

Faculté de médecine et médecine dentaire

**A cognitive and behavioral study:
Influence of the tempo on the rhythm perception**

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Abstract

Listening to music leads to a spontaneous perception of a periodic pulse-like meter. The study of the rhythm can be performed using repetitive musical sequences. There is evidence that specific neuronal populations oscillate when listening to musical sequences, allowing a selective enhancement of metric periodicities. This cross-cultural ability is a cornerstone for rhythmic musical behavior such as dancing. These meter perception phenomena have been investigated and described but remain largely unknown. Here we explore meter perception from a behavioral and neurocognitive point of view using a novel investigation method, "*the frequency tagging*".

Population (P): The study employs healthy participants, free of neurological or auditory problems. Three rhythmic sequences are presented. Each of these sequences are composed of a repeated complex rhythmic pattern (a musical pattern which doesn't express strong periodicities if played). These rhythmic sequences are varying by their tempo (+ and - 13% from a baseline tempo), with a fast tempo sequence, another medium tempo and finally a slower tempo sequence.

Intervention (I): The experiment consists of a listening part. Where we play rhythmic sequences and record the electroencephalogram (EEG). The second part of the experiment consists of a motor task. The participant has to tap according to his own perception of the beat and meter (combined with his internal perception of the rhythm). The participant's tapping signal is recorded.

Control (C): In the listening and motor parts of the experiment, we compare the perception of meter according to the three tempi using a cross-over block scheme. Each block consists of a set of trials played at similar tempi. Each participant listens and taps in a second part of the experiment according to the sequences of the block corresponding to the three tempi. The order in which each block is presented remains random.

Outputs (O): The study suggests a temporal scaling of the perception of the meter when the tempo varies in a limited amplitude.

The study of the response to small changes in tempo allows us to establish a prototype and to refine our knowledge of the temporal range of the perception of meter. Finally, when the tempo is slightly varied, even in complex musical sequences, the perception of the internal rhythm does not seem to be structurally modified, but there is mostly an adaptation according to the temporal scaling.

Research highlights:

- People are able to find a coherent meter even for complex pattern's sequences.
- The majority of participants tapped three meters per pattern repetition, regardless of the difference in tempo between conditions; people who tap at this rate are classified as *three-tappers*.

- No significant reorganisation was observed by shifting the tempo in a limited range. The adaptation of the tapping interval (i.e. a temporal scaling) remains coherent with the tempo change, and the tempo variation was not sufficient to cause a drift (major structural reorganization) in the participants' perception of the meter.
- Frequencies associated with the meter perception are enhanced on the EEG response spectrum for each of the three tempi. Three-tapper people (the majority) have three meter related frequencies enhanced compared to the non three meter related frequencies on the EEG response spectrum, suggesting the existence of a neural population that selects and enhances some frequencies regardless of the spectrum of an input signal.

1 Introduction

Music is universal and present everywhere in our societies (Lenc, 2021 [1]; Mehr et al, 2019 [2]). The ability to listen to and decode certain aspects of music seems natural to humans. Various aspects of musical composition, such as rhythm and beat, have been studied for a long time. However, the neurocognitive mechanisms underlying this ability remain largely unknown (Phillips, 2005 [3]; 2007 [4]; 2008 [5]).

The study of these underlying processes remains challenging and raises many questions about the brain's mechanisms for decoding music. The study of our intuitive ability to understand aspects such as the meter in a melody shows that it involves several complex mechanisms located in different parts of the nervous system. It is only through the optimal functioning and interaction of these systems that we can appreciate all aspects of a melody and respond appropriately. For example, during a concert, when you are able to clap your hands, or when you dance to the rhythm of salsa. (Savage et al, 2015 [6]; Jacoby, 2017 [7]; Mehr, 2019 [2]).

Across cultures, music seems to share some universal characteristics. Music can be described as a temporal modulation of elements that form sequences that induce a periodic recurrence on a timescale relevant to sensorimotor coordination. A similar simplified schematic representation of music is adopted in the current study, in the form of a repetitive pattern itself made up of a specific sequence of acoustic and silent intervals. (Toiviainen, 2003 [8]; Palmer, 1990 [9]; Hannon et al, 2004 [10]; Agawu and Kofi, 2016 [11]).

This musical structure based on recurrence, used here as a schematisation of the musical sequence, induces the perception of a grouping of nested periodic beats. This human internal representation of these nested periodic beats is considered here as the meter (Honing and Bouwer, 2015 [12], 2018 [13]) fig. [8].

Meter is seen as an essential characteristic of personal mental representation of time in music and rhythmic musical behavior (Burger et al, 2013 [14]; Janata et al, 2012 [15]). This perception of the meter may vary according to the individuals and even if certain recurrences in the perception of the meter is observed, it seems specific to each human.

During previous experiments, researchers realized that even if the musical sequence played lacked recurrent features over time, humans were still able to perceive a stable meter. Allowing an accurate synchronization in periodic sensory motor task according to a personal stable meter (e.g. by moving according to the own perception of a perceived musical pattern) (Su et Pöppel, 2012 [16]; Nozaradan and Peretz, 2012 [17]; Large and Herrera, 2015 [18]; Lenc and Keller, 2018 [19]).

This kind of musical sequence is labeled as *complex*, the elements of sound and silence composing the pattern are arranged in a way to don't express a strong periodic pulse. There are therefore fewer periodic cues within the rhythmic pattern. However, in the sequence blueprint used in this experiment, the sequence is still composed of several cycles of this rhythmic pattern (but the pattern is arranged so as not to be periodic itself). Some musical genres, which are less common in Western areas, use less periodic structures. Despite this, people still seem to be able to recognise the beat and dance to such music (London et al, 2017 [20])!

This ability to perceive the meter when the sequence expresses a strong periodic pulse, or even when the sequence is less regular, seems to be based on phenomena whose mechanisms remain largely unknown. When listening to a sequence composed of strongly periodic features, it seems straightforward to detect the meter. A simple model (but incomplete) could be seen as following neural processes that rely only on the periodic features already present in the musical sequence. The model is based on periodic features coming from the external sequence, exogenous, this type of model is based on regularity detection and refers to *meter extraction* (Kotz and Ravignani, 2018 [21]). However, this exogenous model no longer works when a complex sequence is presented, where periodic features are much less present. Previous studies prove that humans are still able to detect a meter, invalidating the model exclusively based on the exogenous meter extraction, our beat and meter perception is not exclusively based on exogenous periodic features and that the brain is not passively following the input exogenous periodicities (Large et al, 2015 [18]; Lenc et al, 2018 [19]; Nozaradan et al, Nozaradan and Peretz, 2012 [17]; Su et Pöppel, 2012 [16]). The meter extraction model cannot fully explain this meter perception ability.

The previous basic model [1] must therefore evolve in order to become more coherent from a neurocognitive point of view and to overcome the presented previous limit. One hypothesis introduces an active phenomenon in the brain as a neural network of endogenous oscillating neurons. This oscillating neural network could have the ability to extract some periodic cues in a stimulus and synchronise with these exogenous inputs, adding a periodic component to the human internal representation. This remains true even if the exogenous sequence itself is weakly periodic. There is therefore an internal process that allows the perception of the beat even when there are no strong periodic features coming from the exogenous musical sequence (Lenc et al, 2021 [1]). This ability to perceive time and rhythm through complex rhythmic pattern sequences is therefore incompatible with the first hypothesis [1] (of a passive process following exclusively external periodic cues) but can be explained by our ability to perceive, recreate or simply remember musical meter and beat. This is probably made possible by the interaction of a mixture of lower and higher level processes related to the internal representation of meter and sensory input (Todd et al, 2015 [22]; Nozaradan, 2014 [23]; Nozaradan et al, 2018 [24]). For example, the use of less regular structures in music is commonly found across ages and cultures. It

remains compatible with activities requiring periodic rhythmic synchronization such as dancing or listening to music (Agawu, 2016 [11]; London et al, 2017 [20]).

This ability to perceive meter is found in different species, some non-human primates are able to express their understanding and to interact coherently with periodic rhythms when listening to sequences with strong periodicities (Gamez George, 2018 [25]; Zarco Wilbert et al, 2009 [26]). This is also could be present in some mammals and birds (Jao Keehn et al, 2019 [27]; Patel Aniruddh et al, 2009 [28]; Schachner et al, 2009 [29]). This ability to understand rhythmic elements extracted from strongly periodic sequences and synchronizes with their rhythm. This ability is dependent on low-level neurophysiological processes associated with the cochlear system and auditory pathways (Rajendran, 2017 [30]). The ability to synchronize with less periodic patterns is a rare trait, observed only in a select few animals and humans. This implies that this ability necessitates higher-level structures and synchronization mechanisms.

The perception and internal representation of strongly periodic events can be found very early in the human development (Demany et al, 1977 [31]; Trehub & Thorpe, 1989 [32]). This suggest at least a predisposition to the perception of the meter (Lenc et al, 2022 [33]).

In adult humans, there is a strong link between perceiving meter and producing movement (Lenc et al, 2021 [1]), such as dancing or clapping to music. Neurophysiological studies suggest that higher-level brain structures, including the supplementary motor area, thalamic and striatal structures, are involved in regulating movement and other higher-level functions (Grahn et al, 2007 [34]; Claassen et al, 2013 [35]; Ross et al, 2018 [36]; Nozaradan et al, 2018 [37]).

The tempo is a crucial component in the perception of music and meter. It refers to the speed at which the elements of a musical sequence are presented, and therefore influences the perception of the melody's speed. Studies have shown that while the perception of meter and synchronization is specific to everyone, there are still general trends that can be observed. (Nozaradan et al, 2012 [17]). This hypothesis suggests that there may be a preferred time range for perceiving two consecutive meters, leading to the formulation of a preferential range of perception for the meter and beat (Large, 2008 [38]). If the tempo is too fast, even in a sequence expressing high periodicity, some periodic elements will be skipped, and only an integer submultiple of periodicities congruent with the preferred perceptual range of the meter will elicit the perception of that meter, allowing compatible and coherent synchronization of the meter perception with a played pattern. For example, by doubling the tempo of a musical sequence, the perception of the meter will drift to a scheme that skips half of the initial periodicities (Nozaradan et al, 2012 [17]; Large, 2008 [38]; Styns et al, 2007 [39]; Repp et al, 2013 [40]).

However, if the tempo varies within a limited range, a different phenomenon appears to occur. Even if the recurrence is modified in the time scale, as long as it remains within this preferred range, there is no reorganization of the meter perception. Instead, there is a slight temporal scaling, and the perception of the meter will be faster or slower according to the slight change of the tempo of the presented sequence to remain coherent with the modified musical rhythmic pattern. This ensures that perception remains an integer couple of meter inside a rhythmic pattern. This phenomenon is observed and described as temporal scaling (Hassall et al, 2022 [41]) and illustrated fig. [2].

The study aims to investigate the perception of meter when the tempo varies within a limited range. A complex sequence is used to explore the endogenous process (Stupacher Jan and Wood, 2017 [42]).

To capture rapid neural processes that occur repeatedly over time, the electroencephalogram (EEG) is an appropriate investigative method due to its excellent temporal resolution, capable of capturing neural processes at the millisecond level (Luck J, 2014 [43]). Additionally, EEG is more accessible and easier to use compared to other less affordable techniques such as magnetic resonance imaging. In this study, we utilized a novel method, frequency tagging in combination with EEG, to capture the neural processes of interest. The method involves presenting a stimulus that comprises a repetitive pattern, which in this case is an audio stimulus that aligns with the description of the music blueprint mentioned earlier [1].

The neural activity elicited by an audio stimulus consisting of a periodic repetition of a pattern can be captured in the form of multiple *frequency-tagged evoked potentials* observed in the spectrum at the corresponding frequencies of the spectral envelope of the rhythmic stimulus and its subsequent harmonics. (Nozaradan et al, 2011 [44]; 2012 [17]).

The envelope spectrum of the stimulus serves as a marker for the spectrum, enabling us to focus on a limited number of frequencies for studying the neuronal response. The fundamental and harmonics of the stimulus envelope act as markers for the spectrum.

The study of the phenomenon is facilitated by selecting a limited number of frequencies, specifically twelve, which correspond to the fundamental frequency of the rhythmic pattern period and its eleven harmonics.

Research has demonstrated that frequencies associated with meter perception are selectively enhanced compared to non-meter related frequencies (Nozaradan et al, 2011 [44]). Moreover, this phenomenon remains valid even when frequencies are not prominent in the spectrum of the audio sequence envelope (Nozaradan et al, 2012 [17]). This phenomenon demonstrates the presence of an internal nonlinear transformation carried out by neural networks associated with the perception of meter and rhythm (Large, 2008 [38], Nozaradan and Peretz, 2012 [17]).

To explore the perception of the beat from a behavioral dimension, we exploit a secondary process as a motor task (Lenc, 2021 [1]): participant are asked to produce a movement according to his own perception of the beat. The assumption is that beat perception and movement production are linked (Trainor Laurel J et al, [45]; Lenc, 2021 [1]), cortico-subcortical structures are coupled and could play an important role in this phenomenon (Dunn and Lowery, 2013, [46]; Grahn et al, 2009, [47]; Lang and Obrig, 1990, [48]).

Two approaches are used to investigate the internal representation of meter. The first is based on neural representation, and the dynamic fluctuation of the neural population is recorded using EEG. This is complemented by recording the representation of meter based on a secondary process, such as movement production.

Hypothesis

Frequency tagging is used to test whether tempo variation in similar structural stimuli induces a change in the perception of the beat and meter (drift) or if there is an adaptation of the perception of the beat according to the tempo (temporal scaling) [1]. Previous experiments have investigated the perception of meter when the tempo changes drastically. The results showed a drift, which means a readaptation and reorganization of the perception of meter when the tempo was significantly different (doubled or even tripled) (Nozaradan et al, 2017 [49]). Here, we focus on subtle variations to clarify the adaptability and temporal scaling of meter perception, and to explore whether the limits of meter perception, according to temporal scaling, have been reached.

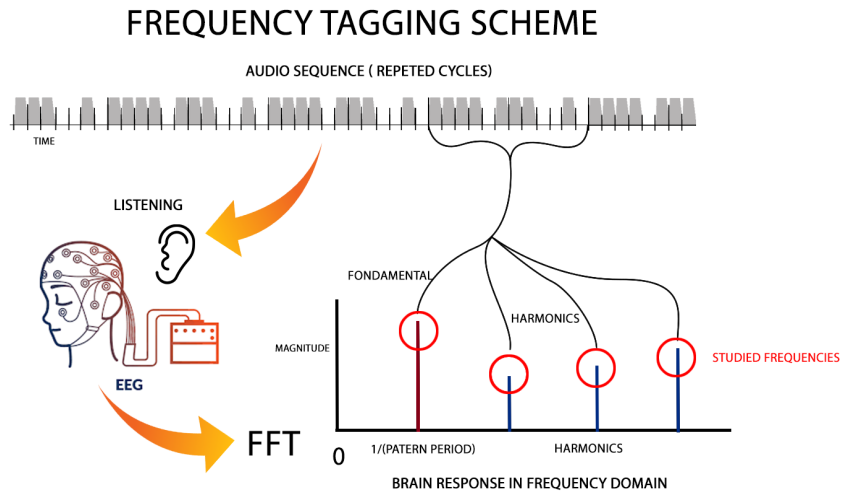


Figure 1: During the listening phase, a periodic pattern is repeated while recording the EEG signal representing the subject's brain response. The signal is then processed and the resulting spectrum displays the energy distribution at each frequency. Within a given frequency range, certain frequencies are distinguishable and can be analysed based on various parameters. These parameters include the perception of the beat and the meter, which are determined in the second phase of the experiment.

This study explores the variation in neural and behavioral responses to small changes in tempo using frequency tagging coupled with EEG on healthy individuals. The main research hypothesis is based on the four hypotheses described above, some of which are tested and discussed in this study.

1. Healthy individuals have an innate ability to perceive rhythms, allowing them to detect and maintain beat and meter even when the sequence is only weakly periodic (Large et al, 2015 [18]; Lenc et al, 2018 [19]; Nozaradan et al, 2012 [17]; Su and Pöppel, 2012 [50]).
2. The capacity to perceive meter is linked to the cerebral structures involved in movement production [1]. In our experiment, this will be exploited in the motor task where participants are asked to tap on a box according to our own perception of the meter (Lenc et al, 2021 [1]).
3. A third hypothesis relates to the preferred range of perception of the bar. By modifying the tempo, it will be possible to determine whether this limit is reached and whether it is common or specific to individuals. However, as the variation in tempo is small, an adaptation of the perception of the meter is expected (Large, 2008 [38]). This temporal scaling is labelled as an adaptation of the meter perception according to the variation of the tempo fig.[2].

4. Finally, it is assumed that the endogenous cerebral processes operate a non-linear transformation at the frequencies and harmonics linked to the input sequence and that the frequencies corresponding to the perception of the meter are selectively enhanced (Nozaradan et al, 2018 [37]). There is a meter related frequencies enhancement on the EEG response spectrum to a played rhythmic pattern sequence fig. [3].

ILLUSTRATION OF THE METER PERCEPTION RANGE

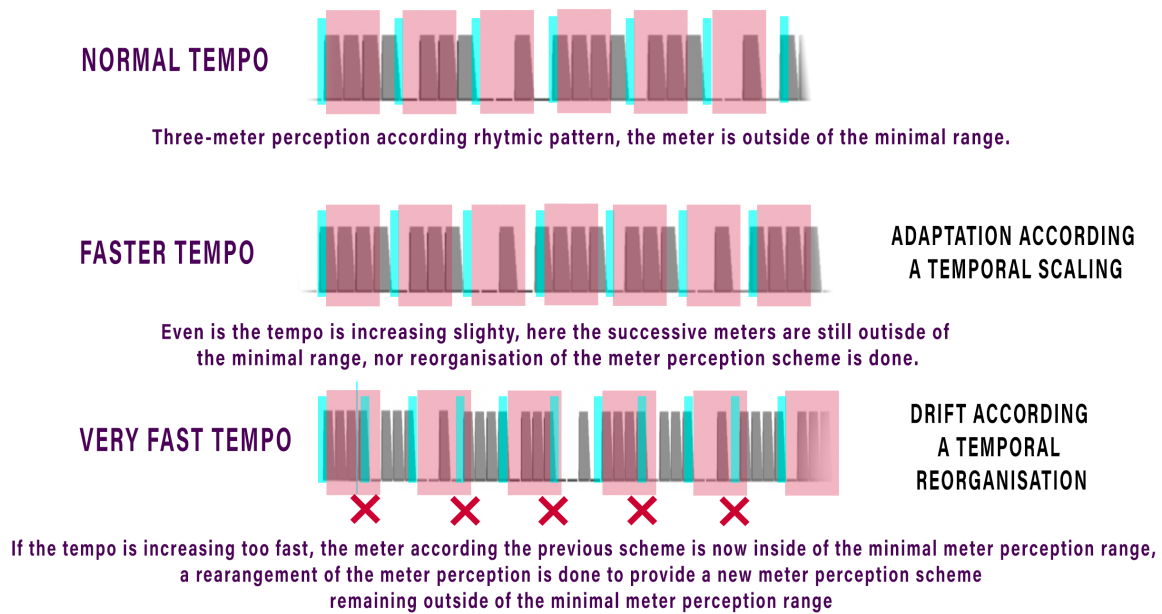


Figure 2: The sequence is displayed at three different tempi. The cyan line represents a theoretical perception of the meter, while the red boxes represent the minimum range between the perception of two successive meters. In the top example, the perception of the meter remains outside the minimum range between two consecutive meters. In the middle example, despite the faster tempo, the meter perception remains outside the minimum range. The scheme for perceiving meter can follow the same structure as the rhythmic pattern. At the fastest tempo, the perception of meter according to the normal tempo scheme is limited. To address this issue, human perception reorganises by skipping some of the meters compared to the meters elicited in the normal tempo when the tempo becomes too fast. To resolve this singularity, we will reorganise the perception of the meter by skipping every second meter according to the initial arrangement. This will reduce by half the number of meters related to the rhythmic pattern. This bypass will allow us to recover a time between the perception of two successive meters outside the minimum range.

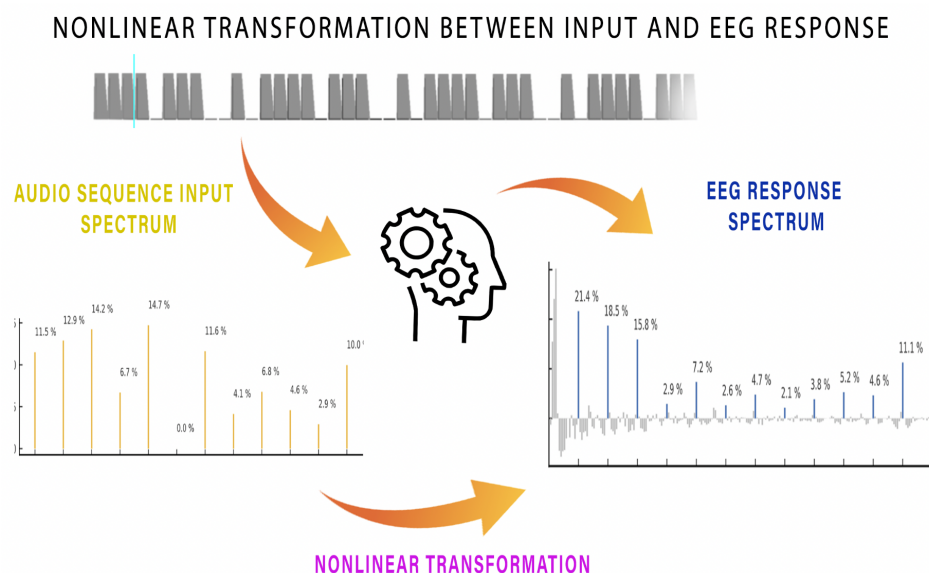


Figure 3: Diagram showing the non-linear transformation phenomenon operated by the brain, which allows certain specific frequencies to be enhanced independently of the spectrum of the input sequence.

It has been shown that when a human listen to a rhythmic stimulus which induces a perception of the meter [4], the neuronal response elicited is selectively enhanced at the frequencies related to the perception of the meter (Tal Idan et al, 2017 [51]; Nozaradan et al, 2017 [49]; Nozaradan et al, 2017 [52]; Nozaradan et al, 2018 [37]; Nozaradan et al, 2012 [17]; Lenc et al, 2020 [53]; Nozaradan, 2014 [54]). Moreover, these frequencies linked to the perception of the meter are still enhanced, even when the frequencies linked to the perceived meter are not prominent in the input stimulus (a musical sequence for example).

The selective enhancement of certain frequencies cannot be entirely explained by the physical structure of the input, and there would be endogenous non-linear processes (Lenc et al, 2018 [33], Sifuentes et al, 2021 [55]; Tal, 2017 [51]; Nozaradan et al, 2018 [37]; Nozaradan et al, 2017 [49]) (Nozaradan et al, 2018 [24]; Lense et al, 2021 [56]).

In addition, this experiment could provide further evidence of our endogenous ability to perceive the meter using audio sequences consisting of a repetition of complex patterns.

This evidence could point towards a model of meter perception (Van Bree, et al, 2021 [57]; Doelling et al, 2019 [58]) because the perception of the meter is not totally explained by the physical elements contained in the input, but that there is also a higher level cerebral elaboration involved in this task.

2 Material and methods

2.1 Participants

Twelve healthy volunteers, consisting of 6 males and 6 females, of which 10 were right-handed and 2 were left-handed, participated in the study after providing written consent. One participant was excluded due to a technical problem before the experiment. The experiment allowed any level of musical or dance ability, which was assessed through a questionnaire administered alongside of the manipulation. Participants had to be psychologically healthy and free of any brain pathology that could affect their hearing ability. They also had to be naive to the experiment, with no prior experience in similar musical rhythm studies. Additionally, they were asked not to be under the influence of any drugs or other substances that could affect perception and cognition. All participants were required to be free of any reported psychological, neural, or auditory diseases. Additionally, none of the participants were under the influence of drugs or psychotic substances during the experiment. The study received prior approval from the UCLouvain Bioethics Committee.

2.2 Auditory stimulus

The experiment involved presenting the participant with three different stimuli that only varying by the tempo. The structure of the sequence presented as a stimulus remained the same for all three stimuli. Each stimulus consisted of a periodic rhythmic pattern that repeated seventeen times. The pattern's rhythm consists of a sequence of sound and silence events. The duration of each event varies with the sequence's tempo but remains constant within the sequence (175 ms for fast tempo, 200 ms for medium tempo, 225 ms for slow tempo). Each sound element is composed of pure tones at 440 Hertz. The sequence includes a slow, medium, and fast tempo stimulus, which is achieved by altering the presentation time of the elements. The sequence includes a slow, medium, and fast tempo stimulus, which is achieved by altering the presentation time of the elements. The duration of the complete rhythmic pattern sequence stimulus varies depending on the tempo: 45.9 seconds for slow tempo (with a 10 ms rise and 50 ms fall time), 40.8 seconds for medium tempo (with a 10 ms rise and 45 ms fall time), and 35.7 seconds for fast tempo (with a 10 ms rise and 40 ms fall time).

RHYTHMIC PATTERN

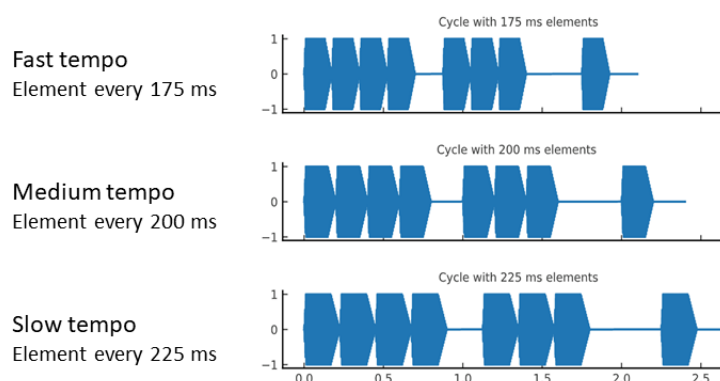


Figure 4: This is a representation of the cycle pattern that consists of twelve elements of sound and silence arranged at regular intervals. The elements in this pattern are not arranged periodically, resulting in a complex sequence when played repeatedly. This sequence expresses little periodicity. The diagram displays three patterns, each representing a different tempo. The top pattern corresponds to a fast tempo, lasting 2.1 seconds, the middle pattern corresponds to a medium tempo, lasting 2.4 seconds, and the bottom pattern corresponds to a slow tempo, lasting 2.7 seconds. These patterns will be used in the listening and behavioral tapping phases of our experiment.

RHYTHMIC SEQUENCE

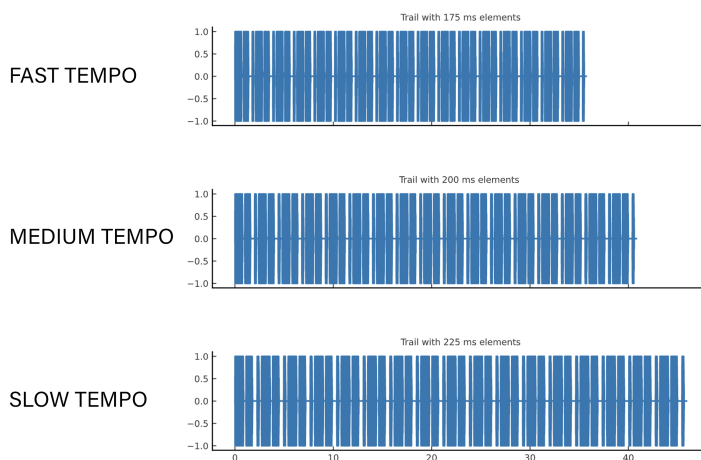


Figure 5: Representation of the entire sequence that was presented to the participant during the listening and tapping tasks. The sequence consists of 17 repetitions of the rhythmic pattern fig. 4. The duration of the task varies depending on the tempo: fast tempo for the top, medium tempo for the middle, and slow tempo for the bottom.

The rhythmic pattern generated for this experiment is labeled as complex (sometimes

labeled as *syncopated* in the literature). Even when the rhythmic pattern is looped within the sequence, the arrangement of the events that make up the rhythmic pattern itself is not strongly periodic and does not provide cues for meter and beat perception [6]. Furthermore, it reduces the impact of external periodicities on the analysis of the EEG spectral response at frequencies that correspond to the stimulus envelope. This is achieved by minimizing the overlap between the fundamental periodicity of the spectral envelope and certain harmonics, which are also linked to the EEG response. When a complex rhythmic pattern sequence is played, it does not express a strong periodicity at regular intervals and therefore does not provide beat cues that could potentially influence the participant's perception of the meter. This makes it suitable for exploring endogenous beat perception.

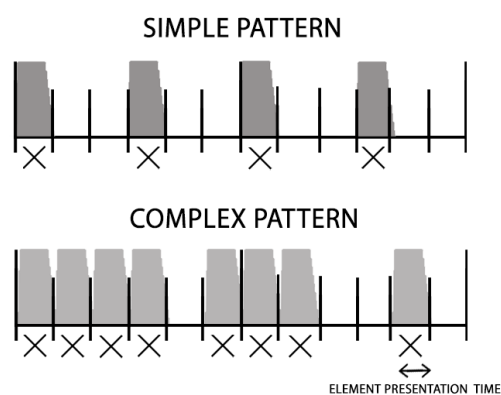


Figure 6: Comparison of simple and complex patterns. Above, the simple rhythmic pattern has a pronounced periodicity during the rhythmic pattern, this elicits a strong beat detection by a listener. In contrast, the complex pattern expresses periodic cues with less prominence or not at all, due to the weak periodicity of its elements.

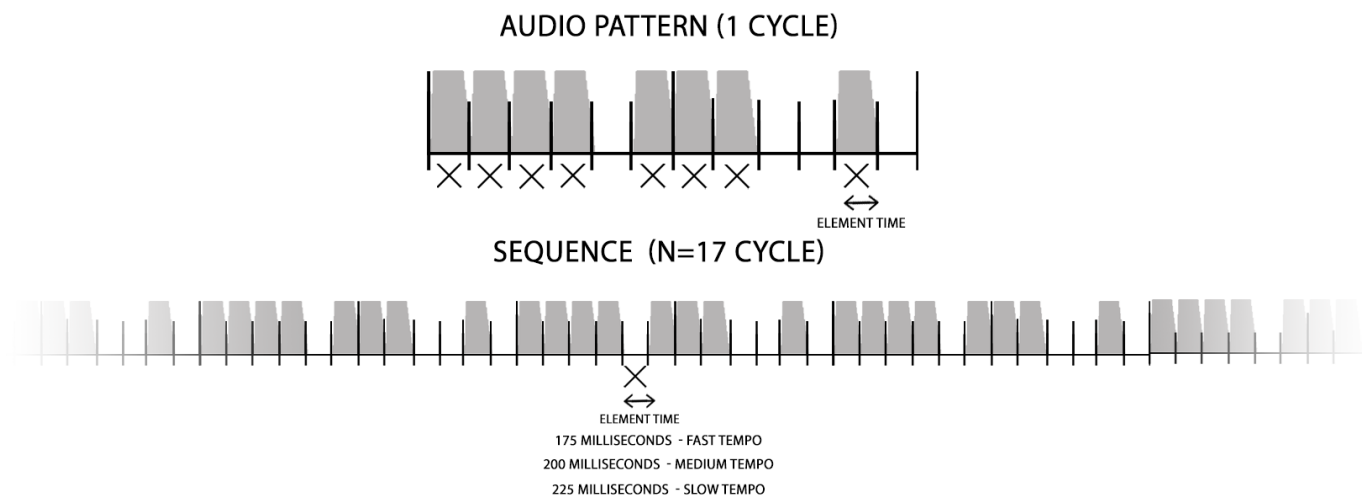


Figure 7: Top: The rhythmic pattern consists of twelve elements made up of pure tone signals at 400Hz. The arrangement of the pattern does not create strong periodicities when heard. Bottom: The rhythmic pattern is repeated to form a sequence. In each trial, the presented sequence is composed of seventeen repetitions of the pattern.

With the presented pattern, participants can perceive several consistent meter perceptions (an integer number of meters per rhythmic pattern) such as a binary perception (two beats per rhythmic pattern). Additionally, a ternary or quaternary perception of the meter is possible if the rhythmic pattern is composed of twelve elements [8]. Because these multiple tapping possibilities remain coherent, this complex rhythmic pattern is referred to as *metrically ambiguous* (Phillips-Silver and Trainor, 2005 [59]).

TAP PATTERN OVER 1 PERIOD

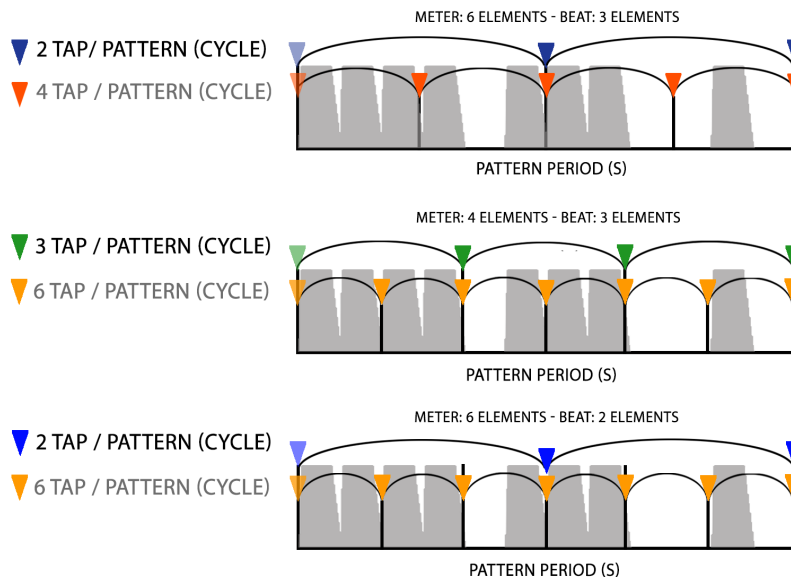


Figure 8: Illustration of the various methods of tapping and perceiving meter and beat in relation to the chosen rhythmic pattern in the experiment. The rhythmic pattern consists of twelve elements, and it is possible to perceive different meters and beats while remaining consistent with the pattern. It is possible to perceive two meters (blue triangle), three meters (green triangle), four meters (orange triangle), or six meters (yellow triangle). Some of these ways of perceiving the meter for sequences consisting of a repetition of these rhythmic patterns are observed in the experiment.

The auditory stimulus was created with audacity 1.2.6 (<http://audacity.sourceforge.net/>) and presented during the experiment binaurally through adapted earphones at a fixed level of sounds between participants, set at a comfortable hearing level. The auditory stimulus are presented using in ear earphones compatible with the EEG, ER-2 Tubal Insert Earphones by Etymotic (United States Of America), 16 kHz bandwidth, 10 Ohms Impedance (<https://shop.neurospec.com/er2-tubal-insert-ear-phones>).

2.3 Experimental procedure

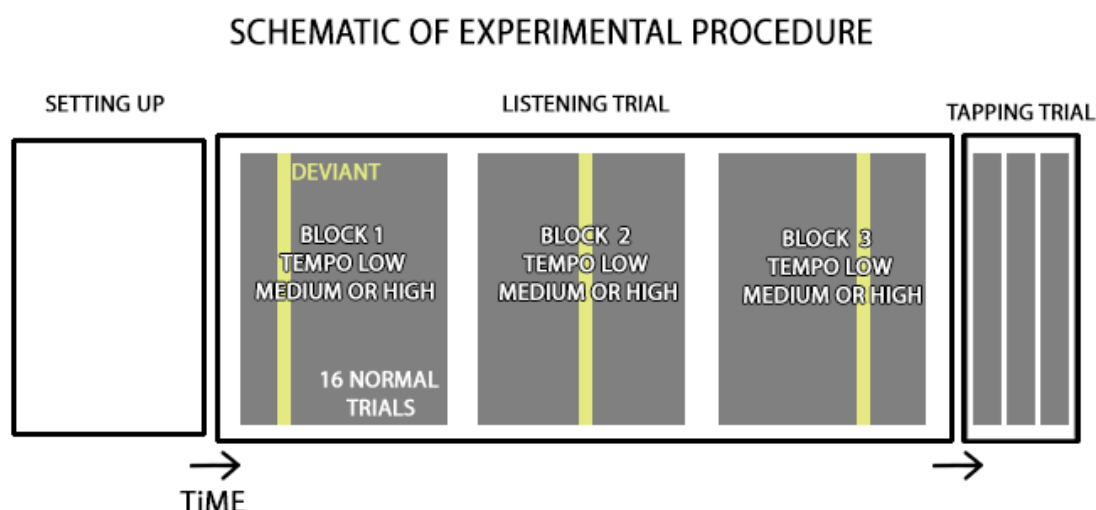


Figure 9: This is a diagram of the experimental procedure. On the left, preparation phase for the experiment, including checking the cabling and topology, explaining the guidelines to the participant, and installing the participant and EEG equipment. On the middle, listening trial divided into three blocks, each containing sixteen audio trials of the same tempo per block, and an additional deviant trial (in yellow) that serves as a detection task for the participant. The order of tempi for each block is randomly selected from three available options, with no repetition of the selected tempo between blocks. The three tempi are played, but the order may differ. On the right, the tapping trial is used as a behavioral task to detect the participant's perception of the meter. There are three blocks of two trials each, with the tempo in each block also randomly chosen without repetition.

The experiment consists of two phases. The first phase involves listening to a stimulus, while the EEG is recorded. The second phase is a behavioral motor task, where the participant taps on a tapping box according to their perception of the beat induced by the presentation of the complex rhythmic pattern sequence.

MONTAGE DIAGRAM

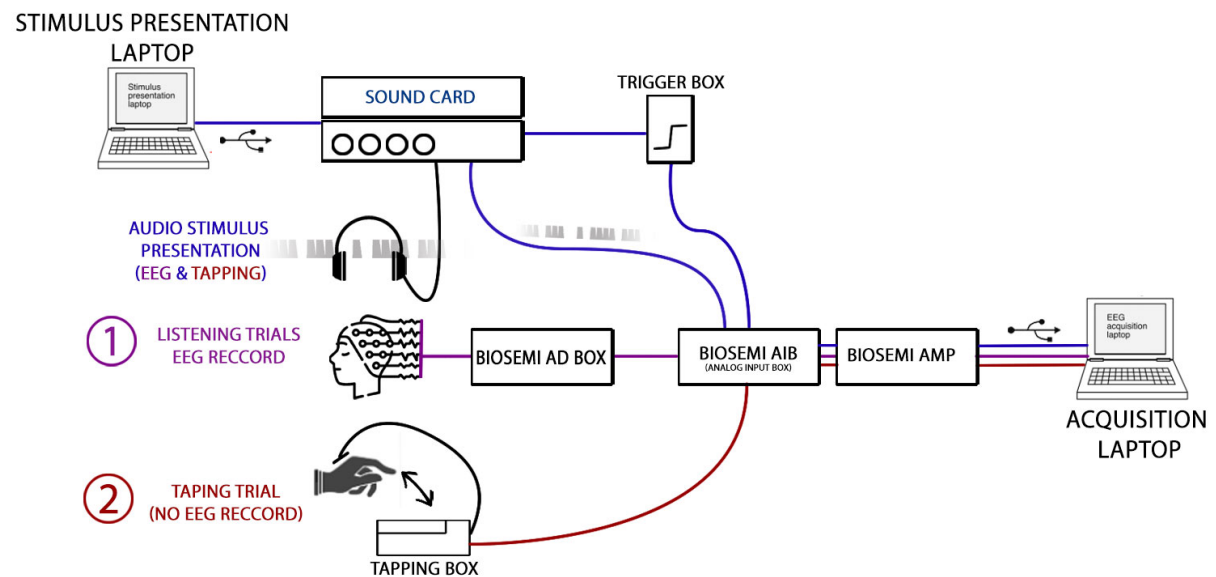


Figure 10: Illustration of the experimental setup, the laptop presentation stimulus drives the entire experiment. Data acquisition was performed using the Biosemi Box, which facilitated EEG recording during the first listening phase and tapping recording during the second behavioral phase.

The listening task is composed of three blocks, each corresponding to a different tempo. The sequences at these three different tempi are presented sixteen times as a block scheme, with each block corresponding to the slow, medium, and fast tempo sequences. The order in which the blocks are presented is randomized.

LISTENING TASK AND ANALYSIS

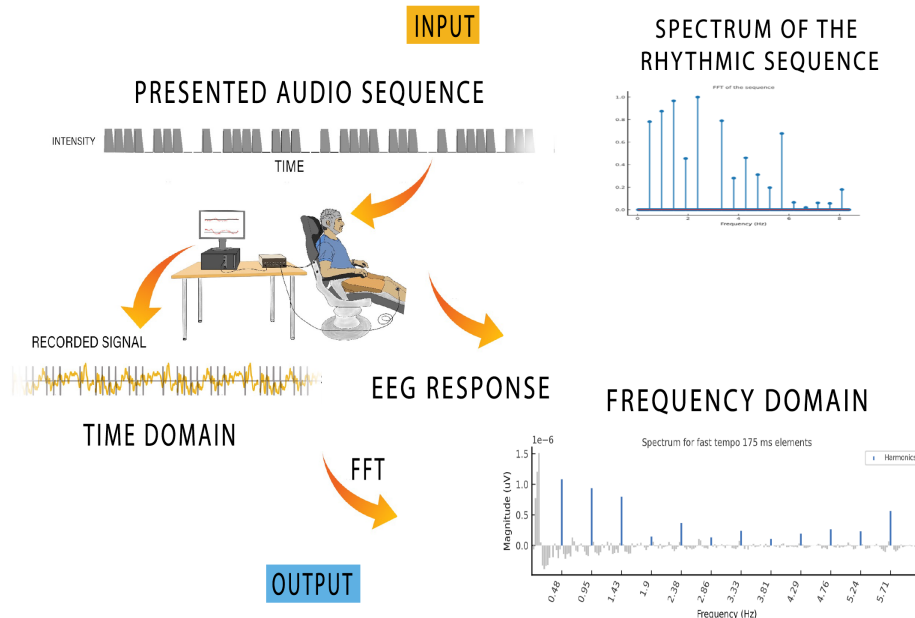


Figure 11: Listening Trial: The participant is instructed to remain still and focus on a fixed point while carefully listening to a sequence (top). While listening, the participant's response is recorded using EEG (mid). Three sequences are presented at varying speeds, with each sequence played sixteen times at the same tempo (bottom). The signal is recorded, processed, and divided into epochs for further analysis. This allows for exploration of the impact of different tempi and the endogenous representation of the pattern in relation to the information provided by the second step of the experiment.

A fixation task is performed using an additional deviant sequence. The tempo within the played rhythmic pattern sequence varies in this deviant sequence. The variation in tempo is minimal within a single rhythmic pattern in the entire sequence, requiring the participant to maintain focus to detect any shift in tempo (Lakatos et al, 2008 [60]). The fixation task is used here to increase the participant's attention during the listening session. The deviant sequence has a structure similar to the classical sequences, except for a single rhythmic pattern with a different tempo compared to the other rhythmic patterns that comprise the sequence. This shift in tempo within the rhythmic pattern is subtle and challenging to perceive, necessitating sustained attention to the audio-musical stimulus being played. The participant is instructed to systematically report any perceived change in tempo at the end of each trial of the listening sequence. The results of the three deviant trials (one per tempo) are excluded from further analysis.

DETECTION TASK

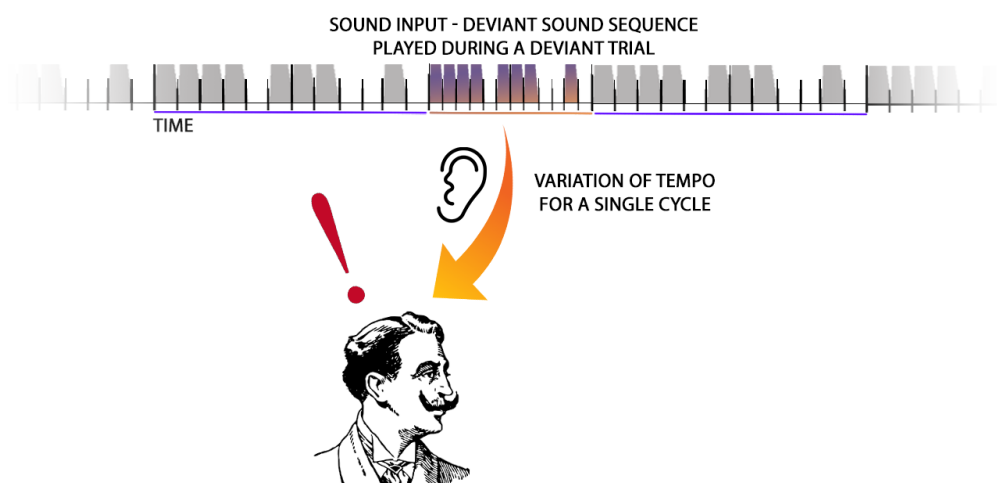


Figure 12: Illustration of the deviant sequence: The tempo within the sequence varies on a single cycle pattern, while the rest of the sequence remains identical to classical sequences. After the sequence presentation, the participant is asked to report whether they detected a tempo variation in the sequence played.

The presentation sequence for each participant follows a block crossover scheme between tempi. This limits any potential systematic bias across participants that could be induced by a predetermined and non-random order of stimulus presentation.

The experiment's second phase involves a behavioral tapping task.

Like the listening trial, the tapping trial is divided into three blocks, each corresponding to a tempo. The stimulus in each block is presented twice, resulting in a total of six stimuli at three tempi. As with the listening phase, each block is presented to the patient in a random order.

The task requires the patient to tap on a tapping box according to their internal perception of the meter. The participant can tap with their preferred hand. During this task, the EEG is no longer recorded, and the participant is free to move to feel the meter in the presented rhythmic pattern sequence. Tapping is recorded when a current loop is closed by contact with the tapping box and an electrode on the back of the tapping hand.

The experimenter remains in the room with the participant, out of sight. The experimenter's role is to set up the equipment correctly, guide the participant through the experiment, explain the procedure correctly, explain the expected task, and ensure good compliance (and moral support) throughout the process. It is important to make the listening and tapping trials as natural as possible for the participant and avoid any external influence except the played sequence.

2.4 EEG recording

The EEG is recorded during the listening trial and the stimuli are presented as a block pattern. While the EEG is being recorded, the participant is seated as relaxed as possible in a chair with a support to rest the head and avoid unnecessary movements of the legs or arms. During stimulus presentation, the participant should avoid moving his/her eyes and maintain a fixed target in front of them [9]. During the trial, participants are permitted to blink. They may also move, talk, or look away between trials, which typically last about one minute depending on the speed. EEG recordings are taken using 64+2+1 active Ag-AgCl electrodes placed on the scalp according to a 10/10 system (Biosemi, Netherlands). Two additional electrodes are added at mastoid level to monitor the voltage in the neck. The electrodes have a maximum impedance of 300 MOhm. The signal was recorded using active electrodes with a central reference. It was then amplified, filtered with a low pass at 500 Hz, and digitised with a sampling frequency of 10KHz. During the second part of the experiment, the EEG is no longer recorded when the participant performs the motor task.

2.5 Motor task recording

Hand movements are recorded using a custom-made box. An electrode is placed on the back of the hand and connected to the tapping box. When the participant taps on the metal part of the box provided for this purpose, a current loop is closed, which is detected. The signal generated by the box is recorded using an additional channel of the EEG recording system. [10].

2.6 Sound pattern analysis

Frequency tagging involves performing frequency domain analysis on a limited set of relative frequencies. To determine these specific frequencies, reference frequencies are taken from the input stimulus for further analysis of the EEG elicited response. Tuning the tempo also tunes the elicited frequencies, and the analysis locations on the frequency spectrum are specific to the tempo.

Three positions on the spectrum are used to study the response, depending on whether the slow, medium or fast tempo is being examined. The temporal envelope of the stimulus is extracted using a Hilbert transform. After removing the carrier frequency, the temporal signal is transformed into the frequency domain using a discrete Fourier transform (Frigo and Johnson, 1998, [61]), giving a magnitude of the spectral response of the temporal signal corresponding to the waveforms of the input stimulus.

The frequencies of interest are limited to low frequencies, because the meter is a very low frequency phenomenon (around a single hertz). Therefore, we have selected the first 12 spikes that correspond to frequencies of less than 4.45 Hz for slow tempo, less than 5 Hz for medium tempo, and less than 5.72 Hz for fast tempo.

The study analysed twelve different frequencies within the given range, from 0.476 Hz (fundamental) to 5.71 Hz (11th harmonic), corresponding to the duration of the rhythmic pattern and the period of a single event, respectively. The frequency range for Medium tempo starts at 0.416 Hz, which corresponds to the duration of the rhythmic pattern, and goes up to 5.00 Hz, which corresponds to the period of a single event. The interval between frequencies is fixed at 0.416 Hz. For Slow tempo, the frequency range starts at 0.37 Hz, corresponding to the duration of the rhythmic pattern, and goes up to 4.44 Hz, which corresponds to the period of a single event. The interval between frequencies is fixed at 0.37 Hz.

Based on a ternary interpretation of the rhythmic pattern (based on the majority tapping trend of the tapping task in this experiment and previous similar experiments (Nozaradan et al, 2012 [17])), certain frequencies are associated with the meter. Out of the 12 selected frequencies, the 3rd, 6th, 9th, and 12th frequencies correspond to the frequency of meter perception, the first and second harmonics, and the unit event, respectively. The remaining frequencies are complementary (1-2-4-5-7-8-10-11th frequencies). (Nozaradan et al, 2012 [17]). The principle remains the same for all three tempi: For each frequency, we can obtain a Z score by using the magnitude of the twelve selected frequencies in the envelope spectrum of the rhythmic pattern. This Z score indicates the distance of a frequency from the average of all frequencies. The Z score is obtained as follows: $z = ((x - \mu)/\sigma)$, where μ and σ correspond respectively to the mean and standard deviation of the magnitudes obtained between the different peaks on the spectrum. This procedure quantifies the contribution of each frequency to the final spectrum. The distribution of energy in the spectrum of the audio stimulus is used as an example, as similar quantification is employed to describe the new distribution of energy in the EEG response at these same frequencies [2.7]. By comparing the contribution of each frequency to the total spectrum, it is possible to compare the presented signal with the signal obtained via EEG. Additionally, it allows for a comparison between the metered and non-metered frequencies.

2.7 EEG analysis

The successive stages of EEG signal analysis are processed using a recently developed data analysis informatics pipeline (Cools, 2022 [62]).

The EEG data were pre-processed as follows: First, the data were epoched to -3 s to the stimulus duration, with +35.7 s for fast tempo, +40.8 s for medium tempo, and +45.9 s for slow tempo, according to the onset of the stimulus. Next, the epochs were filtered using a 4th order Butterworth passband filter from 0.1 to 30 Hz to remove slow drift, industrial, and parasitic high-frequency noise. The segment is downsampled by a factor of 2, resulting in a 1024 samples/second downsampled segment. This allows for faster computation and reduces computer memory requirements. The DC signal has been removed to center the mean amplitude around zero. The bad electrodes are removed after visual inspection. Eyes blinks and other parasitic signals are removed using an

independent component analysis (ICA) (Te-Wo et al, 1990, [63]) and visual inspection of components corresponding to artifact or useless signals.

For each participant and condition, the epochs between trials are averaged. This time-domain averaging removes statistical noise and eliminates random, non-stationary and non-periodic phenomena, and maximizes the *signal to noise ratio* (SNR) of steady stable and phase-locked processes driven by the stimulus.

To obtain the spectrum of the EEG signal, the segment from the beginning of the second rhythmic pattern to the end of the stimulus (17th repetition of the rhythmic pattern) was truncated. This was done to avoid edge effects and to favour the continuous signal over the onset of EEG activity. The time domain averaged signal was then transformed to the frequency domain using a Fast Fourier Transform (FFT) algorithm (Lerud et al, 2014, [64]) yielding a spectrum signal with a resolution of 4 mHz. The application of the Fourier transform to the long time epoch is motivated by the gain in resolution in the spectral domain and the assumption that beat perception remains sufficiently stable across trials, as suggested by the results of the tapping trials [3.2]. To lower the noise (and increase the SNR), the spectrum is filtered using a convolution kernel subtracting at each frequency bin the average of neighbor's bin amplitudes 13 (Picton et al, 2003 [65]). This highlights the significant periodic frequencies in a local range of nearby frequencies and reduces the frequencies considered as noise (which, from a stochastic point of view, has the same average as the average of its neighbours). The kernel filters out stochastic cross-frequency noise and enhances steady, stable periodic components. Filtering is necessary to compare frequencies at different points in the spectrum, remove the tendency of natural decay to follow a 1/f function, and eliminate low-frequency artifacts inherent in any biological signal (Ward, 2001 [66]).

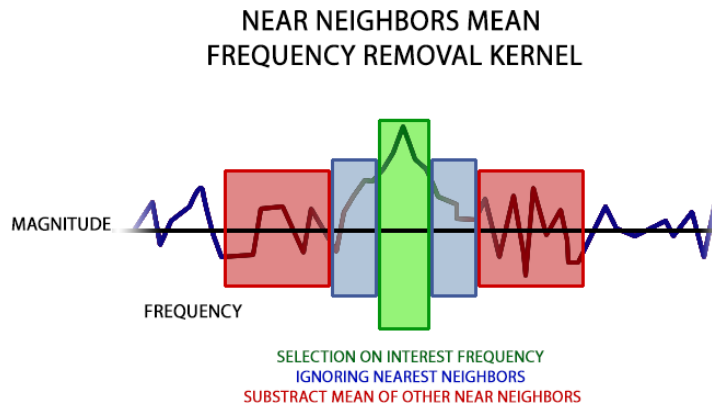


Figure 13: Illustration of the kernel used to filter the signal in the frequency domain. The kernel suppresses the stochastic signal present in all signals and is also a local filter that considers the spectral trend. This text describes the kernel used to filter signals in the frequency domain. In biological signals, the spectral trend is approximated by a decaying function in $1/f$. The kernel is applied to the entire spectrum using a convolution function, which highlights non-randomly distributed frequencies. The philosophy behind this spectrum is to select a main frequency (green) and suppress the average signal from its N nearest neighbours (red), while maintaining a margin between the selected signal and the nearest neighbours to avoid being influenced by spectral leakage (a signal of interest spread over several contiguous frequencies). Applying this type of filter improves signal-to-noise ratio (SNR), eliminates random effects, and expresses steady and stable processes in the spectrum.

2.8 Motor task analysis

The tapping signal recorded by the tapping box is processed to remove the initial taps and retain only the stable harmonic and most stable part of the tapping sequence. The Inter Tapping Interval (ITI) is then calculated based on the time between taps, and the tapping frequency is determined [3.2]. After processing the frequency, the tapping trials of participants with two, three or four metrics can be classified, and bad metrics can be detected and classified.

The classification is based on the maximum similarity to one of the tapping metric models mentioned above. For each potential tapping, which corresponds to an entire sub-period of a rhythmic pattern, a theoretical ITI is calculated, and the model with the maximum homology is selected using an argmax function (Gange et al, 2020, [67]). Finally, the tapping trial is labeled according to the best-fitting model. [3.2].

The bad tappers are tapping out of sync with the rhythmic pattern. The bad tapping period is not an integer sub-multiple of the rhythmic pattern period. This has resulted in a shift between the rhythmic pattern and the tapping, causing them to fail the synchronicity task and find an appropriate and coherent meter between the sequence played and the tapping rate expressed. This classification is made using cyclomatic algebra, where the stability between the tapping period and the rhythmic pattern period can be interpreted,

highlighting any potential shift between tapping intervals and a fixed periodic cycle [3.2].

A chi-squared test can be used to examine the distribution of the proportion of bad trials across different speeds. To test whether there was a difference in the distribution of bad trials based on speed, a significance level was set at $p < 0.05$ [3.2].

After excluding the bad tapping trials, the distribution of the tapping profile with respect to the three speeds was examined using the Chi-square test. The significance level was set at $p < 0.05$. The trials were classified according to tapping behaviour [3.2].

The major tapping profile is selected from the labeled and cleaned data. It is important to note that the tapping trial is linked to meter perception [2].

The study calculates and compares the ITI variability of the majority meter's perceptual profile across three tempi. As the tempi induce a constitutional temporal variability, a relative ITI variation is used for comparison. The ITI variability between the tempi is analyzed using a one-way ANOVA with a significance level of $p < 0.05$ [3.2].

2.9 Topographical distribution of the frequency tagging signal

Frequency tagging responses for audio tasks studying rhythm are thought to be located in frontocentral areas (Cirelli et al, 2016, [68]). A topographic analysis was performed for each selected frequency at each of the three tempi across all participants. The topographic magnitude was processed using spherical interpolation based on the average acquisitions for each tempo per participant. The topographic magnitudes among participants, frequencies, and experimental conditions (tempo variation) were averaged and normalized using a minimum corresponding to the lowest amplitude and a maximum corresponding to the highest amplitude. This grand averaging eliminates any electrode selection bias.

A subset of nine electrodes expressing the largest amplitudes of the magnitudes on the averaged map is selected by choosing a region of interest. The selected subset of electrodes (F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2) corresponds to the central frontal region and the supplementary motor area. Electrode selection should be based on an average of all three tempi to avoid favouring a specific experimental condition. It is important to keep in mind that the average map is based on a spherical brain model, which does not accurately represent the complexity of cerebral circonvolutions. Therefore, the areas that appear to be more active may actually correspond to the activity of the temporal lobes, which represent a spatial tangent. As a result, the extrapolated electrical activity can also be expressed in this area, as well as by the dipole, which expresses the complement of the response recorded by the mastoid electrodes.

2.10 Statistical analysis

The statistical analysis is carried out using python (3.10) using the SciPy package (Virtanen, Pauli and Gommer, 2020, [69]).

The choice of electrode pool was based on several parameters in order to avoid electrode selection bias. Amplitudes were normalized for each of the 3 conditions (slow,

medium,fast tempo), between frequencies and between participants on an average mapping.

Electrodes are selected on the basis of the electrodes expressing the highest amplitudes, the choice is also based on the literature.

TOPOLOGY OF SIGNALS AND SELECTED ELECTRODS

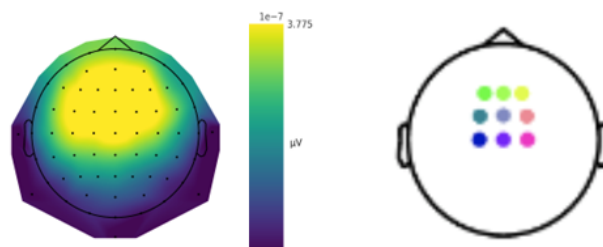


Figure 14: On the left, there is a representation of the averaged topographical signals between frequencies, tempi, and participants. On the right, there is a pool of electrodes selected, which correspond to electrodes expressing average maximum amplitudes between participants, between trials, and between the three tempi. This pool of electrodes defines the region of interest (ROI). Analyses involving EEG responses are based on this pool, and the resulting EEG response spectrum is an average of the signal calculated using this pool of electrodes.

The region of interest (ROI) is composed of a pool of electrodes (9 electrodes: F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2) making up the frontocentral region on the scalp fig. [14].

The overall magnitude of the EEG response is calculated by summing in the frequency domain (corresponding to the envelope extracted from the demodulated frequency signal of the EEG response) the magnitudes at the twelve different frequencies for each tempo. These twelve frequencies correspond to the frequency analogous to the unit period of a rhythmic pattern and the successive harmonics up to the period of the unit event, corresponding to the 11th harmonic. This corresponds to the overall gain of the response and can be compared using an ANOVA with tempo as the discriminant factor, significance level was set at $p < 0.05$.

To address our main hypothesis, it is necessary to compare the EEG response of the meter-related frequencies at the three different tempi. These frequencies are linked to beat perception when listening to musical sequences. The selection of meter-related frequencies is based on the analogous motor task, which reflects the individual's perception of the meter. The study focuses on the majority of tappers, who perceive the leading beat of the musical sequence 2, 3, or 4 times at each rhythmic pattern.

The frequencies related to the meter are linked to the perception of the meter, as stated in the introduction hypotheses [4].

The frequencies related to the meter correspond to a subset of the selected frequencies that are linked to perception, in addition to being linked to the fundamental or one of the harmonics of the rhythmic pattern.

Regarding the analysis of the sound pattern, the amplitudes obtained at the twelve selected frequencies are converted into Z scores for the three tempi. This normalization phase enables the comparison of results obtained for the tempi and the neuronal responses in relation to the audio signal presented (Nozaradan et al, 2012 [17]). The greater the Z score for a specific frequency, the more it deviates from the norm and is more prominent than other frequencies.

A *mean Z-score for meter related frequencies* can be found by averaging the Z-score of the meter-related frequencies. Analogous, the Z-score of the non meter related frequencies (frequencies remaining relative frequencies of interest) to form a mean non meter related Z-score, its value is perfectly complementary to the meter related Z score.

To test whether magnitudes expressed at meter-related frequencies are selectively enhanced, we compared the mean Z-score of meter-related Z-scores to the mean of Z-scores corresponding to the same frequencies in the sound pattern envelope. We used a one-sample t-test three times to compare the magnitude at meter-related frequencies between the EEG spectral response and the sound pattern envelope. The significance level was set at $p < 0.05$ [2.10].

To test whether the magnitude of meter-related frequencies varies between tempi, we compared the mean Z-score of meter-related frequencies at each tempo using an ANOVA. The significance level was set at $p < 0.05$ [3.3].

3 Results

3.1 Participant

At the end of the experiment, participants found it difficult to perceive the meter and beat when the sequence was played. However, all participants were able to complete the required listening and the tapping tasks, as indicated by the results of the tapping task, where the proportion of good tappers remained consistent. However, the comprehension of the task, the number of trials required to complete it correctly, and the accuracy of the detection task varied significantly among participants.

3.2 Motor task movement

Different metrics of tapping coexist between participants, the sequence played is complex, the only imperative is to tap a whole number of times over the duration of each pattern and to be consistent (keep the same subdivision) throughout the trial. The ITI is measured, as shown in figure [15](#) representing the average ITI during each tapping trial. The figure displays a multimodal curve indicating distinct tapper profiles. Local maxima are centred on inter-tap intervals (ITIs) corresponding to four, three, or two tappers for each of the three tempi.

Histogram inter tapping times

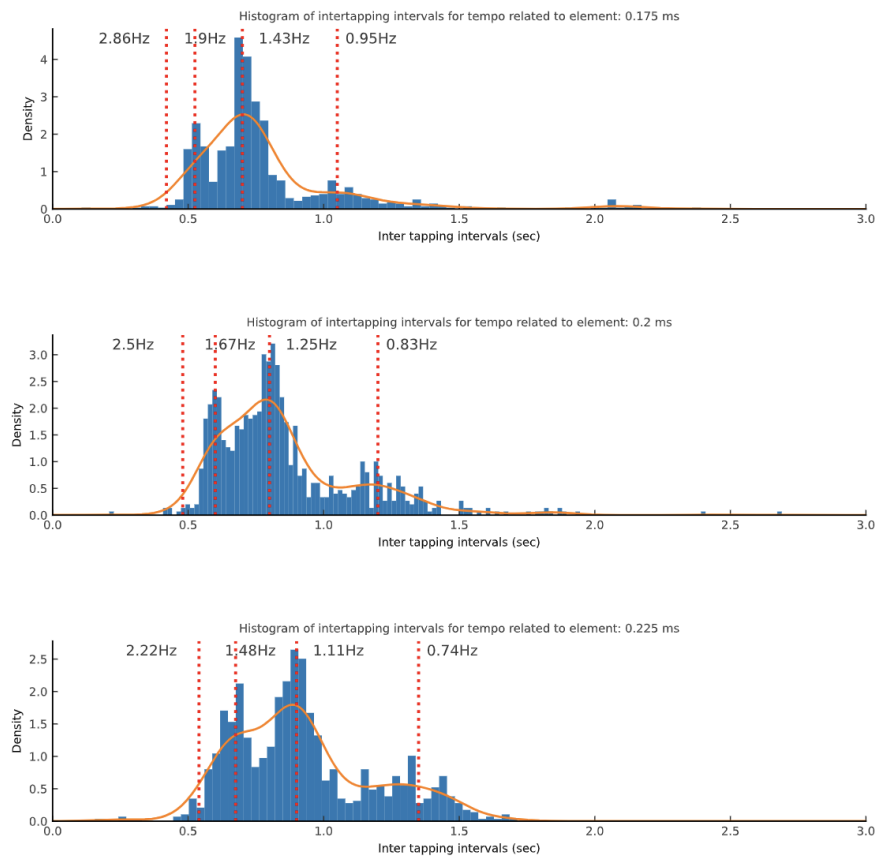


Figure 15: This histogram displays the frequency distribution of ITI measurements for all tapping trials. The distribution is non-Gaussian and follows a multimodal pattern centred on the modes corresponding to the theoretical tapping frequencies.

As shown in figure [16](#), the ITI of each tapping trial is plotted and compared with the theoretical ITIs corresponding to each tapping profile. Some ITIs exhibit greater variability and are not centred around the theoretical value or are completely off. This indicates the presence of bad tappers.

Scatter iti - lag

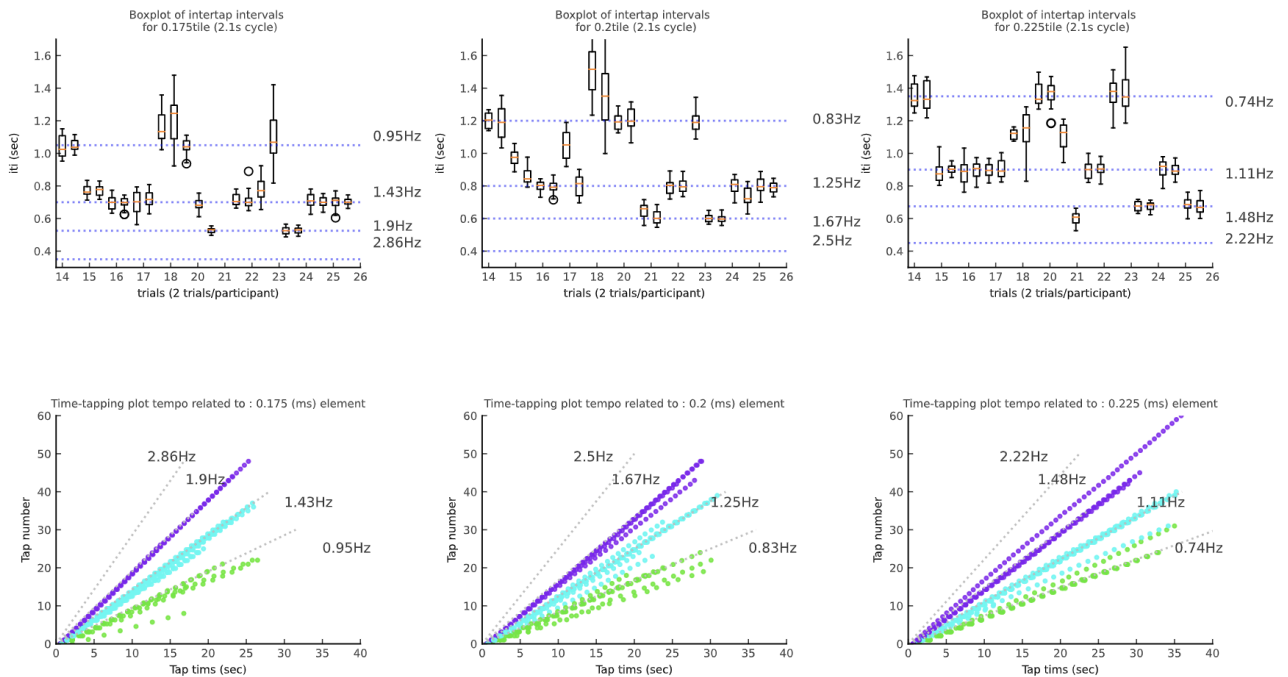


Figure 16: The figure displays the mean and cumulative inter-tapping intervals (ITI) for each tapping trial. The top section shows the average and dispersion of ITIs measurements for each tapping trial among participants. The theoretical ITIs values corresponding to the interval of a two, three, four or six-tapper are also presented. The figure is organised from left to right according to fast, medium and slow tempi. At the bottom of the graph, you can see the cumulative ITIs for each trial. The dotted purple lines represent ITIs approaching the model for a four-tapper, the dotted cyan lines represent ITIs approaching the model for a three-tapper, and the dotted green lines represent ITIs approaching the model for a two-tapper. The graph shows the ITIs for fast, medium, and slow speeds from left to right.

The trials are then classified with respect to a tapping profile using a function *argmax* maximizing the fit between the trial's ITIs and one of the tapping profiles. Additionally, the consistency between the ITIs and the pattern cycle is checked. Trials that are asynchronous with the pattern trial are labelled as bad. Compared with manual classification, an accuracy of 88% and a precision of 92% is calculated. Profile labeling is shown figure [17; 18].

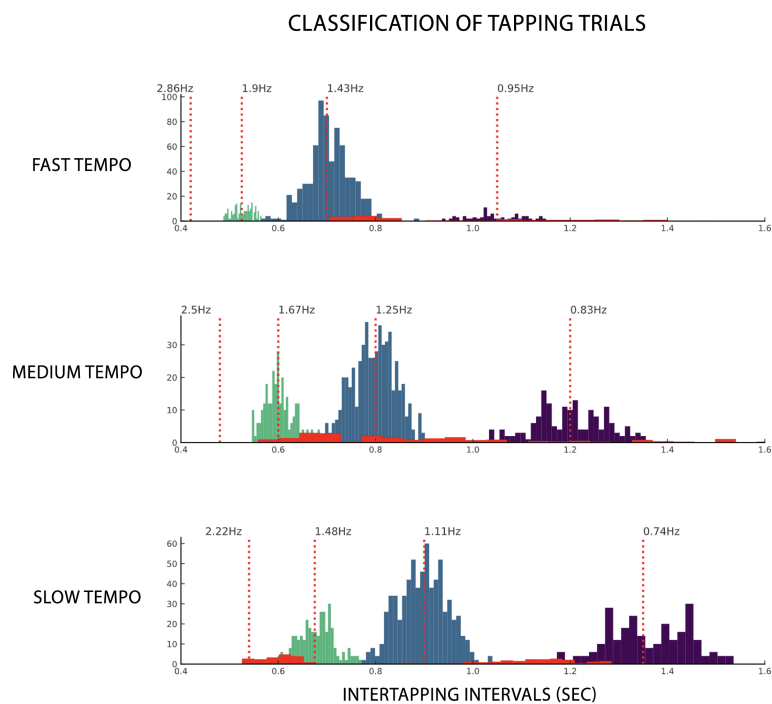


Figure 17: This histogram displays the tapping frequencies corresponding to the ITIs measured for each trial after classification. The corresponding theoretical tapping frequencies for the different tappers are also included. Trials classified as bad are highlighted in red.

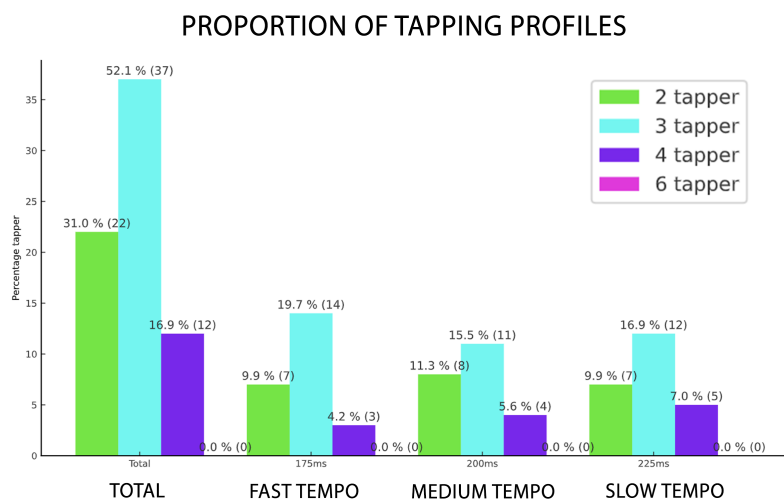


Figure 18: The histogram displays the proportion of tapping trends between tempi. The green bars represent two-tappers, the cyan bars represent three-tappers, and the purple bars represent four-tappers. The tempi are categorized as fast, medium, and slow.

Two questions arise concerning the distribution of the number of inaccurate tappers and the distribution of the tapping profile across the three different tempi.

A chi-squared test suggests no relationship between tempo and the proportion of bad tappers (p -value= 0.69, degrees of freedom (DF)= 3). A Chi-square test also suggests no relationship between the distribution of tapping profiles and tempo (p -value= 0.848, DF= 4).

The tapping profile that dominates displays a tendency towards three-tappers. taps per pattern cycle, as reflected in the three tempi chosen. The experiment shows convergence towards a ternary metric.

The following analyses focus on trials corresponding to a three-tapper profile, excluding other profiles and bad tappers. ITIs can now be calculated for each of the three tempi. For the fast tempo, the average ITI is 0.705sec (std 0.37sec), with an ITI variation of 6.4%.

For the medium tempo, the average ITI is 0.803sec (std 0.26sec), with an ITI variation of 6.4%.

For the slow tempo, the average ITI is 0.899sec (std 0.25sec), with an ITI variation of 5.8%.

The analysis of variance (ANOVA) does not confirm an increase in ITI variation with tempo ($F= 0.25$, $P> 0.75$, $df= 2$).

3.3 Frequency tagging signal

The envelope of the rhythmic pattern consisted of 12 frequencies, which elicited an EEG response at the same frequencies. The EEG spectral response amplitudes were maximal in the fronto-central region, which corresponded to the selected electrode subset. There were no differences in the distribution of spectral response amplitudes on the scalp topography, neither between frequencies nor between the three tempi [18]. Analyses can be performed based on the average amplitude evoked by a subset of electrodes. This allows for a single average amplitude value to be considered, instead of having to perform analyses for each individual electrode.

The overall gain can be determined by grouping the magnitudes of the spectra at each tempo. An ANOVA can be used to compare whether there is a difference between the overall gain derived from the spectrum of responses at different tempi [2.10]. The ANOVA was conducted and it does not support the claim that the total gain differs significantly among the three conditions. The null hypothesis (H_0) was not rejected ($P>0.05$), and this result was confirmed by the post hoc pairwise T-test.

The final stage of the analysis concentrates on examining the frequencies associated with the meter perceived by the participants. It is assumed that the frequencies corresponding to the perception of the meter are the 3rd harmonic of the fundamental and its multiples, as the majority of participants perceived three meters per pattern cycle. To compare frequencies on the same spectrum, it is useful to use a dispersion metric. This metric is the Z-score compared to the average of all magnitudes [2.10].

A one-sample t-test can be used to compare the distribution of the magnitude of the signal at three meter-related frequencies between the envelope of the input stimulus and the EEG response.

Comparison three meter related Z-score between input-output		
Fast tempo (175ms)	medium tempo (200ms)	slow tempo (225ms)
H0 is rejected (t-score = 2.35, P < 0.039)	H0 is rejected (t-score = 2.48, P < 0.033)	H0 is rejected (t-score = 2.59, P < 0.025)

Tests are considered separately, a Bonferonni correction is not required.

The following question pertains to the comparison of the Z-score for the three-meter related to the three tempi. The aim is to determine whether there are any differences in the relative distribution of energy on the EEG response spectrum between the tempi. To answer this question, an ANOVA is used to compare the Z-scores for the three-meter related to the three tempi. The statistical analysis revealed no significant difference in the relative distribution of energy on the EEG response spectrum among the three tempi ($F=0.27$, $P > 0.76$, $df=2$) [3.3; 19].

COMPARAISON OF Z SCORES BETWEEN TEMPI

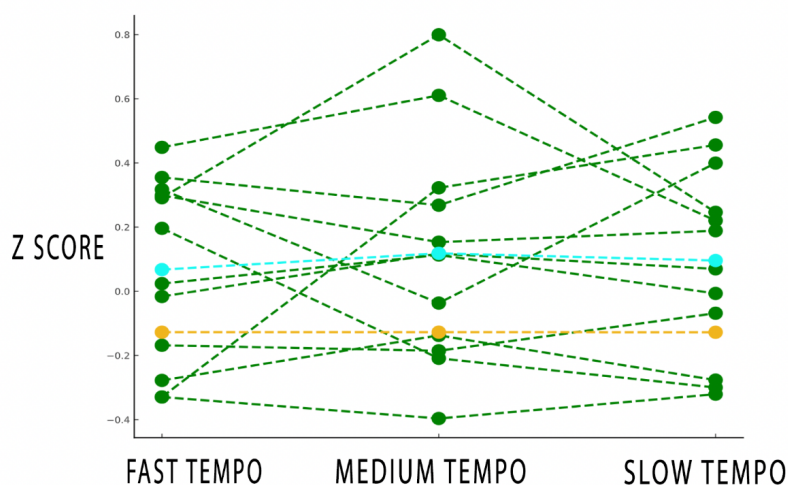


Figure 19: The graph displays the distribution of three-meter related Z-scores across three tempi. The green line represents the Z-score for each individual at the three tempi, while the cyan line represents the average Z-score between participants for the three tempi. The gold line shows the three-meter related Z-score calculated over the spectrum of the stimulus played. The change in the Z-score for three-meter-related frequencies between the input and EEG response indicates the involvement of endogenous processes that enhance these frequencies. Non-three-meter-related Z-scores are not shown, but they are systematically reflected with the zero ordinate by definition.

4 Discussion

This experiment investigates how the perception of beat, meter, and rhythm is affected by variations in tempo within a limited range. The study builds on previous observations of strong sensory-motor synchronization abilities that connect rhythm perception with the ability to perform rhythmic motor tasks [1]. The experiment confirms our ability to perceive rhythm even when sequences are not strongly periodic. This demonstrates our innate sense of rhythm. Here the purpose was to confront the idea of the frequency scaling (W. Large, 2008 [38]) that could be seen as a *coherent temporal scaling* versus a reorganization that could be seen as a *drift in the meter perception* (Nozaradan et al, 2014 [70]) in the rhythm and meter perception when the tempo vary in a limited range.

One interesting mechanism in rhythm perception is the ability to adapt and perceive the beat and meter in various conditions, such as changes in pitch and melody. This ability allows a coherent tuning of meter perception according to subtle tempo variations. The concept behind this idea is based on temporal scaling within a preferred range of perception of the meter, which is highly sensitive to the tempo (Styns, van Noorden, 2007 [39]; Repp et al, 2013 [40], W. Large, 2008, [38]). This work focuses on the frequency tagging evoked potentials that are elicited when listening to rhythmic pattern sequences in three different tempi.

The study yielded evidence that most participants were able to detect a metric consistent with the rhythmic pattern sequence when listening to a complex rhythmic pattern. The meter period was found to be an integer sub-multiple of the rhythmic pattern period. Furthermore, the periodic features of the elicited rhythm were directly related to the periodic elicited signal in the EEG. The magnitudes of frequencies elicited at meter-related frequencies, which are a subset of frequencies determined by the metric interpretation induced by the physical movement of tapping, differ significantly from the magnitudes of non-meter-related frequencies fig. [18]. When comparing the EEG response spectrum to the sound envelope spectrum, it was found that the relative distribution of magnitudes of the frequency tagging evoked potential differed significantly from the relative distribution of the presented musical sequence spectral envelope. This suggests that the rhythmic pattern was cognitively processed with a selective enhancement at a subset composed of meter-related frequencies. This subset of EEG responses corresponds to frequencies that are linked to a specific metric. The metric corresponds to the subdivision of the periodic rhythm by three fig. [19], the frequencies elicited at meter-related frequencies are significantly enhanced compared to the potentials evoked at non-meter-related frequencies. Therefore, the EEG spectrum is no longer solely a linear reflection of the acoustic energy at the corresponding frequencies of the input rhythmic sequence. However, when examining the magnitudes on the EEG response spectrum, this redistribution of energy at certain frequencies can be interpreted as the precise interpretation of the perception of the rhythm, involving a mechanism for selecting frequencies related to the meter. The redistribution of energies at frequencies corresponding to meter perception correlates with tapping behavior. The tapping behavior suggests multiple possible interpretations of meter. However, there is a tendency towards a ternary rhythm for complex periodic patterns lasting between

2.1 to 2.7 seconds at least.

The range of the meter's perception could be approximated as at least one-third of the pattern period. Therefore, the range could be estimated to be between 0.7 seconds (determined using a faster tempo) and 0.9 seconds (determined using a slower tempo). However, it appears that the limits of the meter perception range have not been reached with the tempo variation set used in this experiment. The results across the three tempi are similar, with no reorganization or singular results observed in different proportions. A majority of three tappers are observed, and the proportion of bad tappers remains stable. EEG responses showed enhancement of three meter-related frequencies in a similar way across the three tempi.

The results support the idea that internal mechanisms play a role in perceiving meter. This may be due to selective neural training mechanisms that are not solely based on physical properties of external stimuli. Additionally, the ability to adapt to tempo variations within a limited range while maintaining a consistent perception of relative time highlights the adaptability of these neural training processes. Internal mechanisms quickly process certain external cues, which are modulated by various factors such as rhythmic cues, knowledge, and pre-training (Chemin, 2014 [71]), allowing to detect a meter compatible with a rhythmic sequence played. However, this ability to detect a meter even in complex rhythmic patterns highlights that these temporal rhythmic cues do not necessarily have to be predominant in the external stimulus.

The distribution of EEG responses across the three conditions is not significantly different, indicating that the neuronal circuits remain in close proximity and there is no delocalisation (Nozaradan et al, 2017 [49]).

In conclusion, the study supports previous observations and reinforces certain hypotheses. By subtly adjusting the tempo, we were able to expand the preferred perception zone of the meter.

However, due to the limited number of participants, it is difficult to draw definitive conclusions on more subtle aspects, such as a reorganization of the perception of the meter according to an alternative metric. Moreover, the tested tempo range did not reach the limit of the preferred range for perceiving the meter, nor did it include variations in speed or perception of the meter in this limit zone. To gain a better understanding and characterisation of these phenomena of rhythm perception, further studies are necessary to clarify points of uncertainty, specify the preferred range, and observe behavior in the limit zones. To conduct similar experiments with sufficient statistical power for participants using alternative tapping metrics, such as two, four, or six tappers, it is recommended to increase the sample size.

5 Conclusion

The study illustrates the complex brain mechanisms involved in an intuitive phenomenon. It demonstrates that a synchronization task requires various brain structures to work together. The study also shows that external rhythmic stimuli operating at low frequencies can modulate the endogenous representation of the meter. We therefore witness an interaction between external rhythmic stimuli-neuron couple and endogenous processes highlighting the interaction between the external rhythmic stimuli-neuron couple and endogenous processes. (Parker Tichko, Ji Chul Kim, 2021 [72]), allowing modulation, and a selection of oscillating processes leading to the perception of a rhythmic meter remaining coherent with the external stimulus, for example, your favorite music.

This study investigates how the perception of meter and neural response adapt to different tempi within a limited range. The results indicate that participants demonstrate good adaptation skills in perceiving meter, with consistent shifts in perception corresponding to changes in tempo. This ensures an integer number of meters per rhythmic pattern for each tempo.

The observations demonstrate consistency and stability in tapping behavior across the three tempi tested. This behavior is associated with the selection of related frequencies, which also remained consistent across the three tempi. Overall, this behavioral and cognitive stability suggests that the limit for perceiving meter has not been reached.

Participants with varying levels of experience in music and dance were tested to evaluate their speed of comprehension, accuracy in detecting deviant sequences, and tapping trial performance. The data has been recorded, but further acquisitions are needed due to the limited sample size and imbalance between the groups.

Regarding the EEG response, the neural entrainment to the rhythmic pattern sequence resulted in a selective enhancement of the frequencies corresponding to the perception of the observed meter in the behavioral tapping task. This selection of enhanced frequencies was consistent across all three tempi studied, and no reorganization or drift was observed in the behavioral perception of the meter. These findings are consistent with the cognitive responses observed on the EEG.

The remaining question is to determine and investigate the boundaries of the range of meter perception. This will be achieved through a subsequent experiment that involves extending the range of tempi variation. Previous experiments have demonstrated that doubling the tempo can cause a reorganization in meter perception [1]. With a wider range of tempi, the meter perception is completely reorganized instead of just adapting to tempo changes. This causes a drift in the perception of the meter according to the tempo (Nozaradan et al, 2012 [17]). So leaving the time scaling paradigm for a reorganisation of the meter perception when we leave the range of the meter perception. By exploring the extreme limits of the meter's preferential range of perception, hypotheses can be formed. For example, a majority of participants may abruptly reorganise their perception of the meter when exceeding a fixed tempo limit. Another hypothesis could be the existence of a transition region where this meter perception reorganisation follows a specific distribution. Alternatively, this transition region may induce singular behaviors and singular perceptions

of the meter. Therefore, the question remains unanswered and requires further investigation by increasing the tempo.

Finally, due to the spatial limitations of the EEG, further investigations are necessary to determine the precise location of the integration mechanisms and the active neural networks involved in the processing of stimuli. Allowing complex auditory-motor tasks with a high degree of periodicity. However, the neural activity observed on the cortical map for meter perception activities is maximal in areas previously described as involved in meter perception, at low frequencies. These areas include the supplementary motor area, Heschl's gyrus, and the planum temporale. The activity of certain areas is transposed to the frontocentral region on the scalp due to the spatial limitations of the EEG (Nozaradan et al., 2017 [49]; Cools, 2020 [62]).

The study of music as a phenomenon is intriguing due to its universal and timeless nature. While music has been theorised across generations, the emergence of neuroscience has provided a contrasting perspective. Despite the existing musical theory, the cognitive mechanisms that enable individuals to appreciate the subtleties of a melody remain largely unexplored, despite the increasingly detailed understanding of the involved mechanisms.

The study and understanding of underlying mechanisms, such as the ability to feel and adapt to rhythm, offer perspectives beyond fundamental research. For example, they may serve as biomarkers for specific neurodegenerative pathologies, aid in dissecting the ontogeny of neural system development, or even be applied to the numerous harmonic systems present in humans.

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