integration and speech production (Rauschecker, 2012). Kornysheva and colleagues used repeated transcranial magnetic stimulation (rTMS) to specifically test the role of the vPMC as part of the dorsal auditory stream in auditory-motor integration (Kornysheva & Schubotz, 2011). Impairing the left vPMC with rTMS showed that auditory-motor synchronization, that is, tapping to an auditory beat, is compromised, but tapping to a self-paced beat is not. Another study applied rTMS to the dPMC and SMA, but found an impairment of finger movement synchronization to metrical rhythms only for the right dPMC, whereas synchronization to nonmetrical or isochronous beats was intact (Giovannelli et al., 2012). These findings corroborate the important role of the vPMC in auditory-motor integration, which enables accurate timing and movement adaptation to an auditory rhythm.

Finally, another important organ involved in entrainment—and the pleasure we derive from it—likely lies in the vestibular system (Phillips-Silver, Aktipis, & Bryant, 2010; Todd & Lee, 2015). Bharucha, Curtis, and Paroo (2006) mentioned the importance of motion and particularly of self-motion among the conscious recognition of music and affective experiences in the description of conscious music listening experiences. Indirect evidence for this can be seen in a study that examined the effects of motion on meter perception in 7-month-old infants. Phillips-

Silver and Trainor (2005) bounced infants to every second or third beat while the infants listened to metrically ambiguous (unaccented) rhythm sequences and found that the infants later tended to prefer (accented) sequences that matched the meter they were bounced to. According to the authors, own-body motion is necessary for this preference to develop because having the infants watch an experimenter bounce did not replicate the findings, pointing to the importance of the proprioceptive and vestibular systems and possibly explaining our propensity to head-bob even when not dancing (Janata, Tomic, & Haberman, 2012). Supported by studies showing that the saccule and lagena of various animals' vestibules are also sensitive to sound, there may be an evolutionary explanation for this link in the vestibular system (Bharucha et al., 2006; Phillips-Silver et al., 2010), leading Bharucha and colleagues to propose that perhaps in humans, projections from the saccules to spinal motoneurons underlie these tendencies.

2.4.2. Links between motor entrainment and affect

The popularity of rhythmic movement synchronization in music and dance is the most obvious indicator that motor entrainment is tightly linked to affective experiences. Being in synchrony with the music seems to be a pleasant affective state (Janata et al., 2012). The link between motor entrainment and affect has been shown empirically in a study with infants by Zentner and colleagues (2010), in which they reported that the degree of rhythmical coordination of movements to rhythmical music in babies is related to increased displays of positive affect in the form of smiles. Another aspect is that some types of music also seem to comprise the motivational component of the urge to move to the music. This component of wanting to move with the rhythm of the music has also been called “the groove” (Janata et al., 2012; Madison, 2006; Madison, Gouyon, Ullen, & Hornstrom, 2011), which is a term that comes from popular music (Witek, 2009). Janata and colleagues (2012) showed in an experimental study that motor entrainment to the music increases when this music is judged as having more groove. These authors also found that increased motor synchronization leads to more enjoyment, which is further evidence for the link between motor entrainment and affect. Specific features in the music, such as a medium level of syncopation, as well as staggered instrument entrances, seem to increase the experience of groove and in turn the level of SMS with the music (Hurley, Martens, & Janata, 2014; Witek, Clarke, Wallentin, Kringelbach, & Vuust, 2014). Another example that relates motor entrainment to affect is given in states of trance that can be induced by dancing to repetitive rhythmical sounds, inducing altered states of consciousness that are often described as pleasant experiences (Szabo, 2006).

A neuroanatomical hint for the close connection between rhythm perception and affect could be given by the fact that both are processed in parts of the BG that are also closely connected to the limbic system. Concerning emotion processing, it is known that the ventral part of the striatum in particular, including the nucleus accumbens, is part of the reward system involved in the processing of highly pleasant emotions (for a review, see Berridge & Robinson, 1998). For music, it has also been shown that highly pleasant music involves the ventral striatum (Blood & Zatorre, 2001; Salimpoor et al., 2011; Trost et al., 2012). For rhythm perception and production, however, dorsal parts of the striatum have been shown to play a role, notably the caudate, putamen, and pallidum (Grahn & Brett, 2007). However, given the close connectivity between the different structures of the striatum and the influence of the dopaminergic system on all of them, interactions between these structures might play an important role and may constitute a neuroanatomical reason for rhythmic entrainment as an affect induction mechanism.

Blood and Zatorre (2001) found that the activity in the SMA correlated positively with the subjectively rated intensity of chills, which is another indication of an interaction between the pleasantness of the music and the intention of motor behavior. In addition, Kornysheva and colleagues (2010) found that preferred tempo, regardless of rate, determined aesthetic judgments and enhanced ventral PMC (vPMC) activity, which according to them was caused by the propensity towards mimicking one's own preferred tempo (Kornysheva et al., 2010). Interestingly, these authors found a double role of the vPMC, which seems to be important in auditory-motor synchronization, but also plays a role in subjective rhythmical preferences (Kornysheva & Schubotz, 2011; Kornysheva, von Anshelm-Schiffer, & Schubotz, 2011).

Finally, certain principles of biological motion in humans are known to guide our appreciation and choice of dynamics in music performance, such as the effect of the final *ritardando*, which strongly resembles the function of a runner's deceleration when stopping (Fleischhaker et al., 2011). Thus, it is possible to envision motor entrainment as an entrainment to kinematic information in the music that facilitates affective responses to living organisms (Derogatis, Lipman, & Covi, 1973) via emotional contagion, for instance (Scherer & Zentner, 2001). This is consistent with Bharucha et al.'s (2006) suggestion that experiences of motion are an integral part of the experience of music. It could also explain why motor circuits and the vestibular system, which is crucial for proprioception, are involved when listening to musical rhythms (Trainor, Gao, Lei, Lehtovaara, & Harris, 2009). Furthermore, Bharucha and colleagues have pointed out that "mere synchronization may be a powerful elicitor of emotion" (Bharucha & Curtis, 2008, p. 579), which can be induced by the musical structure itself, but even more important, if the synchronization takes place in a social context, that is, via musically evoked synchronization of movements in a group (Bharucha & Curtis, 2008; Bharucha et al., 2006). This points to the idea that rhythmic entrainment processes in social interactions could be, next to perceptual, autonomic physiological and motor entrainment, another form of entrainment, which also links powerful emotional experiences to synchronization processes.

2.5. Social entrainment

Social entrainment can emerge when listening to or making music together in a group. This is a form of entrainment in a social situation with a musical context, in which the motor actions of two or more people become coordinated in time (for a review on interpersonal coordination, see Keller, Novembre, & Hove, 2014). Social entrainment thus includes interpersonal synchronization, which is characterized by an adaptation of periodic behaviors with another person. Imitating the postures or actions of a partner is a well-known mimicry phenomenon. These imitative actions can then result in synchronized movements such as in the prominent example of synchronized hand clapping in an audience (Neda, Ravasz, Brechet, Vicsek, & Barabasi, 2000). Wiltermuth and Heath (2009) showed that independent of musical activities, acting in synchrony (e.g. walking in step) with partners in a group increased cooperation between the group members. Even seeing or simply hearing the steps of a dyad walking in an in-phase or anti-phase relation, that is, the most stable modes of synchronization, increased judgments of perceived interpersonal rapport (Miles, Nind, & Macrae, 2009). However, by social entrainment, we do not refer to synchronized actions of in-group members, but only to interpersonal synchronization processes in a social context induced by music, for example dancing or making music in a group. Kirschner and Tomasello (2009) showed in an empirical study with children (2 to 4 year olds) that they could synchronize their drumming more accurately with an external rhythm in a social condition, that is, when drumming in the presence of a drumming partner, than when doing the task alone. This finding suggests that in a social context, when playing music in a group for example, the synchronization to a rhythm is facilitated, which also corroborates the Shared Affective Motion Experience model (SAME) of Overy and Molnar-Szakacs (2009). In fact, the SAME model rests precisely on the principle that music is heard as a series of intentional and expressive motor actions and that the synchronization of the above-mentioned networks between performers and listeners leads to “a sense of empathy and social bonding” (Overy, 2012), or, at the very least, to a shared cognitive representation of these acts (Derogatis et al., 1973; Fleischhaker et al., 2011). Hove and Risen (2009) also showed that tapping with a partner in synchrony increased the feeling of affiliation between the partners. Presumably, this is because being in a group and spending time together in a shared activity, such as performing or listening to music as a group, can increase the sensitivity and care for each other, including cooperation and compassion (Valdesolo & Desteno, 2011; Valdesolo, Ouyang, & DeSteno, 2010).

2.5.1. Brain regions involved in social entrainment

Only a few neuroimaging studies have focused explicitly on the aspect of being in synchrony with a musical rhythm within a group. A study by Fairhurst and colleagues (2012) investigated the brain processes of synchronizing finger tapping with a virtual partner, which was in fact manipulated computerized feedback that either gradually adapted to the participant or went out of synchrony with respect to the taps of the participant. The authors found that the more the participants tapped in synchrony with the virtual partner, the more the ventro-medial prefrontal cortex (vmPFC) and posterior cingulate/precuneus were involved. Both of these regions have been reported to be involved in self-related mental representations and in judging one’s own or others’ actions (Cavanna & Trimble, 2006; Ochsner et al., 2004). Furthermore, these brain regions have been shown to be implicated in task sharing (Sebanz, Rebbechi, Knoblich, Prinz, & Frith, 2007) and prosocial behavior (Rameson, Morelli, & Lieberman, 2012). Synchronized drumming with partners has also been shown to increase prosocial behavior, in the form of spontaneous helping (Kokal, Engel, Kirschner, & Keysers, 2011), and this study showed that the level of prosocial commitment was associated with an increase in activity in the caudate nucleus. In an interactive tapping task with two partners and dual EEG, when the partners were adapting their tapping to each other, there was a suppression of alpha and beta oscillations over motor and frontal regions compared with the condition when the interaction was with a nonhuman computer (Konvalinka et al. (2014). In another study that used EEG, Yun, Watanabe, and Shimojo (2012) investigated how social cooperative interactions influence the synchronization of body movements and neural synchronization. Interestingly, using source localization, the authors found that after a session of social cooperation, the activity in the precuneus increased. Moreover, it was observed that the more participants increased synchronicity of finger movements after the social interaction, the more theta frequency activity was found in the vmPFC. The results of these studies show that social interactions that involve synchronized behavior have a direct impact on brain processes in several areas that are also involved in emotion processing, such as the caudate, the precuneus or the vmPFC (Kokal et al., 2011; Konvalinka et al., 2014; Yun et al., 2012).

2.5.2. Links between social entrainment and affect

From the mimicry literature, it is known that if one's vis-à-vis behaves in the same way that he or she does, this behavior is judged as being more pleasant (Chartrand & Bargh, 1999; Kuhn et al., 2010; Kuhn et al., 2011). This effect, which is also sometimes called the "chameleon effect" (Chartrand & Bargh, 1999), works probably because a person feels understood and accepted by a partner if the behavior is mimicked by the partner, which consequently procures positive feelings. The "chameleon effect" might thus explain why listening and moving together to music can be experienced as being pleasant. In this way, social entrainment adds to the effect of motor entrainment. This additional component of the pleasant experience of social interaction with either another listener or a musician can serve as an additional source of pleasure in the music listening experience. Being in synchrony with the music in a group could be experienced as being more pleasant than being in synchrony with the music alone. When individuals are listening to music in a group and moving in synchrony, they can have powerful affective experiences that are not only induced by the music itself, but also by the experience of being in synchrony with the group (Bharucha & Curtis, 2008; Bharucha et al., 2006), which could also facilitate emotional contagion and empathy effects via motor mimicry and proprioceptive feedback processes (Scherer & Coutinho, 2013; Scherer & Zentner, 2001). As stated earlier, synchronous movements to a musical rhythm in a group or with a partner can induce diverse social feelings, such as an increase in trust (Geeves, McIlwain, & Sutton, 2014; Launay, Dean, & Bailes, 2013), compassion and cooperation (Valdesolo & Desteno, 2011; Valdesolo et al., 2010), or empathy (Koehne, Schmidt, & Dziobek, 2015). Even for children who are 14 months of age, being bounced in synchrony by an adult partner increased the helpfulness of the children toward the partner in a later task (Trainor & Cirelli, 2015). Koelsch (2010) suggested that music performance and listening strengthens several social aspects between group members, such as communication, cooperation, empathy, and coordination. This integrative function of music might therefore explain the attractiveness and prevalence of music in so many cultures. In fact, Phillips-Silver and Keller (2012) suggest that entrainment has two components: a temporal one, having to do with the relationship between the music and the listener’s body and brain; and an affective one, having to do with the “mutual sharing of an affective state” (Phillips-Silver & Keller, 2012, p. 1). These authors propose that the latter comes from the pleasure derived from motor entrainment to the music in a social context. In fact, Alcorta, Sosis, and Finkel (2008) suggest that infants likely prefer slow, high-pitched songs with exaggerated rhythms because they probably optimize entrainment between mother and child which, according to these authors, facilitates empathic attachment. This suggestion is consistent with the observation that mothers intentionally highlight metrical structure through singing and synchronized movements (Longhi, 2008).

3. Discussion

In this review, we have presented a new and more detailed view of rhythmic entrainment and its role as an affect induction principle. We have brought forward four different entrainment levels and discussed their underlying brain mechanisms, as well as their links to affective experiences, which we now summarize briefly. In the following sections, we discuss the potential interrelatedness of the different levels of entrainment and their contribution to a subjective component of entrainment, as well as its role in therapy.

3.1. Key brain regions

Juslin and colleagues (Juslin, 2013; Juslin et al., 2010) suggest that rhythmic entrainment mainly involves "networks of multiple oscillators in the cerebellum and the sensorimotor regions" (Juslin et al., 2010, p. 625) as key brain structures. As we have brought forward in the preceding sections, we suggest instead that the brain regions involved in rhythmic entrainment depend on the level of the entrainment process. However, brain structures that seem to have a key position in rhythmic entrainment are the BG, which play a prominent role in rhythm perception as well as in emotion processing. In fact, in the literature on rhythmic entrainment, the involvement of the BG has been reported on the perceptual, motor, and social levels. We suggest therefore that the BG and the dopaminergic circuits that originate in the BG are the central figures in the connection between rhythmic entrainment and affective experiences. In particular, the BG are able to synchronize and influence the synaptic weights of neuronal populations for generating complex stabilized neuronal networks involved in emotional processing and integrated behavior. Péron and colleagues (Péron, Frühholz, Vérin, & Grandjean, 2013) have therefore proposed that the BG are a crucial component in emotional processing because of the various connections of their different nuclei to cortical and other subcortical areas.

However, the BG are just part of a network of brain regions that are involved in entrainment processes. Depending on the level of entrainment involved, motor circuits, frontal cortical regions, parietal cortical regions, or the cerebellum might interplay to produce synchronies.

3.2. Induced affect

In terms of the expected affective experiences, we believe that rhythmic entrainment is mostly involved in the induction of both high and low arousing *positive* emotions, since pieces that are characterized by a slow but regular pulse, such as slow waltzes or lullabies, can have a pleasant calming effect and be equally effective in inducing a pleasant sense of regularity and motion as pieces with a fast tempo. Janata et al. (2012), for instance, found a positive relation between participants' inclination to move and their enjoyment of low, mid, and high "grooving" songs, the latter inducing the greatest amount of body movement (groove being defined as "that aspect of the music that induces a pleasant sense of wanting to move along," p. 56). Therefore, entrainment could be predicted to induce more complex affective experiences, including musical emotions such as peacefulness, but also power and joyful activation, for example (Zentner et al., 2008). Moreover, regarding the level of social entrainment, it has been reported that social synchronization processes can induce different kinds of prosocial interpersonal dispositions and affects, such as trust (Launay et al., 2013), compassion, and cooperation (Valdesolo & Desteno, 2011; Valdesolo et al., 2010). A study on self-reported experiences of entrainment found that two different factors underlying "subjective entrainment," the feeling of wanting to move (motor entrainment factor) and the sensation of having one’s inner rhythms change (visceral entrainment factor), significantly predicted different aesthetic emotions (Labbé & Grandjean, 2014). Other possible outputs, distinct from both mood and emotions, are pleasantness and liking. Concerning pleasantness, we submit that the process of being and feeling entrained is a pleasurable experience in and of itself that is born of our predisposition toward entrainment. On the other hand, liking, which may be understood as an affective *preference* (Brattico, Bogert, & Jacobsen, 2013; Brattico & Pearce, 2013; Juslin, 2013; Scherer, 2004), supposes the involvement of an evaluation or *aesthetic judgement*. This judgement is made on the basis of a series of personal or cultural aesthetic criteria such as beauty, skill, or expression, for example (Juslin, 2013). If a particular performance of a musical piece, song, or rhythm is judged as being “good” or “bad” it may result in preferences such as liking or disliking, respectively. As mentioned earlier, evidence shows that music that grooves more is liked better (Janata et al., 2012); therefore, the groove or how entraining the music is found to be could be an aesthetic criteria for many people. However, if a performance is judged as being extraordinarily good or bad, such aesthetic judgments might themselves lead to full-blown emotions (Juslin, 2013).

3.3. Relationships between levels of entrainment

As pointed out in the Introduction, the relation between different levels of entrainment and their interaction is still an issue for research. Thus far, only a few studies have shown a link between the different entrainment levels. First, regarding the neural and the motor levels, increased tapping accuracy to an external beat is associated with less variability in auditory brain stem responses (Tierney & Kraus, 2013). Some evidence has also shown that the perceptual and the motor levels seem to interact. Moving to an auditory beat increases the accuracy of time interval judgments (Manning & Schutz, 2013) and the accuracy of motor synchronization is positively related to the entrainment of attentional processes, measurable by neurophysiological EEG signatures (Schmidt-Kassow, Heinemann, Abel, & Kaiser, 2013).

Given that only a few empirical studies have focused on rhythmic entrainment and its role in affect induction, the links between the levels remain to be further explored. From the different literature and domains, it might seem that there is little relation between the different levels of entrainment described here. However, we will now borrow an approach used to conceptualize emotion in order to illustrate that such links may in fact exist. Currently, many theorists agree with a multicomponential view of emotion (Moors, 2007; Moors, Ellsworth, Scherer, & Frijda, 2013), that is, that emotions comprise several components such as action tendency, bodily responses, and emotional experience. According to the Component Process Model (CPM) of emotion (Scherer, 2005), there are at least five (cognitive, motivational, neurophysiological, motor expression, subjective feeling) and though each is associated with a different function they are all highly interrelated; changes in one produce changes in the others. In fact, in this framework, it is the synchronized responses of these different components that constitute an emotion. Similarly, it could be proposed that the different levels of entrainment constitute the components of a similar, single unified process. If this is the case, then changes at one level could trigger changes at another, even without listener's awareness. Indeed, in the CPM the feeling component has the special role of integrating and regulating the other processes, but this central representation involves aspects that do not all necessarily enter awareness (Grandjean et al., 2008). Much in the same way, it could be that we *feel* emotionally affected or entrained by music (Labbé & Grandjean, 2014) or find a song "groovier" than another (Janata et al., 2012) without being able to pinpoint why. Conversely, we can find ourselves tapping our feet to the beat without even realizing what we are doing or how it is affecting us.

Thus, we propose that instead of separate independent processes, different levels of entrainment are components of the same phenomenon that can be measured in different ways, all of which can have an impact on the listener's subjective feeling component. Philips-Silver and Keller's "affective entrainment" component certainly seems to support this view because it is based on the interdependence between social entrainment—being in time together—and motor entrainment—being in time with the music. As with emotion, perhaps tapping into one level of entrainment triggers the others. The results of Philips-Silver and Trainer's (2005) bouncing experiment seem to support this idea because own-body motion was necessary to develop the preference for accented sequences.

3.4. Directionality

Another general aspect that is of importance when studying and questioning the role of rhythmic entrainment as an affect induction mechanism is the directionality of the relation. The studies from the literature that test the level of rhythmic entrainment with a certain affective state (affect → entrainment) should be well distinguished from other studies that test the affective reaction, given a certain state of entrainment (entrainment → affect). In fact, since this link has not yet been the subject of many studies, the directionality between induced affect and rhythmic entrainment has not been studied in detail. For example, one study investigated the direction from pleasant music leading to increased perceptual entrainment (Trost et al., 2014) by testing how pleasant music would entrain attentional processes to the meter of the music. Janata and colleagues (2012) showed that spontaneous motor entrainment to the music increases when this music is judged as having more groove. In a different study investigating the opposite direction, self-reported ratings of subjective entrainment were found to significantly predict the intensity of mostly positive musical emotional dimensions, showing that the more entrained listeners feel, the more likely they are to experience positive emotions (Labbé & Grandjean, 2014). Thus, the causal direction in this association remains unclear. More research is needed to formally test the directionality between induced affect and entrainment processes. It is likely that entrainment itself, for example, at the motor level, would induce a kind of dynamic virtuous circle, together with the external musical rhythms, and would then also contribute to reported feelings related to music. Or, it is also possible that the link between affect and entrainment is a bidirectional cyclic phenomenon, where both, the affective reactions as well as the entrainment processes facilitate and foster each other. It could be that the effects of entrainment on affect and especially emotion are in fact an interaction effect between low-level bottom-up processes (afferent feedback) that eventually combine with top-down (efferent) responses leading to a unified response (e.g. Schachter & Singer, 1962).

3.5. Rhythmic entrainment in therapy

In regard to the application of rhythmic entrainment, it should be acknowledged that rhythmic entrainment and its effect on affect can be directly implemented in therapy. In particular, in patients with movement disabilities, rhythmical exercises that are based on entrainment can be beneficial. Interesting examples of pathological motor entrainment come from studies with Parkinson patients. Several studies have shown that listening to or watching rhythmical patterns can help diminish the symptoms in these patients, who are usually impaired in initiating movements, especially in gait, because of degeneration in the substantia nigra, which is strongly connected to the different nuclei of the BG (del Olmo & Cudeiro, 2005; Derogatis, Rickels, & Rock, 1976; Pacchetti et al., 2000; Schwartze, Keller, Patel, & Kotz, 2011). Rhythmic auditory stimulation to facilitate gait has been successfully applied in Parkinson patients (McIntosh, Brown, Rice, & Thaut, 1997; Thaut & McIntosh, 1999), in patients during recovery from a stroke (Thaut, McIntosh, & Rice, 1997), and in patients with spinal cord or traumatic brain injury (de l'Etoile, 2008; Hurt, Rice, McIntosh, & Thaut, 1998). Schwartze and colleagues (Schwartze et al., 2011) showed that patients with focal lesions in the BG had difficulties in adapting their movements to tempo changes (accelerando and ralentando) when asked to tap along with the tempo of a rhythmic sequence. Furthermore, for perception only, researchers have shown that Parkinson patients are also impaired in discriminating beat-based rhythms (Grahn & Brett, 2009). Moreover, music therapy that involves passive listening as well as active motor involvement, and thus entrainment processes, has beneficial effects not only on the motor symptoms, but also on the emotions of Parkinson patients (Pacchetti et al., 2000), which further speaks to the potential role of the basal ganglia in linking entrainment and emotional responses.

Entrainment-based musical activities can improve various outcome measures in elderly, nonclinical populations as well. A specific kind of musical activity that is built on the idea that music is taught through movements is the Eurhythmics of Jaques-Dalcroze (Jaques-Dalcroze, 1919). Regular Dalcroze Eurhythmics exercises reduced not only the risk of falls and gait variability in elderly participants, but also anxiety (Trombetti et al., 2011; Hars et al., 2014). Moreover, Dalcroze Eurhythmics can also be beneficial in clinical populations, such as patients with autism or post-traumatic stress disorder (Berger, 2016).

Given the theoretical and empirical evidence for rhythmic entrainment as an affect induction mechanism, it seems likely that rhythmic entrainment processes at different levels constitute the crucial element of the therapeutic effect. One of the underlying mechanisms of this therapeutic effect definitely seem to be constituted by the emotional power of music, which increases the pleasantness, the motivation, and the compliance of the patient to maintain a certain training intervention. But there are also other underlying mechanisms that are intrinsic to entrainment processes, which would support the therapeutic effect of music- and rhythm-based interventions. First, entrainment of attentional resources on the perceptual level would lead to an increase of attention and an enhanced processing of information in punctual moments (Bolger et al., 2013). Second, entrainment on the autonomic physiological level, such as respiration cycles could lead to a reduction of effort to perform physical exercises (Hoffmann, Torregrosa, & Bardy, 2012). Third, entrainment on the motor level would facilitate the movements (Thaut et al., 1997), and fourth, even more so when the exercises have to be performed in a group (Kirschner & Tomasello, 2009). Assuming that rhythmic entrainment procures and fosters also positive feelings and pleasant emotional states, it seems that entrainment-based musical activities could constitute altogether a sensible and effective intervention for clinical and nonclinical populations.

4. Conclusion

We have reviewed and discussed different aspects of rhythmic entrainment as an affect induction mechanism by reviewing the literature and describing the reported entrainment phenomena. We noted that different phenomena are described as rhythmic entrainment, all of which have a common basis but differ in their level of expression, and therefore we suggested that differentiations should be made between the different phenomena (neural, perceptual, autonomic physiological, motor, and social) in order to identify the processes more precisely (Figure 1). Regarding these different forms of rhythmic entrainment, although quite different phenomena are presented, what they have in common is that the music triggers synchronization behaviors in different biological rhythms and this tuning into the periodicities of the musical rhythms has an affective component. Apart from the neural level at which neural ensembles synchronize, which seems to be at the basis of all entrainment effects, all other forms of entrainment have been described as involving a kind of affective experience. For example, when faster respiration leads to higher felt arousal, moving in synchrony to the rhythm of the music feels pleasant and sharing the same musical experience in a group creates the positive feeling of acceptance and integration. For these reasons, the close relation between musically induced rhythmic entrainment and affective experiences has become of increasing interest in music psychology. More research is needed to further investigate the notion of rhythmic entrainment as an affect induction mechanism.

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References

Ahveninen, J., Jääskeläinen, I. P., Raij, T., Bonmassar, G., Devore, S., Hämäläinen, M., . . . Belliveau, J. W. (2006). Task-modulated “what” and “where” pathways in human auditory cortex. *Proceedings of the National Academy of Sciences of the United States of America, 103*(39), 14608-14613. doi: 10.1073/pnas.0510480103

Alain, C., Arnott, S. R., Hevenor, S., Graham, S., & Grady, C. L. (2001). "What" and "where" in the human auditory system. *Proceedings of the National Academy of Sciences, 98*(21), 12301-12306. doi: 10.1073/pnas.211209098

Alcorta, C. S., Sosis, R., & Finkel, D. (2008). Ritual harmony: Toward an evolutionary theory of music. *Behavioral and Brain Sciences, 31*(5), 576-+. doi: 10.1017/S0140525x08005311

Arnal, L. H., & Giraud, A.-L. (2012). Cortical oscillations and sensory predictions. *Trends in Cognitive Sciences, 16*(7), 390-398. doi: 10.1016/j.tics.2012.05.003

Bååth, R. (2015). Subjective rhythmization: A replication and an assessment of two theoretical explanations. *Music Perception: An Interdisciplinary Journal, 33*(2), 244-254. doi: 10.1525/mp.2015.33.2.244

Bardy, B. G., Hoffmann, C. P., Moens, B., Leman, M., & Dalla Bella, S. (2015). Sound-induced stabilization of breathing and moving. *Annals of the New York Academy of Sciences, 1337*, 94-100. doi: 10.1111/nyas.12650

Bechbache, R. R., & Duffin, J. (1977). The entrainment of breathing frequency by exercise rhythm. *The Journal of physiology, 272*(3), 553-561. doi: 10.1113/jphysiol.1977.sp012059

Benarroch, E. E. (1997). *Central autonomic network: Functional organization and clinical correlations* (E. E. Benarroch Ed.). Armonk, NY: Futura Publishing Company.

Bengtsson, S. L., Ullen, F., Ehrsson, H. H., Hashimoto, T., Kito, T., Naito, E., . . . Sadato, N. (2009). Listening to rhythms activates motor and premotor cortices. *Cortex, 45*(1), 62-71. doi: 10.1016/j.cortex.2008.07.002

Bernardi, L., Porta, C., Casucci, G., Balsamo, R., Bernardi, N. F., Fogari, R., & Sleight, P. (2009). Dynamic interactions between musical, cardiovascular, and cerebral rhythms in humans. *Circulation, 119*(25), 3171-3180. doi: 10.1161/circulationaha.108.806174

Berntson, G. G., Sarter, M., & Cacioppo, J. T. (2003). Ascending visceral regulation of cortical affective information processing. *European Journal of Neuroscience, 18*(8), 2103-2109. doi: 10.1046/j.1460-9568.2003.02967.x

Berridge, K. C., & Robinson, T. E. (1998). What is the role of dopamine in reward: Hedonic impact, reward learning, or incentive salience? *Brain Research Reviews, 28*(3), 309-369. doi: 10.1016/S0165-0173(98)00019-8

Bharucha, J. J., & Curtis, M. (2008). Affective spectra, synchronization, and motion: Aspects of the emotional response to music. *Behavioral and Brain Sciences, 31*(5), 579-+. doi: 10.1017/S0140525x08005335

Bharucha, J. J., Curtis, M., & Paroo, K. (2006). Varieties of musical experience. *Cognition, 100*(1), 131-172. doi: 10.1016/j.cognition.2005.11.008

Bienvenu, Thomas C. M., Busti, D., Magill, Peter J., Ferraguti, F., & Capogna, M. (2012). Cell-type-specific recruitment of amygdala interneurons to hippocampal theta rhythm and noxious stimuli in vivo. *Neuron, 74*(6), 1059-1074. doi: 10.1016/j.neuron.2012.04.022

Blood, A. J., & Zatorre, R. J. (2001). Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proceedings of the National*

Academy of Sciences of the United States of America, 98(20), 11818-11823. doi: 10.1073/pnas.191355898

Bolger, D., Coull, J. T., & Schön, D. (2014). Metrical rhythm implicitly orients attention in time as indexed by improved target detection and left inferior parietal activation. *Journal of Cognitive Neuroscience, 26*(3), 593-605. doi: 10.1162/jocn_a_00511

Bolger, D., Trost, W., & Schön, D. (2013). Rhythm implicitly affects temporal orienting of attention across modalities. *Acta Psychologica, 142*(2), 238-244. doi: 10.1016/j.actpsy.2012.11.012

Bolton, T. L. (1894). Rhythm. *The American Journal of Psychology, 6*(2), 145-238. doi: 10.2307/1410948

Brattico, E., Bogert, B., Alluri, V., Tervaniemi, M., Eerola, T., & Jacobsen, T. (2016). It's sad but I like it: The neural dissociation between musical emotions and liking in experts and laypersons. *Frontiers in Human Neuroscience, 9*. doi: 10.3389/fnhum.2015.00676

Brattico, E., Bogert, B., & Jacobsen, T. (2013). Toward a neural chronometry for the aesthetic experience of music. *Frontiers in Psychology, 4*, 206. doi: 10.3389/fpsyg.2013.00206

Brattico, E., & Pearce, M. (2013). The neuroaesthetics of music. *Psychology of Aesthetics, Creativity, and the Arts, 7*(1), 48-61. doi: 10.1037/a0031624

Brochard, R., Abecasis, D., Potter, D., Ragot, R., & Drake, C. (2003). The "ticktock" of our internal clock: Direct brain evidence of subjective accents in isochronous sequences. *Psychological Science, 14*(4), 362-366. doi: 10.1111/1467-9280.24441

Brosch, M., Budinger, E., & Scheich, H. (2002). Stimulus-related gamma oscillations in primate auditory cortex. *Journal of Neurophysiology, 87*(6), 2715-2725. doi: 10.1152/jn.00583.2001

Brown, S., Martinez, M. J., & Parsons, L. M. (2006). The neural basis of human dance. *Cerebral Cortex, 16*(8), 1157-1167. doi: 10.1093/cercor/bhj057

Burger, B., Thompson, M. R., Luck, G., Saarikallio, S. H., & Toiviainen, P. (2014). Hunting for the beat in the body: On period and phase locking in music-induced movement. *Frontiers in Human Neuroscience, 8*, 903. doi: 10.3389/fnhum.2014.00903

Buzsáki, G. (2006). *Rhythms of the brain*. New York, NY: Oxford University Press.

Canolty, R. T., & Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends in Cognitive Sciences, 14*(11), 506-515. doi: 10.1016/j.tics.2010.09.001

Cavanna, A. E., & Trimble, M. R. (2006). The precuneus: A review of its functional anatomy and behavioural correlates. *Brain, 129*(Pt 3), 564-583. doi: 10.1093/brain/awl004

Chartrand, T. L., & Bargh, J. A. (1999). The Chameleon effect: The perception-behavior link and social interaction. *Journal of Personality and Social Psychology, 76*(6), 893-910. doi: 10.1037//0022-3514.76.6.893

Chauvigné, L. A. S., Gitau, K. M., & Brown, S. (2014). The neural basis of audiomotor entrainment: An ALE meta-analysis. *Frontiers in Human Neuroscience, 8*, 776. doi: 10.3389/fnhum.2014.00776

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008a). Listening to musical rhythms recruits motor regions of the brain. *Cerebral Cortex, 18*(12), 2844-2854. doi: 10.1093/cercor/bhn042

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008b). Moving on time: Brain network for auditory-motor synchronization is modulated by rhythm complexity and musical training. *Journal of Cognitive Neuroscience, 20*(2), 226-239. doi: 10.1162/jocn.2008.20018

Chen, J. L., Zatorre, R. J., & Penhune, V. B. (2006). Interactions between auditory and dorsal premotor cortex during synchronization to musical rhythms. *Neuroimage, 32*(4), 1771-1781. doi: 10.1016/j.neuroimage.2006.04.207

Clayton, M., Sager, R., & Will, U. (2005). In time with the music: The concept of entrainment and its significance for ethnomusicology. *European Seminar in Ethnomusicology, 1*, 3-75.

Cook, P., Rouse, A., Wilson, M., & Reichmuth, C. (2013). A California sea lion (Zalophus californianus) can keep the beat: Motor entrainment to rhythmic auditory stimuli in a non vocal mimic. *Journal of Comparative Psychology, 127*(4), 412-427. doi: 10.1037/a0032345

Craig, A. D. (2009). Emotional moments across time: A possible neural basis for time perception in the anterior insula. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 364*(1525), 1933-1942. doi: 10.1098/rstb.2009.0008

Critchley, H. D. (2004). The human cortex responds to an interoceptive challenge. *Proceedings of the National Academy of Sciences of the United States of America, 101*(17), 6333-6334. doi: 10.1073/pnas.0401510101

Critchley, H. D. (2005). Neural mechanisms of autonomic, affective, and cognitive integration. *The Journal of Comparative Neurology, 493*(1), 154-166. doi: 10.1002/cne.20749

Cummins, F. (2009). Rhythm as an affordance for the entrainment of movement. *Phonetica, 66*(1-2), 15-28. doi: 10.1159/000208928

Damasio, A. R. (1996). The somatic marker hypothesis and the possible functions of the prefrontal cortex. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 351*(1346), 1413-1420. doi: 10.1098/rstb.1996.0125

de Dreu, M. J., van der Wilk, A. S. D., Poppe, E., Kwakkel, G., & van Wegen, E. E. H. (2012). Rehabilitation, exercise therapy and music in patients with Parkinson's disease: A meta-analysis of the effects of music-based movement therapy on walking ability, balance and quality of life. *Parkinsonism & Related Disorders, 18, Supplement 1*, S114-S119. doi: 10.1016/S1353-8020(11)70036-0

de l'Etoile, S. K. (2008). The effect of rhythmic auditory stimulation on the gait parameters of patients with incomplete spinal cord injury: An exploratory pilot study. *International Journal of Rehabilitation Research, 31*(2), 155-157. doi: 10.1097/MRR.0b013e3282fc0f44

del Olmo, M. F., & Cudeiro, J. (2005). Temporal variability of gait in Parkinson disease: Effects of a rehabilitation programme based on rhythmic sound cues. *Parkinsonism & Related Disorders, 11*(1), 25-33. doi: 10.1016/j.parkreldis.2004.09.002

Derogatis, L. R., Lipman, R. S., & Covi, L. (1973). SCL-90: An outpatient psychiatric rating scale--preliminary report. *Psychopharmacology Bulletin, 9*(1), 13-28.

Derogatis, L. R., Rickels, K., & Rock, A. F. (1976). The SCL-90 and the MMPI: A step in the validation of a new self-report scale. *The British Journal of Psychiatry, 128*, 280-289.

Dousty, M., Daneshvar, S., & Haghjoo, M. (2011). The effects of sedative music, arousal music, and silence on electrocardiography signals. *Journal of Electrocardiology, 44*(3), 396 e391-396. doi: 10.1016/j.jelectrocard.2011.01.005

Eerola, T., Lartillot, O., & Toiviainen, P. (2009). *Prediction of multidimensional emotional ratings in music from audio using multivariate regression models.* Paper presented at the International Conference on Music Information Retrieval.

Ellis, R. J., & Thayer, J. F. (2010). Music and autonomic bervous system (dys)function. *Music Perception, 27*(4), 317-326. doi: 10.1525/mp.2010.27.4.317

Erickson, L. C., Rauschecker, J. P., & Turkeltaub, P. E. (2016). Meta-analytic connectivity modeling of the human superior temporal sulcus. *Brain Structure and Function*, 1-19. doi: 10.1007/s00429-016-1215-z

Etzel, J. A., Johnsen, E. L., Dickerson, J., Tranel, D., & Adolphs, R. (2006). Cardiovascular and respiratory responses during musical mood induction. *International Journal of Psychophysiology, 61*(1), 57-69. doi: 10.1016/j.ijpsycho.2005.10.025

Fairhurst, M. T., Janata, P., & Keller, P. E. (2012). Being and feeling in sync with an adaptive virtual partner: Brain mechanisms underlying dynamic cooperativity. *Cerebral Cortex*. doi: 10.1093/cercor/bhs243

Fancourt, D., Ockelford, A., & Belai, A. (2014). The psychoneuroimmunological effects of music: A systematic review and a new model. *Brain, Behavior, and Immunity, 36*, 15-26. doi: 10.1016/j.bbi.2013.10.014

Fitch, W. T. (2009). Biology of music: Another one bites the dust. *Current Biology, 19*(10), R403-404. doi: 10.1016/j.cub.2009.04.004

Fleischhaker, C., Bohme, R., Sixt, B., Bruck, C., Schneider, C., & Schulz, E. (2011). Dialectical Behavioral Therapy for Adolescents (DBT-A): a clinical trial for patients with suicidal and self-injurious behavior and borderline symptoms with a one-year follow-up. *Child and Adolescent Psychiatry and Mental Health, 5*(1), 3. doi: 10.1186/1753-2000-5-3

Friedman, B. H. (2010). Feelings and the body: The Jamesian perspective on autonomic specificity of emotion. *Biological Psychology, 84*(3), 383-393. doi: 10.1016/j.biopsycho.2009.10.006

Fries, P. (2005). A mechanism for cognitive dynamics: Neuronal communication through neuronal coherence. *Trends in Cognitive Sciences, 9*(10), 474-480. doi: 10.1016/j.tics.2005.08.011

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 360*(1456), 815-836. doi: 10.1098/rstb.2005.1622

Fujioka, T., Fidali, B., & Ross, B. (2014). Neural correlates of intentional switching from ternary to binary meter in a musical hemiola pattern. *Frontiers in Psychology, 5*. doi: 10.3389/fpsyg.2014.01257

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2009). Beta and gamma rhythms in human auditory cortex during musical beat processing. *Annals of the New York Academy of Sciences, 1169*, 89-92. doi: 10.1111/j.1749-6632.2009.04779.x

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *Journal of Neuroscience, 32*(5), 1791-1802. doi: 10.1523/JNEUROSCI.4107-11.2012

Fujioka, T., Trainor, L. J., & Ross, B. (2013). Neuromagnetic beta-band oscillation for rhythmic processing induced by subjectively accented structure. *The Journal of the Acoustical Society of America, 134*(5), 4064. doi: 10.1121/1.4830835

Fujioka, T., Zendel, B. R., & Ross, B. (2010). Endogenous neuromagnetic activity for mental hierarchy of timing. *Journal of Neuroscience, 30*(9), 3458-3466. doi: 10.1523/JNEUROSCI.3086-09.2010

Gabrielson, A. (2009). The relationship between musical structure and perceived expression. In I. Cross, S. Hallam & M. Thaut (Eds.), *Oxford Handbook of Music Psychology* (pp. 141-150). New York, NY: Oxford University Press.

Geeves, A., McIlwain, D. J., & Sutton, J. (2014). The performative pleasure of imprecision: A diachronic study of entrainment in music performance. *Frontiers in Human Neuroscience, 8*. doi: 10.3389/fnhum.2014.00863

Geiser, E., Walker, K. M. M., & Bendor, D. (2014). Global timing: A conceptual framework to investigate the neural basis of rhythm perception in humans and non-human species. *Frontiers in Psychology, 5*. doi: 10.3389/fpsyg.2014.00159

Giovannelli, F., Innocenti, I., Rossi, S., Borgheresi, A., Ragazzoni, A., Zaccara, G., . . . Cincotta, M. (2012). Role of the dorsal premotor cortex in rhythmic auditory-motor entrainment: A perturbational approach by rTMS. *Cerebral Cortex*. doi: 10.1093/cercor/bhs386

Giraud, A.-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: Emerging computational principles and operations. *Nature Neuroscience, 15*(4), 511-517. doi: 10.1038/nn.3063

Gomez, P., & Danuser, B. (2007). Relationships between musical structure and psychophysiological measures of emotion. *Emotion, 7*(2), 377-387. doi: 10.1037/1528-3542.7.2.377

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience, 19*(5), 893-906. doi: 10.1162/jocn.2007.19.5.893

Grahn, J. A., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex, 45*(1), 54-61. doi: 10.1016/j.cortex.2008.01.005

Grahn, J. A., & Rowe, J. B. (2012). Finding and feeling the musical beat: Striatal dissociations between detection and prediction of regularity. *Cerebral Cortex*. doi: 10.1093/cercor/bhs083

Grandjean, D., Sander, D., & Scherer, K. R. (2008). Conscious emotional experience emerges as a function of multilevel, appraisal-driven response synchronization. *Consciousness and Cognition, 17*(2), 484-495. doi: 10.1016/j.concog.2008.03.019

Grewe, O., Nagel, F., Kopiez, R., & Altenmüller, E. (2007). Emotions over time: Synchronicity and development of subjective, physiological, and facial affective reactions to music. *Emotion, 7*(4), 774-788. doi: 10.1037/1528-3542.7.4.774

Grondin, S. (2010). Timing and time perception: A review of recent behavioral and neuroscience findings and theoretical directions. *Attention, Perception & Psychophysics, 72*(3), 561-582. doi: 10.3758/APP.72.3.561

Grube, M., & Griffiths, T. D. (2009). Metricality-enhanced temporal encoding and the subjective perception of rhythmic sequences. *Cortex, 45*(1), 72-79. doi: 10.1016/j.cortex.2008.01.006

Guhn, M., Hamm, A., & Zentner, M. (2007). Physiological and musico-acoustic correlates of the chill response. *Music Perception: An Interdisciplinary Journal, 24*(5), 473-484. doi: 10.1525/mp.2007.24.5.473

Haas, F., Distenfeld, S., & Axen, K. (1986). Effects of perceived musical rhythm on respiratory pattern. *Journal of Applied Physiology, 61*(3), 1185-1191.

Hoffmann, C. P., Torregrosa, G., & Bardy, B. G. (2012). Sound stabilizes locomotor-respiratory coupling and reduces energy cost. *PloS One, 7*(9), e45206. doi: 10.1371/journal.pone.0045206

Honing, H., Merchant, H., Haden, G. P., Prado, L., & Bartolo, R. (2012). Rhesus monkeys (Macaca mulatta) detect rhythmic groups in music, but not the beat. *PloS One, 7*(12), e51369. doi: 10.1371/journal.pone.0051369

Hove, M. J., & Risen, J. L. (2009). It's all in the timing: Interpersonal synchrony increases affiliation. *Social Cognition, 27*(6), 949-960. doi: 10.1521/soco.2009.27.6.949

Hove, M. J., Stelzer, J., Nierhaus, T., Thiel, S. D., Gundlach, C., Margulies, D. S., . . . Merker, B. (2016). Brain network reconfiguration and perceptual decoupling during an absorptive state of consciousness. *Cerebral Cortex, 26*(7), 3116-3124. doi: 10.1093/cercor/bhv137

Hurley, B. K., Martens, P. A., & Janata, P. (2014). Spontaneous sensorimotor coupling with multipart music. *Journal of Experimental Psychology: Human Perception and Performance, 40*(4), 1679-1696. doi: 10.1037/a0037154

Hurt, C. P., Rice, R. R., McIntosh, G. C., & Thaut, M. H. (1998). Rhythmic auditory stimulation in gait training for patients with traumatic brain injury. *Journal of Music Therapy, 35*(4), 228-241. doi: 10.1093/jmt/35.4.228

Husain, G., Thompson, W. F., & Schellenberg, E. G. (2002). Effects of musical tempo and mode on arousal, mood, and spatial abilities. *Music Perception, 20*(2), 151-171. doi: 10.1525/mp.2002.20.2.151

Ivry, R. B., Spencer, R. M., Zelaznik, H. N., & Diedrichsen, J. (2002). The cerebellum and event timing. *Annals of the New York Academy of Sciences, 978*, 302-317. doi: 10.1111/j.1749-6632.2002.tb07576.x

Janata, P., Tomic, S. T., & Haberman, J. M. (2012). Sensorimotor coupling in music and the psychology of the groove. *Journal of Experimental Psychology: General, 141*(1), 54-75. doi: 10.1037/a0024208

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review, 96*(3), 459-491. doi: 10.1037/0033-295X.96.3.459

Juslin, P. N. (2013). From everyday emotions to aesthetic emotions: Towards a unified theory of musical emotions. *Physics of Life Reviews, 10*(3), 235-266. doi: 10.1016/j.plrev.2013.05.008

Juslin, P. N., Liljeström, S., Västfjäll, D., & Lundqvist, L.-O. (2010). How does music evoke emotions? Exploring the underlying mechanisms. In P. Juslin & J. Sloboda (Eds.), *Handbook of music and emotion: Theory, research, applications* (pp. 605-642). New York, NY: Oxford University Press.

Kaiser, J., & Lutzenberger, W. (2003). Induced gamma-band activity and human brain function. *Neuroscientist, 9*(6), 475-484. doi: 10.1177/1073858403259137

Karageorghis, C. I., & Jones, L. (2013). On the stability and relevance of the exercise heart rate–music-tempo preference relationship. *Psychology of Sport and Exercise, 15*(3), 299-310. doi: 10.1016/j.psychsport.2013.08.004

Keller, P. E., Novembre, G., & Hove, M. J. (2014). Rhythm in joint action: Psychological and neurophysiological mechanisms for real-time interpersonal coordination. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1658), 20130394. doi: 10.1098/rstb.2013.0394

Khalfa, S., Roy, M., Rainville, P., Dalla Bella, S., & Peretz, I. (2008). Role of tempo entrainment in psychophysiological differentiation of happy and sad music? *International Journal of Psychophysiology, 68*(1), 17-26. doi: 10.1016/j.ijpsycho.2007.12.001

Kirschner, S., & Tomasello, M. (2009). Joint drumming: Social context facilitates synchronization in preschool children. *Journal of Experimental Child Psychology, 102*(3), 299-314. doi: 10.1016/j.jecp.2008.07.005

Koehne, S., Schmidt, M. J., & Dziobek, I. (2015). The role of interpersonal movement synchronisation in empathic functions: Insights from Tango Argentino and Capoeira. *International Journal of Psychology*, 1-5. doi: 10.1002/ijop.12213

Koelsch, S. (2010). Towards a neural basis of music-evoked emotions. *Trends in Cognitive Sciences, 14*(3), 131-137. doi: 10.1016/j.tics.2010.01.002

Koelsch, S. (2014). Brain correlates of music-evoked emotions. *Nature Reviews Neuroscience, 15*(3), 170-180. doi: 10.1038/nrn3666

Koelsch, S., & Jäncke, L. (2015). Music and the heart. *European Heart Journal*. doi: 10.1093/eurheartj/ehv430

Kokal, I., Engel, A., Kirschner, S., & Keysers, C. (2011). Synchronized drumming enhances activity in the caudate and facilitates prosocial commitment - if the rhythm comes easily. *PloS One, 6*(11), e27272. doi: 10.1371/journal.pone.0027272

Konoike, N., Kotozaki, Y., Miyachi, S., Miyauchi, C. M., Yomogida, Y., Akimoto, Y., . . . Nakamura, K. (2012). Rhythm information represented in the fronto-parieto-cerebellar motor system. *Neuroimage, 63*(1), 328-338. doi: 10.1016/j.neuroimage.2012.07.002

Konvalinka, I., Bauer, M., Stahlhut, C., Hansen, L. K., Roepstorff, A., & Frith, C. D. (2014). Frontal alpha oscillations distinguish leaders from followers: Multivariate decoding of mutually interacting brains. *Neuroimage, 94*, 79-88. doi: 10.1016/j.neuroimage.2014.03.003

Konvalinka, I., Xygalatas, D., Bulbulia, J., Schjodt, U., Jegindo, E. M., Wallot, S., . . . Roepstorff, A. (2011). Synchronized arousal between performers and related spectators in a fire-walking ritual. *Proceedings of the National Academy of Sciences of the United States of America, 108*(20), 8514-8519. doi: 10.1073/pnas.1016955108

Kornysheva, K., & Schubotz, R. I. (2011). Impairment of auditory-motor timing and compensatory reorganization after ventral premotor cortex stimulation. *PloS One, 6*(6), e21421. doi: 10.1371/journal.pone.0021421

Kornysheva, K., von Anshelm-Schiffer, A. M., & Schubotz, R. I. (2011). Inhibitory stimulation of the ventral premotor cortex temporarily interferes with musical beat rate preference. *Human Brain Mapping, 32*(8), 1300-1310. doi: 10.1002/hbm.21109

Kornysheva, K., von Cramon, D. Y., Jacobsen, T., & Schubotz, R. I. (2010). Tuning-in to the beat: Aesthetic appreciation of musical rhythms correlates with a premotor activity boost. *Human Brain Mapping, 31*(1), 48-64. doi: 10.1002/hbm.20844

Krabs, R. U., Enk, R., Teich, N., & Koelsch, S. (2015). Autonomic effects of music in health and Crohn's disease: The impact of isochronicity, emotional valence, and tempo. *PloS One, 10*(5), e0126224. doi: 10.1371/journal.pone.0126224

Krause, V., Schnitzler, A., & Pollok, B. (2010). Functional network interactions during sensorimotor synchronization in musicians and non-musicians. *Neuroimage, 52*(1), 245-251. doi: 10.1016/j.neuroimage.2010.03.081

Krumhansl, C. (2000). Rhythm and pitch in music cognition. *Psychological Bulletin, 126*(1), 159-179. doi: 10.1037//0033-2909.126.1.159

Kuhn, S., Muller, B. C., van Baaren, R. B., Wietzker, A., Dijksterhuis, A., & Brass, M. (2010). Why do I like you when you behave like me? Neural mechanisms mediating positive consequences of observing someone being imitated. *Social Neuroscience, 5*(4), 384-392. doi: 10.1080/17470911003633750

Kuhn, S., Muller, B. C., van der Leij, A., Dijksterhuis, A., Brass, M., & van Baaren, R. B. (2011). Neural correlates of emotional synchrony. *Social Cognitive and Affective Neuroscience, 6*(3), 368-374. doi: 10.1093/scan/nsq044

Kung, S.-J., Chen, J. L., Zatorre, R. J., & Penhune, V. B. (2013). Interacting cortical and Basal Ganglia networks underlying finding and tapping to the musical beat. *Journal of Cognitive Neuroscience, 25*(3), 401-420. doi: 10.1162/jocn_a_00325

Kuśmierek, P., & Rauschecker, J. P. (2014). Selectivity for space and time in early areas of the auditory dorsal stream in the rhesus monkey. *Journal of Neurophysiology, 111*(8), 1671-1685. doi: 10.1152/jn.00436.2013

Labbé, C., & Grandjean, D. (2014). Musical emotions predicted by feelings of entrainment. *Music Perception: An Interdisciplinary Journal, 32*(2), 170-185. doi: 10.1525/mp.2014.32.2.170

Large, E. W. (2008). Resonating to musical rhythm: Theory and experiment. In S. Grondin (Ed.), *Psychology of time* (pp. 189-232). Bingley, UK: Emerald.

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review, 106*(1), 119-159. doi: 10.1037/0033-295X.106.1.119

Large, E. W., & Kolen, J. F. (1994). Resonance and the perception of musical meter. *Connection Science, 6*(2-3), 177-208. doi: 10.1080/09540099408915723

Lartillot, O., Eerola, T., Toiviainen, P., & Fornari, J. (2008). *Multi-feature modeling of pulse clarity: Design, calidation, and optimization.* Paper presented at the 9th International Conference on Music Information Retrieval, Philadelphia, PA.

Launay, J., Dean, R. T., & Bailes, F. (2013). Synchronization can influence trust following virtual interaction. *Experimental Psychology, 60*(1), 53-63. doi: 10.1027/1618-3169/a000173

Lerdahl, F., & Jackendoff, R. (1983). An overview of hierarchical structure in music. *Music Perception, 1*(2), 229-252. doi: 10.2307/40285257

Liégeois-Chauvel, C., Lorenzi, C., Trébuchon, A., Régis, J., & Chauvel, P. (2004). Temporal envelope processing in the human left and right auditory cortices. *Cerebral Cortex, 14*(7), 731-740. doi: 10.1093/cercor/bhh033

Lindh, W. Q., Pooler, M. S., & Tampa, C. D. (2006). *Thomson Delmar Learning's comprehensive medical assisting: Administrative and clinical competencies* (3rd ed.). Clifton Park, NY: Thomson Delmar Learning.

Loewy, J., Stewart, K., Dassler, A.-M., Telsey, A., & Homel, P. (2013). The effects of music therapy on vital signs, feeding, and sleep in premature infants. *Pediatrics, 131*(5), 902-918. doi: 10.1542/peds.2012-1367

London, J. (2004). *Hearing in time: Psychological aspects of musical meter*. New York, NY: Oxford University Press.

Longhi, E. (2008). Emotional responses in mother-infant musical interactions: A developmental perspective. *Behavioral and Brain Sciences, 31*(5), 586-+. doi: 10.1017/S0140525x08005402

Luck, G., Toiviainen, P., Erkkila, J., Lartillot, O., Riikkila, K., Makela, A., . . . Varri, J. (2008). Modelling the relationships between emotional responses to, and musical content of, music therapy improvisations. *Psychology of Music, 36*(1), 25-45. doi: 10.1177/030573560707914

Madison, G. (2006). Experiencing groove induced by music: Consistency and phenomenology. *Music Perception: An Interdisciplinary Journal, 24*(2), 201-208. doi: 10.1525/mp.2006.24.2.201

Madison, G., Gouyon, F., Ullen, F., & Hornstrom, K. (2011). Modeling the tendency for music to induce movement in humans: first correlations with low-level audio descriptors across music genres. *Journal of experimental psychology. Human perception and performance, 37*(5), 1578-1594. doi: 10.1037/a0024323

Manning, F., & Schutz, M. (2013). "Moving to the beat" improves timing perception. *Psychonomic Bulletin & Review*. doi: 10.3758/s13423-013-0439-7

Mason, S., Mccormick, B., & Wood, S. (1988). Auditory brain-stem response in pediatric audiology. *Archives of Disease in Childhood, 63*(5), 465-467.

McConnell, M. M., & Shore, D. I. (2011). Upbeat and happy: Arousal as an important factor in studying attention. *Cognition & Emotion, 25*(7), 1184-1195. doi: 10.1080/02699931.2010.524396

McIntosh, G. C., Brown, S. H., Rice, R. R., & Thaut, M. H. (1997). Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. *Journal of Neurology, Neurosurgery and Psychiatry, 62*(1), 22-26. doi: 10.1136/jnnp.62.1.22

Melloni, L., Molina, C., Pena, M., Torres, D., Singer, W., & Rodriguez, E. (2007). Synchronization of neural activity across cortical areas correlates with conscious perception. *The Journal of Neuroscience, 27*(11), 2858-2865. doi: 10.1523/jneurosci.4623-06.2007

Merker, B. H., Madison, G. S., & Eckerdal, P. (2009). On the role and origin of isochrony in human rhythmic entrainment. *Cortex, 45*(1), 4-17. doi: 10.1016/j.cortex.2008.06.011

Meyer, L. B. (1956). *Emotion and meaning in music*: University of Chicago Press.

Miles, L. K., Nind, L. K., & Macrae, C. N. (2009). The rhythm of rapport: Interpersonal synchrony and social perception. *Journal of Experimental Social Psychology, 45*(3), 585-589. doi: 10.1016/j.jesp.2009.02.002

Molinari, M., Leggio, M. G., De Martin, M., Cerasa, A., & Thaut, M. (2003). Neurobiology of rhythmic motor entrainment. *Annals of the New York Academy of Sciences, 999*, 313-321. doi: 10.1196/annals.1284.042

Molinari, M., Leggio, M. G., & Thaut, M. H. (2007). The cerebellum and neural networks for rhythmic sensorimotor synchronization in the human brain. *Cerebellum, 6*(1), 18-23. doi: 10.1080/14734220601142886

Moors, A. (2007). Can cognitive methods be used to study the unique aspect of emotion: An appraisal theorist's answer. *Cognition & Emotion, 21*(6), 1238-1269. doi: 10.1080/02699930701438061

Moors, A., Ellsworth, P. C., Scherer, K. R., & Frijda, N. H. (2013). Appraisal theories of emotion: State of the art and future development. *Emotion Review, 5*(2), 119-124. doi: 10.1177/1754073912468165

Müller, V., & Lindenberger, U. (2011). Cardiac and respiratory patterns synchronize between persons during choir singing. *PloS One, 6*(9), e24893. doi: 10.1371/journal.pone.0024893

Murray, R. J., Brosch, T., & Sander, D. (2014). The functional profile of the human amygdala in affective processing: Insights from intracranial recordings. *Cortex, 60*(0), 10-33. doi: 10.1016/j.cortex.2014.06.010

Neda, Z., Ravasz, E., Brechet, Y., Vicsek, T., & Barabasi, A. L. (2000). The sound of many hands clapping: Tumultuous applause can transform itself into waves of synchronized clapping. *Nature, 403*(6772), 849-850. doi: 10.1038/35002660

Nobre, A. C., & Rohenkohl, G. (2014). Time for the fourth dimension in attention. In A. C. Nobre & S. Kastner (Eds.), *The Oxford Handbook of Attention*: Oxford University Press.

Nozaradan, S., Peretz, I., Missal, M., & Mouraux, A. (2011). Tagging the neuronal entrainment to beat and meter. *Journal of Neuroscience, 31*(28), 10234-10240. doi: 10.1523/JNEUROSCI.0411-11.2011

Nozaradan, S., Peretz, I., & Mouraux, A. (2012). Selective neuronal entrainment to the beat and meter embedded in a musical rhythm. *Journal of Neuroscience, 32*(49), 17572-17581. doi: 10.1523/JNEUROSCI.3203-12.2012

Nozaradan, S., Zerouali, Y., Peretz, I., & Mouraux, A. (2015). Capturing with EEG the neural entrainment and coupling underlying sensorimotor synchronization to the beat. *Cerebral Cortex, 25*(3), 736-747. doi: 10.1093/cercor/bht261

Nyklicek, I., Thayer, J. F., & van Doornen, L. J. P. (1997). Cardiorespiratory differentiation of musically-induced emotions. *Journal of Psychophysiology, 11*(4), 304-321.

Ochsner, K. N., Knierim, K., Ludlow, D. H., Hanelin, J., Ramachandran, T., Glover, G., & Mackey, S. C. (2004). Reflecting upon feelings: An fMRI study of neural systems supporting the attribution of emotion to self and other. *Journal of Cognitive Neuroscience, 16*(10), 1746-1772. doi: 10.1162/0898929042947829

Overy, K. (2012). Making music in a group: Synchronization and shared experience. *Annals of the New York Academy of Sciences, 1252*, 65-68. doi: 10.1111/j.1749-6632.2012.06530.x

Overy, K., & Molnar-Szakacs, I. (2009). Being together in time: Musical experience and the mirror neuron system. *Music Perception: An Interdisciplinary Journal, 26*(5), 489-504. doi: 10.1525/mp.2009.26.5.489

Paccalin, C., & Jeannerod, M. (2000). Changes in breathing during observation of effortful actions. *Brain Research, 862*(1-2), 194-200. doi: 10.1016/s0006-8993(00)02145-4

Pacchetti, C., Mancini, F., Aglieri, R., Fundarò, C., Martignoni, E., & Nappi, G. (2000). Active music therapy in Parkinson's Disease: An integrative method for motor and emotional rehabilitation. *Psychosomatic Medicine, 62*(3), 386-393. doi: 10.1097/00006842-200005000-00012

Panksepp, J. (1995). The Emotional Sources of "Chills" Induced by Music. *Music Perception: An Interdisciplinary Journal, 13*(2), 171-207. doi: 10.2307/40285693

Patel, A. D., Iversen, J. R., Bregman, M. R., & Schulz, I. (2009). Experimental evidence for synchronization to a musical beat in a nonhuman animal. *Current Biology, 19*(10), 827-830. doi: 10.1016/j.cub.2009.03.038

Paterson, D. J., Wood, G. A., Morton, A. R., & Henstridge, J. D. (1986). The entrainment of ventilation frequency to exercise rhythm. *European Journal of Applied Physiology and Occupational Physiology, 55*(5), 530-537. doi: 10.1007/bf00421649

Péron, J., Frühholz, S., Vérin, M., & Grandjean, D. (2013). Subthalamic nucleus: A key structure for emotional component synchronization in humans. *Neuroscience and Biobehavioral Reviews, 37*(3), 358-373. doi: 10.1016/j.neubiorev.2013.01.001

Phillips-Silver, J., Aktipis, C. A., & Bryant, G. A. (2010). The ecology of entrainment: Foundations of coordinated rhythmic movement. *Music Perception: An Interdisciplinary Journal, 28*(1), 3-14. doi: 10.1525/mp.2010.28.1.3

Phillips-Silver, J., & Keller, P. E. (2012). Searching for roots of entrainment and joint action in early musical interactions. *Frontiers in Human Neuroscience, 6*. doi: 10.3389/Fnhum.2012.00026

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the beat: Movement influences infant rhythm perception. *Science, 308*(5727), 1430-1430. doi: 10.1126/science.1110922

Potter, D. D., Fenwick, M., Abecasis, D., & Brochard, R. (2009). Perceiving rhythm where none exists: Event-related potential (ERP) correlates of subjective accenting. *Cortex, 45*(1), 103-109. doi: 10.1016/j.cortex.2008.01.004

Power, A. J., Mead, N., Barnes, L., & Goswami, U. (2012). Neural entrainment to rhythmically presented auditory, visual, and audio-visual speech in children. *Frontiers in Psychology, 3*, 216. doi: 10.3389/fpsyg.2012.00216

Rameson, L. T., Morelli, S. A., & Lieberman, M. D. (2012). The neural correlates of empathy: experience, automaticity, and prosocial behavior. *Journal of Cognitive Neuroscience, 24*(1), 235-245. doi: 10.1162/jocn_a_00130

Rauschecker, J. P. (2011). An expanded role for the dorsal auditory pathway in sensorimotor control and integration. *Hearing Research, 271*(1–2), 16-25. doi: 10.1016/j.heares.2010.09.001

Rauschecker, J. P. (2012). Ventral and dorsal streams in the evolution of speech and language. *Frontiers in Evolutionary Neuroscience, 4*, 7. doi: 10.3389/fnevo.2012.00007

Rauschecker, J. P., & Tian, B. (2000). Mechanisms and streams for processing of “what” and “where” in auditory cortex. *Proceedings of the National Academy of Sciences, 97*(22), 11800-11806. doi: 10.1073/pnas.97.22.11800

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review, 12*(6), 969-992. doi: 10.3758/bf03206433

Repp, B. H., & Su, Y. H. (2013). Sensorimotor synchronization: A review of recent research (2006-2012). *Psychonomic Bulletin & Review, 20*(3), 403-452. doi: 10.3758/s13423-012-0371-2

Rosenblum, M., & Pikovsky, A. (2003). Synchronization: From pendulum clocks to chaotic lasers and chemical oscillators. *Contemporary Physics, 44*(5), 401-416. doi: 10.1080/00107510310001603129

Ross, J. M., & Balasubramaniam, R. (2014). Physical and neural entrainment to rhythm: Human sensorimotor coordination across tasks and effector systems. *Frontiers in Human Neuroscience, 8*. doi: 10.3389/fnhum.2014.00576

Russell, J. A. (1980). A circumplex model of affect. *Journal of Personality and Social Psychology, 39*(6), 1161-1178. doi: 10.1037/H0077714

Russell, J. A. (2003). Core affect and the psychological construction of emotion. *110*, 145-172. doi: 10.1037/0033-295X.110.1.145

Salimpoor, V. N., Benovoy, M., Larcher, K., Dagher, A., & Zatorre, R. J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nature Neuroscience, advance online publication*. doi: 10.1038/nn.2726

Salimpoor, V. N., Benovoy, M., Longo, G., Cooperstock, J. R., & Zatorre, R. J. (2009). The rewarding aspects of music listening are related to degree of emotional arousal. *PloS One, 4*(10), e7487-e7487. doi: 10.1371/journal.pone.0007487

Salimpoor, V. N., van den Bosch, I., Kovacevic, N., McIntosh, A. R., Dagher, A., & Zatorre, R. J. (2013). Interactions between the nucleus accumbens and auditory cortices predict music reward value. *Science, 340*(6129), 216-219. doi: 10.1126/science.1231059

Salk, L. (1962). Mothers heartbeat as an imprinting stimulus. *Transactions of the New York Academy of Sciences, 24*(7), 753-763. doi: 10.1111/j.2164-0947.1962.tb01441.x

Schachner, A., Brady, T. F., Pepperberg, I. M., & Hauser, M. D. (2009). Spontaneous motor entrainment to music in multiple vocal mimicking species. *Current Biology, 19*(10), 831-836. doi: 10.1016/j.cub.2009.03.061

Schachter, S., & Singer, J. (1962). Cognitive, social, and physiological determinants of emotional state. *Psychological Review, 69*(5), 379-399. doi: 10.1037/h0046234

Scherer, K. R. (2004). Which emotions can be induced by music? What are the underlying mechanisms? And how can we measure them? *Journal of New Music Research, 33*(3), 239-251. doi: 10.1080/0929821042000317822

Scherer, K. R. (2005). What are emotions? And how can they be measured? *Social Science Information, 44*(4), 695-729. doi: 10.1177/0539018405058216

Scherer, K. R., & Coutinho, E. (2013). How music creates emotion: A multifactorial process approach. In T. Cochrane, B. Fantini & K. R. Scherer (Eds.), *The emotional power of music* (pp. 121-145). New York, NY: Oxford University Press.

Scherer, K. R., & Zentner, M. (2001). Emotional effects of music: Production rules. In P. N. Juslin & J. A. Sloboda (Eds.), *Music and emotion: Theory and research* (pp. 361-392). New York, NY: Oxford University Press.

Schmidt-Kassow, M., Heinemann, L. V., Abel, C., & Kaiser, J. (2013). Auditory–motor synchronization facilitates attention allocation. *Neuroimage, 82*, 101-106. doi: 10.1016/j.neuroimage.2013.05.111

Schwartze, M., Keller, P. E., Patel, A. D., & Kotz, S. A. (2011). The impact of basal ganglia lesions on sensorimotor synchronization, spontaneous motor tempo, and the detection of tempo changes. *Behavioural Brain Research, 216*(2), 685-691. doi: 10.1016/j.bbr.2010.09.015

Sebanz, N., Rebbechi, D., Knoblich, G., Prinz, W., & Frith, C. D. (2007). Is it really my turn? An event-related fMRI study of task sharing. *Social Neuroscience, 2*(2), 81-95. doi: 10.1080/17470910701237989

Smith, C. R., & Steinschneider, A. (1975). Differential Effects of Prenatal Rhythmic Stimulation on Neonatal Arousal States. *Child Development, 46*(2), 574-578. doi: 10.1111/j.1467-8624.1975.tb03353.x

Snyder, J. S., & Large, E. W. (2005). Gamma-band activity reflects the metric structure of rhythmic tone sequences. *Cognitive Brain Research, 24*(1), 117-126. doi: 10.1016/j.cogbrainres.2004.12.014

Strack, F., Martin, L. L., & Stepper, S. (1988). Inhibiting and facilitating conditions of the human smile: A nonobtrusive test of the facial feedback hypothesis. *Journal of Personality and Social Psychology, 54*(5), 768-777.

Sumbre, G., Muto, A., Baier, H., & Poo, M. M. (2008). Entrained rhythmic activities of neuronal ensembles as perceptual memory of time interval. *Nature, 456*(7218), 102-U106. doi: 10.1038/Nature07351

Szabo, C. (2006). The effects of listening to monotonous drumming on subjective experiences. In D. Aldridge & J. Fachner (Eds.), *Music and altered states*: Jessica Kingsley Publishers.

Thaut, M., Kenyon, G. P., Schauer, M. L., & McIntosh, G. C. (1999). The connection between rhythmicity and brain function. *Engineering in Medicine and Biology Magazine, IEEE, 18*(2), 101-108. doi: 10.1109/51.752991

Thaut, M., & McIntosh, G. C. (1999). Music therapy in mobility training with the elderly: A review of current research. *Care management journals: Journal of case management; The journal of long term home health care, 1*(1), 71-74.

Thaut, M., McIntosh, G. C., & Hoemberg, V. (2015). Neurobiological foundations of neurologic music therapy: Rhythmic entrainment and the motor system. *Frontiers in Psychology, 5*. doi: 10.3389/fpsyg.2014.01185

Thaut, M., McIntosh, G. C., & Rice, R. R. (1997). Rhythmic facilitation of gait training in hemiparetic stroke rehabilitation. *Journal of the Neurological Sciences, 151*(2), 207-212. doi: 10.1016/S0022-510X(97)00146-9

Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders, 61*(3), 201-216. doi: 10.1016/S0165-0327(00)00338-4

Tierney, A., & Kraus, N. (2013). Neural responses to sounds presented on and off the beat of ecologically valid music. *Frontiers in Systems Neuroscience, 7*, 14. doi: 10.3389/fnsys.2013.00014

Todd, N. P. M., & Lee, C. (2015). The sensory-motor theory of rhythm and beat induction 20 years on: A new synthesis and future perspectives. *Frontiers in Human Neuroscience, 9*(444). doi: 10.3389/fnhum.2015.00444

Trainor, L. J., & Cirelli, L. (2015). Rhythm and interpersonal synchrony in early social development. *Annals of the New York Academy of Sciences, 1337*(1), 45-52. doi: 10.1111/nyas.12649

Trainor, L. J., Gao, X., Lei, J.-j., Lehtovaara, K., & Harris, L. R. (2009). The primal role of the vestibular system in determining musical rhythm. *Cortex, 45*(1), 35-43. doi: 10.1016/j.cortex.2007.10.014

Trost, W., Ethofer, T., Zentner, M., & Vuilleumier, P. (2012). Mapping aesthetic musical emotions in the brain. *Cerebral Cortex, 22*(12), 2769-2783. doi: 10.1093/cercor/bhr353

Trost, W., Fruhholz, S., Cochrane, T., Cojan, Y., & Vuilleumier, P. (2015). Temporal dynamics of musical emotions examined through intersubject synchrony of brain activity. *Social Cognitive and Affective Neuroscience*. doi: 10.1093/scan/nsv060

Trost, W., Frühholz, S., Schön, D., Labbé, C., Pichon, S., Grandjean, D., & Vuilleumier, P. (2014). Getting the beat: Entrainment of brain activity by musical rhythm and pleasantness. *Neuroimage, 103C*, 55-64. doi: 10.1016/j.neuroimage.2014.09.009

Trost, W., & Vuilleumier, P. (2013). ‘Rhythmic entrainment’ as a mechanism for emotion induction and contagion by music: A neurophysiological perspective. In T. Cochrane, B. Fantini & K. R. Scherer (Eds.), *The emotional power of music* (pp. 213-225). New York, NY: Oxford University Press.

Valdesolo, P., & Desteno, D. (2011). Synchrony and the social tuning of compassion. *Emotion, 11*(2), 262-266. doi: 10.1037/a0021302

Valdesolo, P., Ouyang, J., & DeSteno, D. (2010). The rhythm of joint action: Synchrony promotes cooperative ability. *Journal of Experimental Social Psychology, 46*(4), 693-695. doi: 10.1016/j.jesp.2010.03.004

Vickhoff, B., Malmgren, H., Åström, R., Nyberg, G., Engvall, M., Snygg, J., . . . Jörnsten, R. (2013). Music determines heart rate variability of singers. *Frontiers in Psychology, 4*. doi: 10.3389/fpsyg.2013.00334

Vuust, P., & Witek, M. A. G. (2014). Rhythmic complexity and predictive coding: A novel approach to modeling rhythm and meter perception in music. *Frontiers in Psychology, 5*, 1111. doi: 10.3389/fpsyg.2014.01111

Will, U., & Berg, E. (2007). Brain wave synchronization and entrainment to periodic acoustic stimuli. *Neuroscience Letters, 424*(1), 55-60. doi: 10.1016/j.neulet.2007.07.036

Wiltermuth, S. S., & Heath, C. (2009). Synchrony and cooperation. *Psychological Science, 20*(1), 1-5. doi: 10.1111/j.1467-9280.2008.02253.x

Winkielman, P., & Berridge, K. (2003). Irrational wanting and subrational liking: How rudimentary motivational and affective processes shape preferences and choices. *Political Psychology, 24*(4), 657-680. doi: 10.1046/j.1467-9221.2003.00346.x

Winkler, I., Haden, G. P., Ladinig, O., Sziller, I., & Honing, H. (2009). Newborn infants detect the beat in music. *Proceedings of the National Academy of Sciences of the United States of America, 106*(7), 2468-2471. doi: 10.1073/pnas.0809035106

Witek, M. A. G. (2009). *Groove experience: Emotional and physiological responses to groove-based music.* Paper presented at the Triennial Conference of European Society for the Cognitive Sciences of Music (ESCOM 2009), Jyväskylä, Finland.

Witek, M. A. G., Clarke, E. F., Wallentin, M., Kringelbach, M. L., & Vuust, P. (2014). Syncopation, body-movement and pleasure in groove music. *PloS One, 9*(4), e94446. doi: 10.1371/journal.pone.0094446

Womelsdorf, T., & Fries, P. (2007). The role of neuronal synchronization in selective attention. *Current Opinion in Neurobiology, 17*(2), 154-160. doi: 10.1016/j.conb.2007.02.002

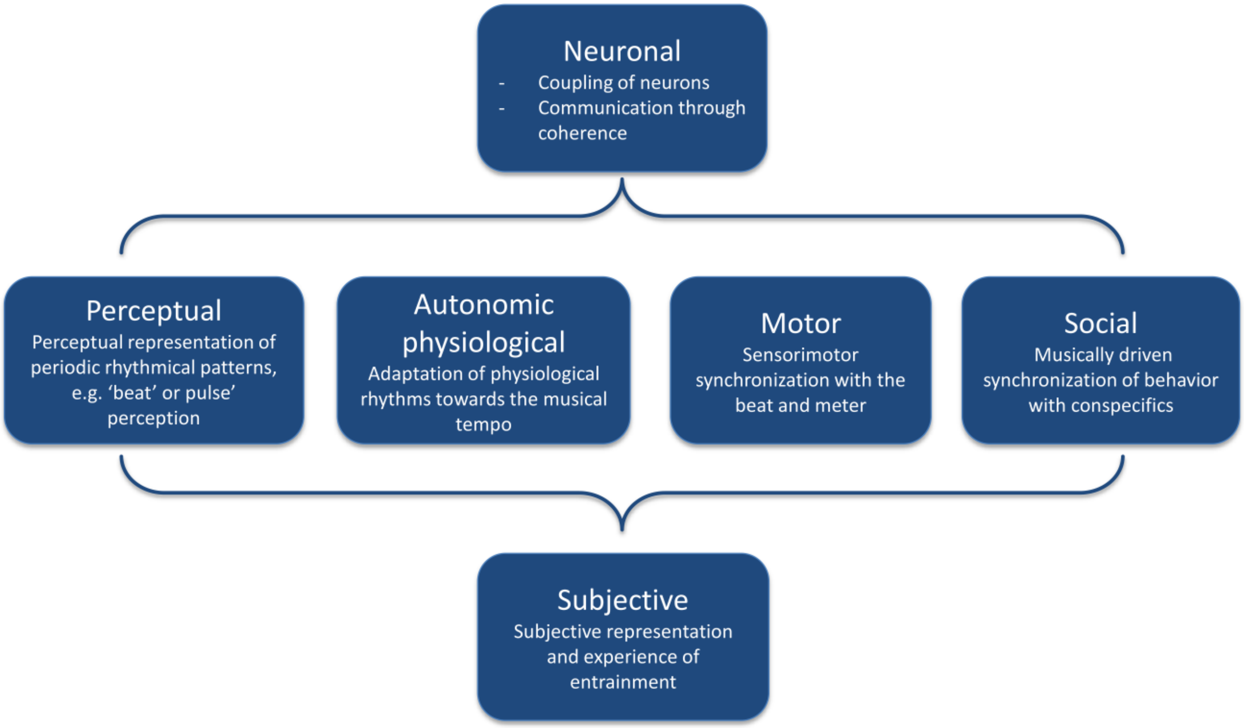
Yun, K., Watanabe, K., & Shimojo, S. (2012). Interpersonal body and neural synchronization as a marker of implicit social interaction. *Scientific Reports, 2*, 959. doi: 10.1038/srep00959

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory-motor interactions in music perception and production. *Nature reviews. Neuroscience, 8*(7), 547-558. doi: 10.1038/nrn2152

Zentner, M., & Eerola, T. (2010). Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences of the United States of America, 107*(13), 5768-5773. doi: 10.1073/pnas.1000121107

Zentner, M., Grandjean, D., & Scherer, K. R. (2008). Emotions evoked by the sound of music: Characterization, classification, and measurement. *Emotion, 8*(4), 494-521. doi: 10.1037/1528-3542.8.4.494

Figure 1. Diagram of the rhythmic entrainment levels and the relationship between them.



Highlights:

- Rhythmic entrainment represents a music-specific affect induction mechanism.
- Rhythmic entrainment occurs on the perceptual, autonomic, motor, and social level.
- The basal ganglia play a key role in the link of rhythmic entrainment and affect.
- Rhythmic entrainment supposedly induces positive valence and social dispositions.