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Evidence for multimodal learning of the musical beat through short-term audiovisual training

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Quelques clarifications selon certains termes en anglais ont été demandé grâce à l'outil ChatGPT.

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Code, aide à la programmation, ou algorithmes

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Correction d'erreurs dans les lignes de code lors de l'utilisation du logiciel d'analyse statistique (Rstudio) et lors de l'utilisation de MATLAB.

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Acknowledgment

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I. Introduction

Music is ubiquitous and has accompanied human activities since the dawn of time in every society (e.g., social interaction, dance; Mehr et al., 2019; Savage et al., 2021). One of the universal behavior to music is to make us move (Fitch, 2016), as when we bob our head, or clap our hands to the rhythm of music. Interest in rhythm processing in music emerged about fifty years ago, with the study of sensorimotor synchronization (i.e., the ability to synchronize one's movement with external cue as when humans develop temporal expectations that can help them to coordinate their movements with rhythmic inputs). This phenomenon explains the ability of musicians to coordinate with a metronome or dancers to move accordingly to a musical rhythm (Cohn, 2020; Guérin et al., 2024; Repp, 2005). Furthermore, the development of new neurophysiological techniques (e.g. electroencephalography [EEG], functional magnetic resonance imaging [fMRI]) allows us to study brain processes related to rhythm perception.

To coordinate movements with rhythmic inputs, an internal representation of time, often referred to as meter, is required. Meter can be defined as a set of periodic pulses organized hierarchically (Figure 1). Musicians often talk about beat as well, which is the most prominently perceived metric pulses (Cohn, 2020; Lenc et al., 2021; London, 2004). Crucially, there is no one-to-one mapping of metric pulses onto rhythmic inputs. A single musical rhythm interpretation can lead to several beat perceptions and one beat perception can lead to several rhythms (Lenc et al., 2021; Nozaradan et al., 2018). For example, one rhythm (Figure 2) could lead to two distinct metrical interpretations, dividing the repeated rhythmic pattern in either three- of four- periodic pulses. Conversely, different rhythmic patterns could lead to the same metrical interpretation (e.g. Metallica's song *Nothing Else Matters* and a waltz).

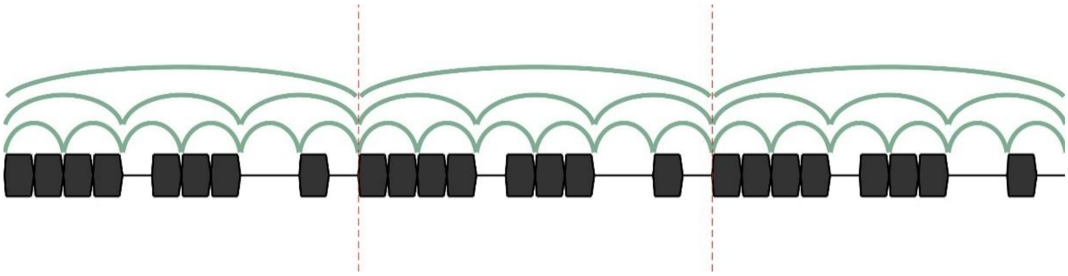


Fig. 1 Several pulses layers of one metrical perception of a specific rhythmic pattern (in black). Each vertical red line marks the repetition of the rhythmic pattern. The lowest green line shows a fast pulse on every 2 temporal events. Just above is a pulse which takes twice the time of the fast one. Finally, the largest line showed the slowest pulse one can feel in the meter.

Meter perception is also possible in responses to rhythms that weakly cue metric pulses. Syncopated or weakly periodic rhythms, where the beat is off the rhythm, still allow to coordinate movement to music (Fitch & Rosenfeld, 2007). Additionally, neurophysiological studies showed an enhancement of meter-related frequencies in the neural responses even when rhythms were lacking these frequencies. Therefore, beat perception can be defined as the ability to perceive periodicities, even in rhythms that are not periodic (Nozaradan et al., 2012, 2018).

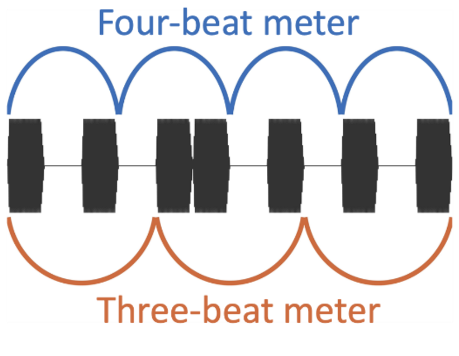


Fig. 2. *Mapping of distinct metric pulses onto one single rhythmic pattern (rhythm from Central and West African traditional musical repertoire in black). Four-beat meter (in blue) is the common African perception; African-enculturated individuals usually perceive one pulsation every three temporal event. Three-beat meter (in orange) is the common Western perception; Western-enculturated individuals usually perceive one pulsation every four temporal event.*

The mapping of a metrical interpretation onto a specific rhythm input is highly flexible, and may depend on a multitude of factors, such as the human development, culture, musical expertise, inter-individual differences, familiarity with specific musical genres, or body movement training. As shown in Hannon & Trainor (2007), exposure to music during development gives us basic musical competence the same way when we develop our spoken language since our childhood. Infants are therefore capable of using metrical structure in music learning. Hannon & Johnson (2005), examined 7-month-old infants in three different experiments. They discovered that infants could perceive metrical structure even with occasional ambiguities. The effects of culture has been demonstrated in musical development, showing an impact on musical rhythm processing (Cameron et al., 2015; Kaplan et al., 2022). Cameron et al. (2015), tested East African and North American adults with rhythms from East African and Western music. It was shown that participants tapped more precisely with rhythms from their culture. In addition, fMRI results showed greater recruitment of the prefrontal cortex (underlying executive functions like working memory) in musicians than in nonmusicians. Therefore, while every human can perceive music, it is often described that musical expertise plays a role in improving rhythmic perception (Chen et al., 2008; Matthews et al., 2016).

Lately, a relationship between body movement and rhythm perception has been studied behaviorally (Phillips-Silver & Trainor, 2005). Body movement was shown to have an influence on adult's rhythm perception (Phillips-Silver & Trainor, 2007). More specifically, in their study, participants had to recognize an auditory rhythm that matched the one they had experienced moving to earlier. It has been shown that these participants could better recognize the auditory rhythm if they moved to it before. The vestibular system could potentially explain this phenomenon. It was indeed shown that movement of the head had an impact on auditory perception, while movement of the leg had no influence (Phillips-Silver & Trainor, 2007, 2008). It was then demonstrated by Chemin et al. (2014) that brain responses to rhythm, as measured with electroencephalography, were significantly amplified at frequencies corresponding to the meter to which the participant had previously moved. The author highlighted the impact of body movement on the internal representation of musical rhythm shaping. Chemin et al. (2014) also brings out another important question: What components of body movements could specifically explain the effect of movement on rhythm perception? Many components of body movement, such as the vestibular inputs or motor cortex activation, could possibly cause the effect observed.

Motor mental imagery is another process that could explain the observed effect of body movement on rhythm perception. Motor mental imagery refers to internal imagery where people imagine moving but are actually not moving. It is said that motor imagery and motor control would share some neural mechanisms (Decety, 1996). Decety (1996) talked about the prefrontal cortex being responsible for the creation and maintenance of explicit representations that guide thought and action. Furthermore, motor and auditory elements could be linked in the human brain. When pianists listened to piano music without playing themselves, studies showed motor activity involving the contralateral primary motor cortex (Bangert et al., 2006; Haueisen & Knösche, 2001). Because motor mental imagery activates motor area, it could be sufficient to influence rhythm perception.

The main purpose of this study was to examine if motor mental imagery, induced by an audio-visual training, is sufficient to enhance the behavioral and neural representation of meter. Forty western participants took part in a three-session experiment, where clapping and neural responses were recorded before and after an audio-visual training session. The audio-visual training session consisted of ~20 min of watching a video clip of a dancer moving to a rhythm in synchrony with an overlaid drum sound indicating a specific metrical interpretation of the rhythm (three- vs. four-beat meter). Half of the participants ($n = 20$) were assigned to the three-beat meter audio-visual training condition, while the other half ($n = 20$) were assigned to the four-beat meter audio-visual training condition. The neural responses of participants were recorded during the pre- and post-audiovisual training sessions using electroencephalography while they stayed still in a chair. An accelerometer was placed on the participant's head to control for the absence of body movement. Each of the pre- and post-audio-visual training sessions was followed by a series of trials in which participants clapped along to the rhythm and were recorded using a microphone.

Several analyses were conducted. First, we predicted an enhanced representation of the beat periodicities in the post-training neural (H_1) and behavioral (H_2) responses to the rhythmic input. In addition, the post-training neural and behavioral responses enhancement was expected to be selective to the beat periodicities conveyed by the audiovisual-training session (H_3). In order to confirm the three-beat perception to be the common Western perception, we tested any prior preference for one metrical interpretation (H_4).

I. Methods

1. Ethical Clearance

The ethics committee of the Université Catholique de Louvain, Belgium, approved the present study (ref. 2018-353). Informed consent was obtained from all the participants prior to inclusion in the proposed study. Participants received a financial compensation for their time (30€).

2. Participants

Adult volunteers considered eligible to participate in the study were aged between 18 and 45 years, non-musicians and non-dancers, and free of sensory (i.e., no auditory impairment or uncorrected visual impairment) and motor dysfunctions (i.e., no upper- and/or lower-limb disorders). In the present study, non-musicians or non-dancers were defined as those meeting at least two out of the three following criteria: (a) not considering themselves as such, (b) not having more than four years of practice, and (c) not having played an instrument/danced in a concert or performance on stage in front of an audience.

To enable comparisons with Guérin et al. (2024)'s study, for participants to be included in this study, they needed to self-report that (a) themselves or both their parents have lived, at least for the first 15 years of their lives, in one of the following countries: Belgium, France, United Kingdom, Netherlands, Luxembourg, Germany, Spain, Portugal, Italy, or Switzerland; and (b) they speak fluently and at least 1h/week one of the idioms (i.e., languages, dialects) from the above-mentioned countries.

3. Experimental Procedure and Tasks

- ***Experimental Procedure***

Each participant was administered three experimental sessions (~20 min each) on the same day. In the pre- and post-training sessions, the participant was asked to perform a separate listening and hand-clapping task in a fixed order (see Figure 3). Brain activity of the participant was recorded with EEG during the listening task and behavioral data were collected during the hand-clapping task. In the audio-visual training session, half of the participants engaged in the three-beat meter condition while the other half participated in the four-beat meter condition (i.e., between-subjects study design with repeated measures). EEG data was not collected during the audio-visual training session. To control for the absence of body movement, the accelerometer was placed on the participant's head throughout the experiment.

In the three experimental sessions, the participant was seated in a comfortable chair, with their head resting against the back of the chair. In the pre- and post-training sessions, the participant was instructed to relax, avoid any unnecessary movement, and keep their eyes fixated on a marker displayed on the wall ~1 m in front of them (to minimize large eye movements). During the audio-visual training session, the participant was required to watch the video displayed on a 53.5–31 cm screen and to avoid moving.

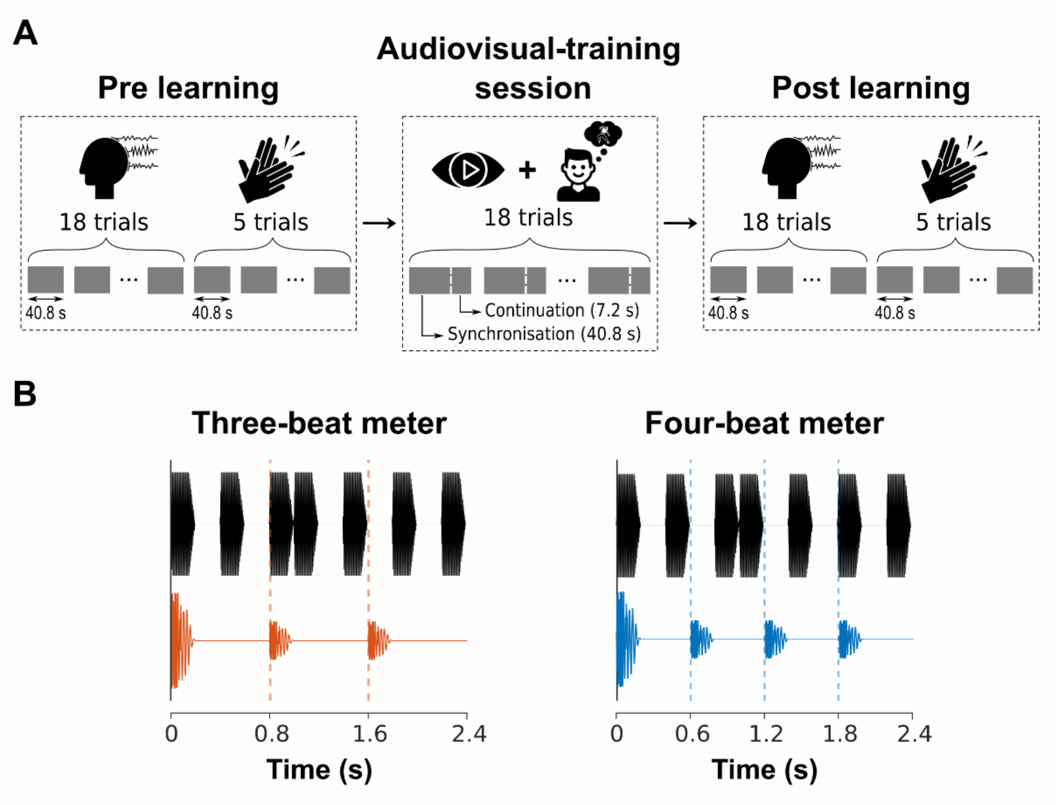


Fig. 3 *Experimental Design and Material. (A) Diagrammatic representation of the experimental design. (B) Rhythmic pattern with the overlaid drum sound that will be used during the body-movement session in the three-beat (left) and four-beat (right) metre condition. Icon sources: 'EEG' by Aenne Brielmann, 'Clap hand' by Ainul Muttaqin, and 'Dancing' by Jack (modified) from the Noun Project under CC BY 3.0 license.*

- ***Auditory Stimulus***

Description. The rhythmic pattern used throughout the experiment originates from West and Central Africa and is often referred to as Bembé, bell/clave pattern, or standard timeline. In this experiment, this pattern had a duration of 2.4 s and was seamlessly repeated 17 times to form a long sequence, with a total duration of 40.8 s (see Figure 3, Panel A). Its 'x.x.xx.x.x.x' structure is based on a 12-intervals grid (200 ms × 12 = 2.4 s), following a specific arrangement of seven 200-ms sound events (depicted by the 'x', and made of a 200-Hz pure tones with 10-ms rise and 50-ms fall linear ramps) and five 200-ms silent intervals (depicted by the '.').

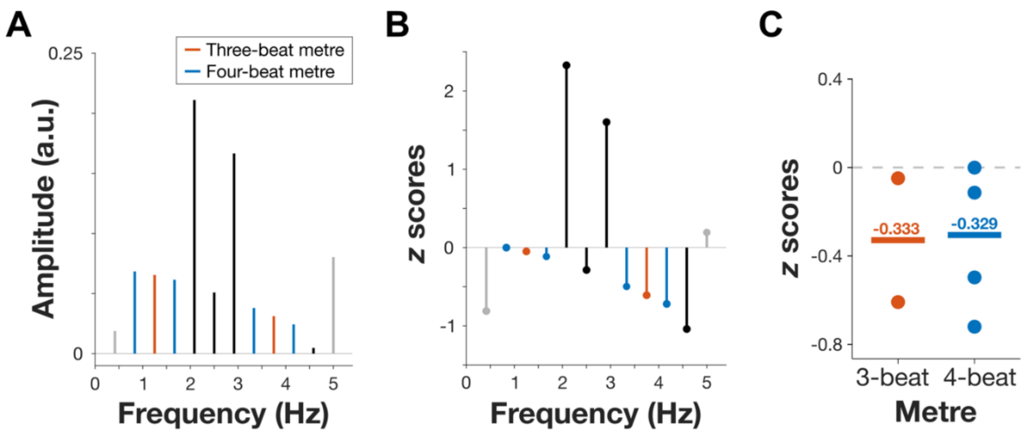


Fig. 4. *Auditory Stimuli Analyses. Three-beat meter related frequencies (i.e., 1.25 and 3.75 Hz) are highlighted in orange and four-beat meter related frequencies (i.e., and 0.83, 1.67, 3.33, and 4.17 Hz) in blue. In the right-hand figure, each dot represents an individual frequency and the horizontal line represents the mean value. a.u. = arbitrary unit.*

This rhythmic stimulus is particularly relevant to the proposed study because unlike stimuli used in the majority of prior studies (Chemin et al., 2014; Phillips-Silver & Trainor, 2005, 2007), the groups of tones making up the pattern are arranged in a way that a tone does not systematically coincide with each beat, thus reducing the likelihood of acoustic or low-level sensory confounds (see Lenc et al., 2021; Nozaradan et al., 2016). This holds for beat pulses that are used in both the three- or four-beat meter condition. Moreover, an overlap between the internal beat and the arrangement of tones in the rhythm cannot be achieved by simply shifting the phase (or alignment) of the beat with respect to the stimulus.

In the audio-visual training session, a metronome-like acoustic pulse was added to the auditory stimulus and served as a cue to the beat from the targeted meter. This pulse consisted of a low-pitched drum sound presented isochronously with an inter-onset interval of 800 ms in the three-beat meter condition and 600 ms in the four-beat meter condition, thus yielding three or four drum cues per repetition of the 2.4-s rhythmic pattern, respectively. In the three-beat meter condition, the pulses were aligned with the first, fifth, and ninth time point on the grid used to generate the rhythmic pattern. In the four-beat meter condition, the pulses occurred at the first, fourth, seventh, and tenth grid point (see Figure 3, Panel B). The drum sound coinciding with the first grid point was accented (sound intensity increased by 2.5 dB) to emphasize the onset of each repetition of the pattern. Three additional repetitions of the rhythmic pattern without the overlaid pulse were appended at the end of the auditory stimulus (40.8 s of auditory stimulation with the overlaid pulse and 7.2 without, for a total trial duration of 48 s; see Figure 4, Panel C). An additional sound event was included in the last repetition of the rhythmic pattern. This final auditory target could occur either in synchrony with the previously cued metrical interpretation or not (see Figure 5). The three auditory stimuli were generated using MATLAB (version R2022a; MathWorks, Portola Valley, CA).

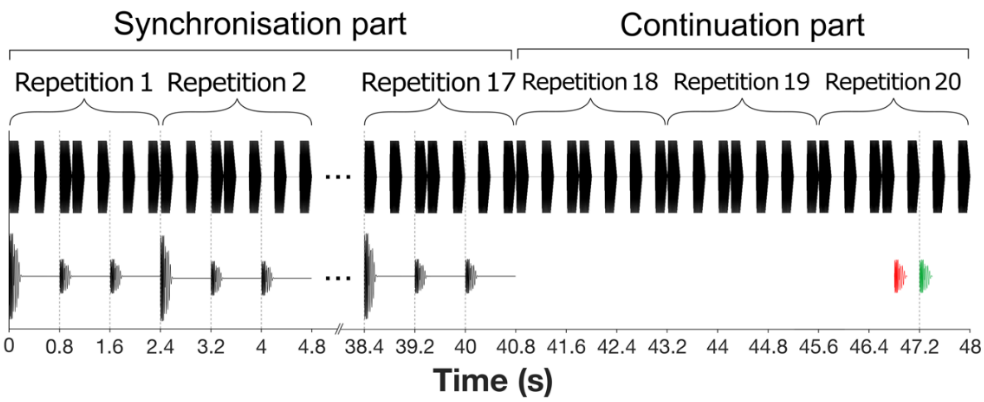


Fig. 5. *Audio-visual training session. Diagrammatic representation of the auditory stimulus used in the audio-visual training session for the three-beat meter condition. The final auditory target could occur either in synchrony with the previously cued metric interpretation (green) or not (in red).*

Sound Analysis. To control for acoustic or low-level sensory confounds that may bias the results, it is critical to first measure how prominent the periodicities corresponding to the three- and four-beat metrical interpretations are in the rhythmic stimulus (Lenc et al., 2021). To measure this, the amplitude envelope of the 40.8-s auditory sequence was extracted using a Hilbert transform and converted into the frequency domain using a fast Fourier transform (Lenc et al., 2021; Nozaradan, Mouraux, & Cousineau, 2017), allowing to estimate the prominence of periodicities in the continuous modulation of the stimulus acoustic features. The obtained envelope spectrum contains 12 distinct amplitude peaks (see Figure 4, Panel A), corresponding to the repetition frequency of the whole rhythmic pattern (i.e., 1/2.4 s = 0.42 Hz) and its harmonics up to the shortest intervals between single events (i.e., 1/0.2 s = 5 Hz) (Lenc et al., 2021). To match the analysis of the EEG signals (see below "EEG Data" subsection), the first and last frequencies of the spectrum were discarded from further computation.

To assess the relative prominence of frequencies considered as related to the meter vs. the other, meter-unrelated frequencies, the magnitudes of responses at the 10 frequencies of interest were then converted into *z* scores following Equation 1 (see Figure 4, Panel B; Lenc et al., 2018):

$$z_i = \frac{A_i - \overline{A}_{\text{all}}}{s_{\text{all}}} \quad (1)$$

where i is a given frequency of interest, A is the amplitude, and s is the standard deviation. Finally, the obtained *z* scores were averaged across meter frequencies (i.e., the frequency corresponding to the meter periodicity and harmonics: 1.25 and 3.75 Hz in the three-beat condition, and 0.83, 1.67, 3.33 and 4.17 Hz in the four-beat condition). Note that the sixth frequency (i.e., 2.5 Hz) was dismissed as it is found in both metrical interpretations. As displayed in Figure 4 (Panel C), the stimulus contains a virtually equivalent low acoustic energy (*z* scores < 0) at either of the two meter periodicities considered here, when compared to the remaining frequencies constituting the envelope spectrum of the rhythm.

- ***Tasks Description***

The auditory stimuli were presented binaurally via insert earphones (ER-2, Etymotic Research; air-conducted sound from the level of the participant's clavicle to decrease magnetic interferences), connected to a Fireface UC audio interface (RME Audio, Haimhausen, Germany; sampling frequency = 44100 Hz; sound volume = 73 dB sound pressure level [SPL]). In the listening task (i.e., during which EEG signals were collected), the auditory stimulus was played to the participant while they were required to perform an orthogonal task to encourage attentive listening. More precisely, the participant was instructed to detect speed reduction in the temporal structure of the auditory stimulus and report their response at the end of each trial (i.e., to avoid speech-related artifacts during the EEG recording). This tempo change was applied to the tenth repetition of the rhythmic pattern within the trial by increasing the spacing of the underlying time grid by 7.5%, lengthening the duration of that repetition from 2.4 s to 2.58. There was a total of two trials per session containing this deviant period (with those trials being randomly positioned across participants), and these trials were discarded from further analyses. In the hand-clapping task (i.e., which directly followed the listening task in both the pre- and post-training sessions; see Figure 3), the participant was instructed to clap along with the beat they perceived in the auditory stimulus ('Clap your hands as you would clap in sync with the music at a concert').

During the audio-visual training session (i.e., without EEG recordings), the participant was asked to watch videos of an individual clapping and stepping on-the-spot in synchrony with the beat according to a specific metrical interpretation of the rhythmic pattern, as indicated with the drum cue. The participant was asked to imagine themself in the individual's place, as if they were moving to the beat themself. They were explicitly instructed not to engage in any movement, but only to imagine moving. In the last three repetitions of the rhythmic pattern, the video and the pulse prompter stopped, while the auditory rhythm was still playing. The participant had to detect whether the final auditory target was synchronized with the movements previously performed by the individual in the video (see Figure 5).

- ***Experimental Design***

The experiment used a fixed block-design procedure (see Figure 3), with each trial lasting 40.8 s in the pre- and post-training sessions and 48 s in the training session. The pre- and post-training sessions were composed of 18 trials for the listening task (including two randomly placed trials containing the deviant period to be detected for the orthogonal task), followed by five trials for the hand-clapping task. The training session consisted of 18 trials. To assess the participant's familiarity with the stimulus, they were asked during a debriefing session at the end of the experiment whether they recognized the rhythmic pattern. The total duration of the experimental procedure was ~1 hr.

4. Data Acquisition and Pre-processing Analyses

Data acquisition was performed using an ActiveTwo system (BioSemi, Amsterdam, Netherlands) and facilitated by the ActiView software (version 8.13). All the pre-processing analyses were performed using MATLAB (version R2022a).

- ***EEG Data***

The EEG data were recorded with 64 Ag/AgCl pin-type active electrodes placed on the participant's scalp according to the International 10–20 system guidelines for standard electrode placement (Jasper, 1958). In addition, two flat-type active electrodes were located over the left and right mastoids. Signals were referenced to the common-mode sense electrode and digitized at a 1024-Hz sampling rate. Electrodes offset relative to the common mode sense (CMS) and driven leg (DRL) electrode loop was kept below ± 50 mV.

The EEG data were pre-processed using Letswave6 built-in functions (https://github.com/NOCIONS/letswave6) and custom MATLAB scripts. The raw data was band-pass filtered using a 0.1–64 Hz Butterworth filter (4th order) in order to eliminate very slow drifts and high frequencies irrelevant to the present study (while also allowing further down sampling of the data if necessary). The filtered signals were segmented from -5 s to +45.8 s (i.e., 5-s buffer at the beginning and end) with respect to the onset to each trial. Based on visual inspection, channels containing excessive artefacts or noise were linearly interpolated using the three closest channels (based on Cartesian coordinates). Note that a channel that was interpolated in one EEG session was also interpolated in the other EEG session of the same participant to prevent confounds. 5% of the channels were interpolated on this basis. In addition, trials showing excessive artefacts were rejected. Across all participants, 20 trials were rejected on this basis. The full data set of a participant were removed prior to further analyses if > 15% of the channels were interpolated and/or > 3 trials per session were rejected (see Figure 6). No participants were removed on this basis. Any excluded participants were replaced to ensure that n = 20 per group.

Independent component analysis was applied to concatenated segments (from 0 to 40.8 s relative to the trial onset) of all trials and sessions, down sampled to 256 Hz with the purpose of reducing computation time. For each participant, the independent component related to eye blinks was identified through visual inspection of the first 10 independent components' waveform and topography, and removed from the EEG signals. Data were then re-referenced to the mean of the two mastoids electrodes, averaged across trials, and epoched from 2.4 to 40.8 s with respect to trial onset (i.e., removal of the 5-s buffer and first pattern repetition), resulting in epochs of 38.4 s.

For each electrode, the averaged waveforms were transformed into the frequency domain using fast Fourier transform, yielding a spectrum of signal amplitudes (in µV) ranging from 0 to 512 Hz, with a frequency resolution of 0.026 Hz (i.e., 1/38.4 s). To obtain valid estimates of the EEG responses, the contribution of residual background noise was minimized by subtracting, at each frequency bin, the mean amplitude of the four neighboring bins (2nd to 5th on both sides; see Bouvet et al., 2020; Lenc et al., 2023). The frequencies were then averaged across a cluster of nine fronto-central electrodes (i.e., F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2), which have been found to exhibit strong frequency-tagged responses to rhythmic stimuli in previous studies (see Nozaradan et al., 2012, 2016, 2017).

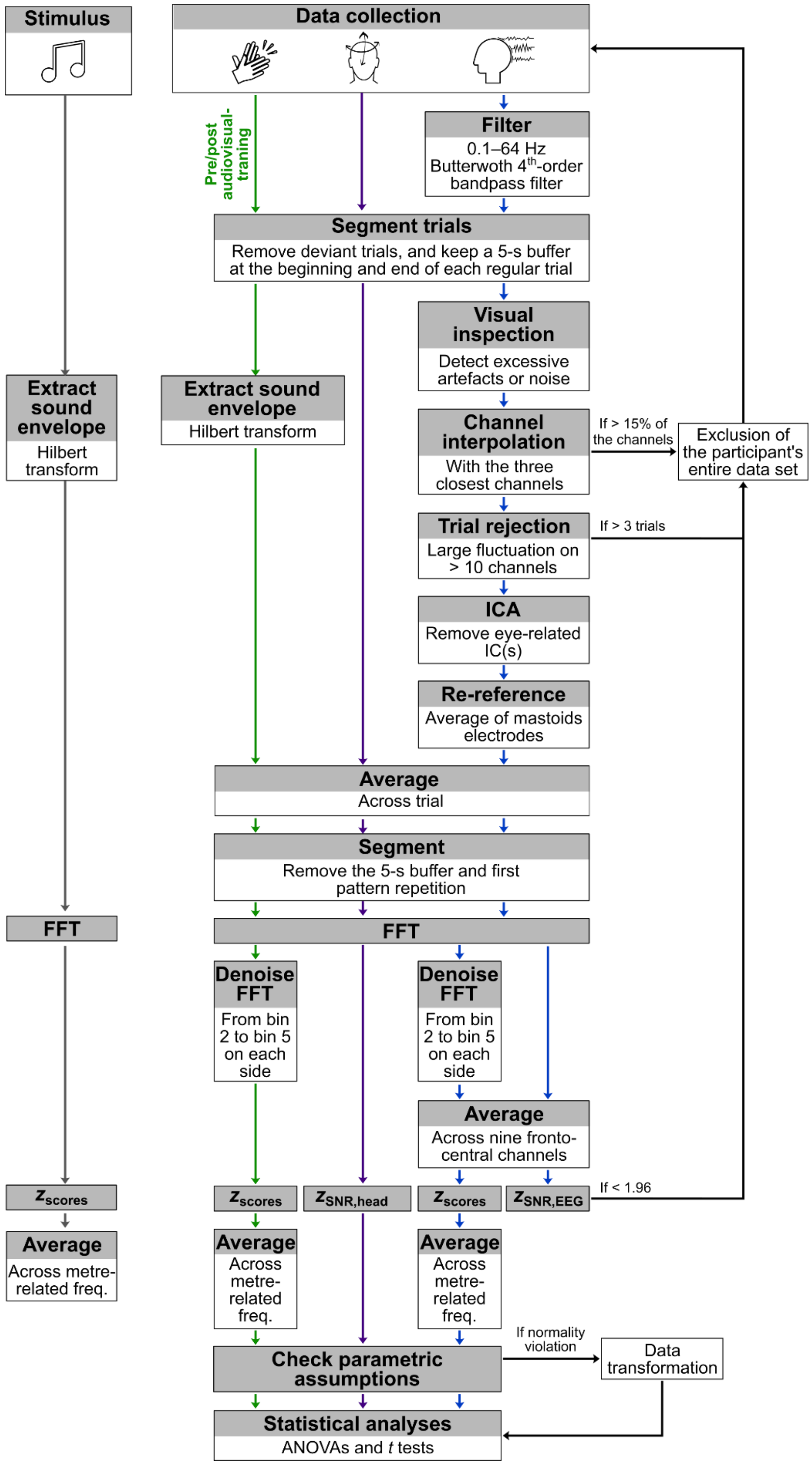


Fig. 6. *Data-Processing Pipeline. ICA = independent component analysis; FFT = fast-Fourier transform; freq. = frequency; ANOVA = analysis of variance. Icon sources: 'Music and multimedia' by Colourcreatype (modified), 'Clap hand' by Ainul Muttaqin, 'Head' by Hunotika (modified), and 'EEG' by Aenne Brielmann (modified) from the Noun Project under CC BY 3.0 license.*

For each participant and session, the amplitude was measured at frequencies of interest that are defined based on the temporal structure of the rhythmic pattern. Specifically, these frequencies of interest corresponded to the pattern repetition rate and harmonics (1/2.4 s = 0.42 Hz), up to the frequency equivalent to the shortest interval between the onset of individual sounds composing the rhythmic pattern (1/0.2 s = 5 Hz). This frequency range of interest was determined based on previous studies (see e.g., Lenc et al., 2020, 2023), showing that surface EEG responses to rhythmic acoustic patterns – similar to the one that was used in the present study – mainly project onto this frequency range. From the resulting set of 12 harmonic frequencies, the first frequency (i.e., 0.42 Hz) was discarded prior to further analyses, because located in a frequency range that is typically strongly affected by the characteristic $1/f$ background noise observed in EEG spectra (i.e., prone to unreliable measurement; Cirelli et al., 2016; Lenc et al., 2023). The last harmonic frequency (i.e., 5 Hz) was also dismissed, as its amplitude is likely driven by the shape of the individual 200-ms sounds composing the rhythmic pattern (see Figure 4, Panel A, for depiction of these frequencies as identified in the modulation spectrum of the stimulus).

From this set, the purpose of the study was to assess the relative prominence of frequencies considered as related to the meter periodicity vs. the other, meter-unrelated frequencies (Lenc et al., 2018). To this aim, the amplitudes at each of these 10 frequencies of interest were converted into z scores (see Equation 1). Finally, the obtained z scores were averaged across meter frequencies (i.e., 1.25 and 3.75 Hz in the three-beat condition [i.e., $\overline{z}_{\text{EEG,3-beat}}$], and 0.83, 1.67, 3.33, and 4.17 Hz in the four-beat condition [i.e., $\overline{z}_{\text{EEG,4-beat}}$]). Along the lines of the sound analysis, the sixth frequency (i.e., 2.5 Hz) was dismissed as it is found in both metrical interpretations.

- ***Behavioral Data***

Hand Clapping. Hand clapping was collected using a microphone (ATR20; Audio-Technica, Machida, Japan) and digitized through the Fireface UC audio interface (sampling rate = 44100 Hz). The continuous sound signal recorded during the pre- and post-training sessions was segmented into epochs lasting 38.4 s (from 2.4 to 40.8 s with respect to trial onset). Note that the first pattern repetition of each epoch was removed to match epoching of the EEG data. Claps were detected in the sound signal using the 'findpeaks' function and IRIs were computed for each trial.

The recorded clapping signal was also analyzed in the frequency domain, similarly to the EEG and sound signals. The continuous sound signal was averaged across trials. The amplitude envelope of this mean signal was extracted using a Hilbert transform and transformed in the frequency domain using a fast Fourier transform (frequency resolution = 0.026 Hz; i.e., 1/38.4 s trial duration). To match with the analysis procedure applied on EEG data, noise subtraction was also applied to the obtained spectra. Finally, $\overline{z}_{\text{clapping}}$ was computed following the same method described for the EEG data (see Equation 1).

- ***Control Measures***

Effectiveness of Auditory Stimulation. A prerequisite to our hypotheses was the ability to capture the neural responses to an auditory rhythm with EEG. As a control measure for this assumption, the frequencies of interest as determined above (i.e., 0.83, 1.25, 1.67, 2.08, 2.5, 2.92, 3.33, 3.75, 4.17, and 4.17 Hz) should significantly stand out relatively to background noise in the EEG signal (see Lenc et al., 2018; Nozaradan, 2014; Nozaradan et al., 2018). Thus, as a positive control, an index of standardized signal-to-noise ratio ($z_{\text{SNR,EEG}}$) of the frequencies of interest was computed from the raw, non-subtracted amplitude spectrum of EEG data averaged across the fronto-central channels (see Figure 6; Bottari et al., 2020; Vettori et al., 2020).

In each participant's averaged spectrum (without noise subtraction), the amplitude at each frequency of interest along with its 20 neighboring bins (10 on both sides, representative of local background noise) was selected, thus resulting in 10 segments of 21 values. These segments were then averaged, yielding an averaged segment where the 11th value thus corresponded to the averaged amplitude across the 10 frequencies of interest. This averaged segment was then standardized into a z score with Equation 2:

$$z_{SNR,EEG} = \frac{A_{11\text{th}} - \overline{A}_{\text{background}}}{s_{\text{background}}} \tag{2}$$

where A is the amplitude and s is the standard deviation. This index served as a measure of the overall prominence of EEG responses to the auditory stimulus over background noise.

Absence of Rhythmic Head Movements During EEG Recordings. A possible confounding factor of the present study was that the selective enhancement of EEG responses at meter frequencies was not due to neural responses per se, but to unintentional rhythmic movements of the participant's head while they listened to the rhythmic stimulus. To control for this potential artefact, head movements were recorded using an accelerometer throughout the experiment. The $z_{\text{SNR,head}}$ at meter frequencies was computed following the same method described for the EEG data (see Equation 3), as an index of head movement synchronization at meter frequencies.

5. Statistical Analyses

- ***Data Eligible for Analysis***

As described in more details above, only data coming from participants with ≤ 15% of interpolated channels and ≤ 3 rejected trials per session were analyzed (see Figure 6). No participant's data set was excluded from the analyses because $z_{\text{SNR,EEG}} < 1.96$ (i.e., $\alpha > .020$), indicating that neural responses were elicited by the rhythmic stimulus in every participant.

- ***Performed Analyses***

R was used for the statistical analyses, with alpha set at $p < .050$. For each statistical comparison, the effect sizes (i.e., η^2_p, Cohen's d) are reported as a quantification of the experimental-effect magnitude and interpreted in accordance with Cohen (1988)'s guidelines. For effect sizes that are presented as Cohen's *d*, *d* < 0.5 is considered as small, *d* ≥ 0.5 as medium, and *d* ≥ 0.8 as large. Where effect sizes are presented as η^2_p, $\eta^2_p \geq .01$ is considered as small, $\eta^2_p \geq .06$ as medium, and $\eta^2_p \geq .14$ as large.

To examine H_1 and H_2, a two-way mixed-model analysis of variance (ANOVA; Session [pre vs. post training] × Audio-visual Training Condition [three- vs. four-beat meter]) was applied on the two dependent variables, $\overline{z}_{\text{EEG}}$ and $\overline{z}_{\text{clapping}}$. To demonstrate that periodic head movements did not contribute significantly to the effects found in the EEG (if any), an identical ANOVA model was applied on $z_{\text{SNR,head}}$.

Normality of residuals was checked using the R 'performance' package (Lüdecke et al., 2021). Where Mauchly's tests indicated violations of the sphericity assumption, Greenhouse–Geisser corrections were applied. Independent and pairwise post hoc *t* tests with Bonferroni adjustments for multiple comparisons were used where necessary to identify where differences lie.

II. Results

1. EEG Data

The RM ANOVA showed no significant main effect of session, $F(1, 38) < 0.01$, $p = .946$, $\eta^2_p < .01$, or audio-visual training condition, $F(1, 38) = 3.87$, $p = .057$, $\eta^2_p = .09$. The Session × Audio-visual training condition interaction was also nonsignificant, $F(1, 38) = 0.86$, $p = 0.359$, $\eta^2_p = .02$. Overall, the results indicated that the amplitude of neural responses at meter frequencies were not enhanced after vs. before the audio-visual training session (see Figure 7).

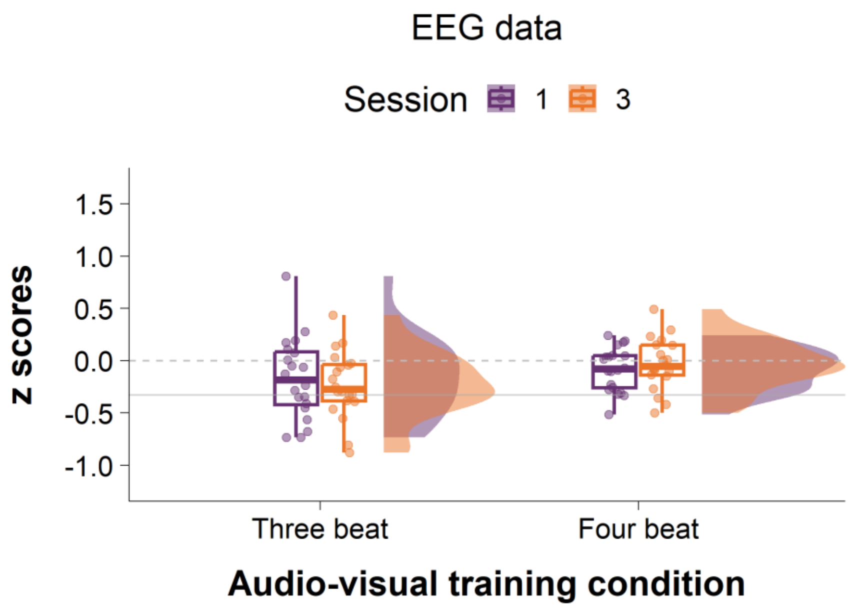


Fig. 7. *Neural meter-related z-scores of each participant obtained during pre- and post-audio-visual training session and for the three-beat meter vs four-beat meter condition.*

2. Behavioral Data

Visual analysis of the inter-response intervals (IRIs) showed that participants often struggled when asked to clap their hands along with the rhythm, especially in the pre-audio-visual training session. In post-audio-visual training session, participants seemed to clap more in line with theorical rates, corresponding to 0.4

or 0.8 s in the three-beat meter condition and to 0.6 s in the four-beat meter condition (see Figure 8).

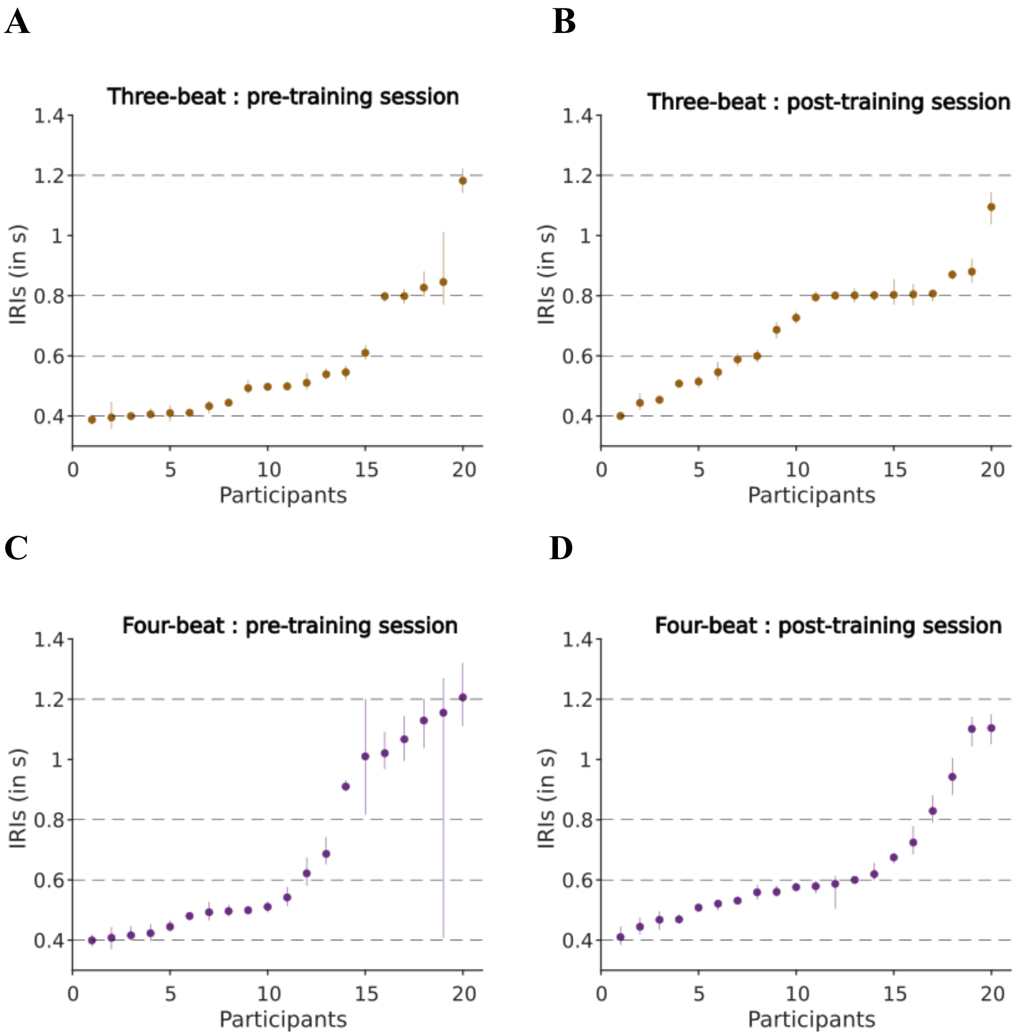


Fig. 8. *IRIs of the pre- and post-training session of each training condition. (A) Three-beat condition in the pre-training session, (B) three-beat condition in the post-training session, (C) four-beat condition in the pre-training session, (D) four-beat condition in the post-training session. Participants in the three-beat post-training session are expected to clap along with 0.4 s or 0.8 s. Participants in the four-beat post-training session are expected to clap along with 0.6 s or 1.2 s.*

The RM ANOVA showed a significant main effect of session, $F(1, 38) = 7.90$, $p = .008$, $\eta^2_p = .17$, with larger meter-related z scores after ($M = 0.187$, $SD = 0.711$) when compared to before the audio-visual training ($M = -0.097$, $SD = 0.592$, $d = -0.44$; see Figure 8). The effect of audio-visual training condition was nonsignificant, $F(1, 38) = 3.12$, $p = .085$, $\eta^2_p = .08$. The Session × Audio-visual training Condition interaction was also nonsignificant, $F(1, 38) = 1.18$, $p = 0.285$, $\eta^2_p = .03$. Overall, the results indicated that the behavioral responses were enhanced after vs. before the audio-visual training sessions (Figure 8 and 9).

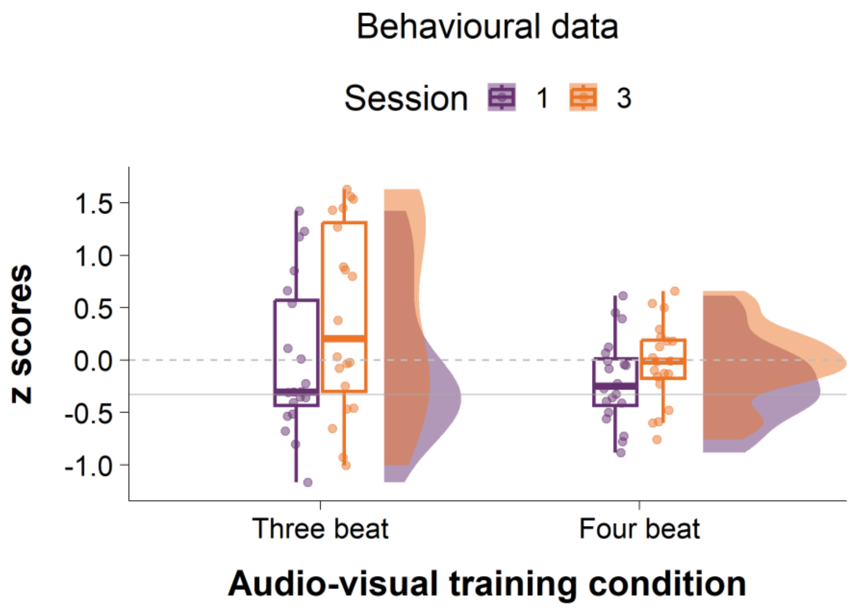


Fig. 9. *Behavioral meter-related z-scores of each participant obtained during pre- and post-audio-visual training session and for the three-beat meter vs four-beat meter group.*

3. T-test against zero

We used a t-test against zero to compare the stimulus z score with the EEG and clapping *z* scores. This allows us to search for any selective enhancement of neural or behavioral activity at meter-related frequencies compared to the stimulus, and which could reflect endogenous processes involved in meter perception.

- ***EEG data***

The t-test showed that neural responses in three-beat condition were not selectively enhanced when compared to stimulus in the pre-audio-visual training session, $p_{adjust} = .148$, nor in post-audio-visual training session, $p_{adjust} = .318$. Neural responses in the four-beat condition were selectively enhanced when compared to stimulus in the pre-audio-visual training session, p_{adjust} = < .001, and in post-audio-visual training session, p_{adjust} = < .001.

- ***Behavioral data***

The t-test showed that behavioral responses in three-beat condition were not selectively enhanced when compared to stimulus in the pre-audio-visual training session, p_{adjust} = .108, but were selectively enhanced compared to stimulus in post-audio-visual training session, p_{adjust} = .003. In addition, behavioral responses in the four-beat condition were not selectively enhanced when compared to stimulus in the pre-audio-visual training session, p_{adjust} = .328, but were selectively enhanced when compared to stimulus in the post-audio-visual training session, p_{adjust} = .004.

4. Metrical interpretation in pre-learning

- ***EEG data***

A *t* test was applied to analyze if there was any preference in the neural responses for one particular metrical interpretation in the pre-audio-visual training session. Despite our initial hypothesis, there was no significant enhancement of the neural responses at three-beat meter compared to four-beat meter frequencies, $t(39) = -1.36$, $p = .181$, $d = -0.22$ (see Figure 10).

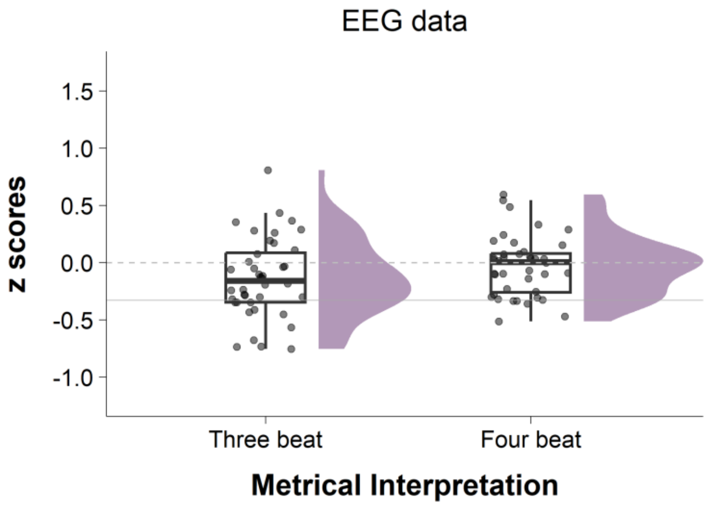


Fig. 10. *Raincloud plots of the neural meter-related z-scores of the metrical interpretation in the pre-training session.*

- ***Behavior data***

Non-normality of residuals (*p* = 0.003) and heteroscedasticity (*p* = 0.031) was detected. Consequently, a Wilcoxon test was applied to examine if there was a preference in the behavioral responses for one metrical interpretation in the pre-audiovisual-training session. There was no significant enhancement of the neural responses at three-beat meter compared to four-beat meter frequencies, *V* = 406, *p* = .960 (see Figure 11).

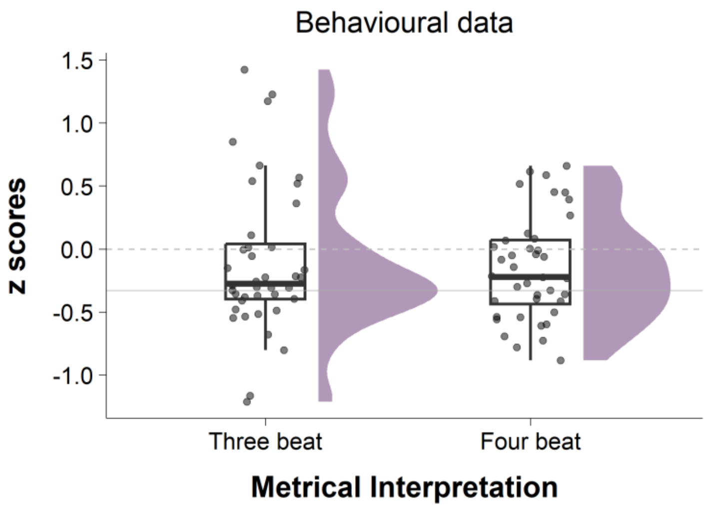


Fig. 11. *Raincloud plots of the behavioral meter-related z-scores of the metrical interpretation in the pre-training session.*

III. Discussion

Following Chemin et al., (2014) steps who highlighted the impact of body movement on the shaping of musical rhythm perception, the present study explored the interaction between rhythm perception and motor mental imagery, as induced by audio-visual training. To examine any selective enhancement of meter-related frequencies in neural and behavioral responses, we respectively used electroencephalography and a microphone to collect the neural and behavioral (i.e., hand clapping) responses.

Our results showed a selective enhancement of neural responses at meter-related frequencies when compared to the stimulus in the four-beat meter condition. This enhancement has been shown in both the pre- and post-audio-visual training session. This selective enhancement in four-beat meter condition, that we do not find in the three-beat meter condition, could potentially be explained by a very prominent second harmonic, at 0.83 Hz, which is comprised in the four-beat meter-related frequencies (see Appendix 5). Because only few participants clapped at this slow rate (i.e., IRI of 1200ms corresponding to this 0.83 Hz), future analyses taking only two metre-related frequencies (i.e., 1.67 Hz, corresponding to IRIs of 0.6 s, and its harmonic at 3.33 Hz) in the four-beat metre condition could be conducted to reduce this possible bias boosting the four-beat metre-related *z* scores. Behaviorally, we showed a selective enhancement in both three-beat and four-beat meter related frequencies but only in the post-audio-visual training session.

However, we showed no significant effect of session nor audio-visual training condition in the neural responses of participants after the audio-visual training. It confirms the findings of Guérin et al. (2024) that showed no significant results in the neural responses when using a similar experimental design but with a motor training instead. Furthermore, our results showed a significant effect of session in the post-training behavioral response at meter-related frequencies. While surface EEG responses to rhythmic stimuli is believed to primarily reflect activity from the auditory cortex, behavioral responses further involve motor and associative areas

(Merchant & Honing, 2013; Nozaradan et al., 2017). The discrepancy between the main effect of the audio-visual training session observed in the behavioral, but not the neural responses would therefore suggest that the motor mental imagery mostly impacts higher lever cortical areas, later involved in movement production.

As introduced before, culture has an impact on musical rhythm processing (Cameron et al., 2015; Kaplan et al., 2022). The common western perception being the three-beat meter condition, we hypothesized larger responses in the three-beat compared to the four-beat meter condition because of the familiarity with this particular perception. Despite our starting hypothesis concerning the metrical interpretation in the pre-audio-visual training sessions, the results showed no significant difference between three vs. four-beat meter-related frequencies in the neural nor behavioral amplitude responses. Therefore, three-beat meter-related frequencies were not enhanced compared to four-beat meter-related frequencies in both the neural and behavioral responses. As we can see in Figure 9, most of the participants had difficulties clapping along with any of the two plausible metrical interpretations. This could be due to the complexity of the input rhythm we used during the tests. This ambiguous rhythm from Africa was very complex and could be perceived in two different ways (three-beat meter or four-beat meter) depending of our cultural background (Guérin et al., 2024; Locke, 1982). The temporal structure of this rhythm pattern does not favor one metrical interpretation over the other (see Figure 4). It was very difficult for western-enculturated participants to perceive and clap a steady beat. Participants could have not felt any pulses and clapped with their own natural speed without taking the input rhythm in notice.

In the future, these results could be compared with the motor-training session from Guérin et al. (2024)'s project who used a similar protocol. Thus, we could see if there was any effect from one training condition compared to the other (i.e., Audio-visual training vs Motor-training). Perhaps participants had a better effect of post-session because of the movement they really had to perform and thus they were more concentrated. We could also think that movement training had better performance because the way that participants moved was specific to them. In the audio-visual training session from our study, every participant experienced the very same training. Thus, their training might not have been sufficiently personal. Additionally, it would be interesting to see if the neural response would be enhanced after an audio-visual training session if it was a simpler rhythm used during the stimulus (e.g., unsyncopated rhythm which possess meter-related frequencies already present in the stimulus spectra).

IV. Limitations

Some limitations are to be quoted for this study, even if the experimental protocol was strongly conducted.

Because the rhythm we used in our study was complex (syncopated rhythm from the West- and Central African musical repertoire, unfamiliar to the western-enculturated participants recruited in this study), it may be the rhythmic input who prevented from any neural effect and not the audiovisual training itself. Maybe we have reached a limit in the complexity of the rhythmic input listened to for the majority of the participants.

Another limitation could be the explanation given to the participant during the testing. In order not to differ in the speech given to each participant, we wrote a specific instruction text. However, some participants had some difficulties understanding these instructions and had difficulties in the pre-training clapping session.

Finally, participants felt that the testing was very long and thus some of them had difficulties to stay sufficiently aware at the end of the test. This could have influenced the results in not having any effect.

V. Conclusion

The present study searched for the effect of a short audiovisual-training (more precisely motor mental imagery) on rhythm perception. We used electroencephalography to collect neural responses and asked participants to clap in their hands to collect behavioral responses.

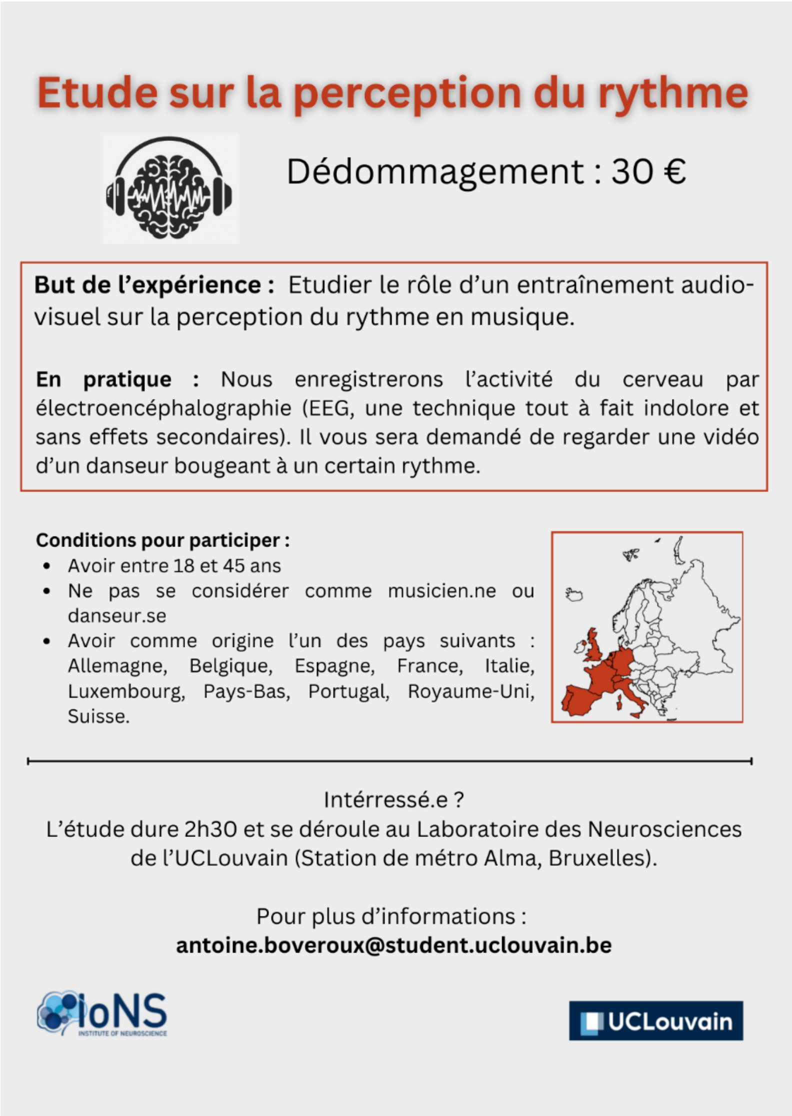
Our results showed a selective enhancement of neural responses for the meter-related frequencies compared to the stimulus in the four-beat meter condition. However, this enhancement could be due to a very prominent second harmonic. Behaviorally, we showed a selective enhancement in both three-beat and four-beat meter related frequencies but only in the post-audio-visual training session.

The electroencephalography showed no significant effect of the audio-visual training. However, we showed an effect of the behavioral data after the audiovisual-training session. From these results, we hypothesized that this effect of session could be due to the motor cortex or associative area but not from the auditory cortex.

Our study contributed in the progress of comprehension about rhythm perception and the impact of movement and motor mental imagery.

VI. Appendices

Appendix 1: Recruitment Flyer



Appendix 2: Musical aptitude questionnaire

QUESTIONNAIRE

Nom, Prénom : ______________________________

Genre (Homme, Femme, Autre) : ______________________________

Date de naissance : ______________________________

Main dominante : ☐ Droite ☐ Gauche

Données démographiques

Q1 : Pays dans lequel **vous** avez grandi (plusieurs options sont possibles) :

____

(Si autre que la Belgique, veuillez préciser l'âge auquel vous êtes arrivés en Belgique : __________)

Q2 : Culture dans laquelle **vous** avez baigné (plusieurs options sont possibles) :

____

Q3 : Pays dans lequel **vos parents** ont grandi (plusieurs options possibles) :
(S'ils ont migré en Belgique, veuillez préciser l'âge auquel ils sont arrivés : _________)

Parent n°1 : ______________________ Parent n°2 : ______________________

Q4 : Culture dans laquelle **vos parents** ont baigné (plusieurs options sont possibles) :

Parent n°1 : ______________________ Parent n°2 : ______________________

Langues pratiquées couramment

Q5 : Langue (ou idiome) maternelle (plusieurs options sont possibles) :

____

Q6 : Langue(s) (ou idiomes) secondaire(s) (plusieurs options sont possibles) :

____

Q7 : Durée moyenne pendant laquelle la(les) langue(s) secondaire(s) est(sont) parlée(s) :

Langue secondaire n°1 : ______ h/semaine
Langue secondaire n°2 : ______ h/semaine
Langue secondaire n°3 : ______ h/semaine

Expertise et préférences musicales

Q8 : Avez-vous déjà suivi des cours de musique de manière régulière, seul·e ou en groupe ?

☐ Oui ☐ Non

Si oui, veuillez spécifier la période / l'âge, l'instrument et le nombre moyen d'heures de pratique musicale par semaine :

PERIODE (par exemple, entre 10 et 12 ans)	INSTRUMENT ET/OU AUTRE	NOMBRE MOYEN D'HEURE PAR SEMAINE
______________________	______________________	____________
______________________	______________________	____________
______________________	______________________	____________
______________________	______________________	____________

Q9 : Quel qualificatif vous correspond le mieux ? (veuillez cocher votre réponse)

- Non-musicien·ne
- Non-musicien·ne mais grand·e amateur·ice de musique
- Musicien·ne amateur·ice
- Musicien·ne amateur·ice sérieux·se
- Musicien·ne semi-professionnel·le
- Musicien·ne professionnel·le

Q10 : Êtes-vous familier·ère (écoutez-vous, jouez-vous ou dansez-vous souvent) à la musique typique de l'une des régions ou pays énumérés ci-dessous ?

(si oui, veuillez préciser le style / la région et le nombre moyen d'heure d'écoute hebdomadaire) :

- L'Occident (Europe, Amérique du Nord) : ☐ Oui ☐ Non
  Si oui, style / région : ___________________________ pendant ____ h/semaine
- L'Afrique : ☐ Oui ☐ Non
  Si oui, style / région : ___________________________ pendant ____ h/semaine
- L'Amérique centrale et latine ☐ Oui ☐ Non
  Si oui, style / région : ___________________________ pendant ____ h/semaine
- L'Asie : ☐ Oui ☐ Non
  Si oui, style / région : ___________________________ pendant ____ h/semaine
- Autre : ☐ Oui ☐ Non
  Si oui, style / région : ___________________________ pendant ____ h/semaine

Expertise en danse

Q11 : Avez-vous déjà suivi des cours de danse de manière régulière, seul·e ou en groupe ?

☐ Oui ☐ Non

Si oui, veuillez spécifier la période / l'âge, le type de danse et le nombre moyen d'heures de pratique musicale :

PERIODE (par exemple, entre 10 et 12 ans)	**TYPE DE DANSE**	**NOMBRE MOYEN D'HEURE PAR SEMAINE**
______________	______________	__________
______________	______________	__________
______________	______________	__________
______________	______________	__________

Appendix 3: Post-experimental questionnaire

<u>Familiarité avec le pattern rythmique utilisé pendant l'expérience</u>

Q12 : A quel point était-il difficile de taper dans les mains en suivant le rythme ?

- Vous pouvez choisir entre 0 (pas du tout difficile), 100% (très difficile), et les niveaux intermédiaires de 25%, 50% et 75%

☐ 0% ☐ 25% ☐ 50% ☐ 75% ☐ 100%

Q13 : A quel point avez-vous aimé le rythme ?

- Le format de réponse est le même : vous pouvez choisir entre 0 (vous n'avez pas du tout aimé), 100% (vous avez extrêmement aimé), et les niveaux intermédiaires de 25%, 50% et 75%

☐ 0% ☐ 25% ☐ 50% ☐ 75% ☐ 100%

Q14 : Dans quelle mesure le rythme vous a-t-il semblé inconnu et étrange ?

- Le format de réponse est le même : vous pouvez choisir entre 0 (vous ne l'avez pas du tout trouvé étrange), 100% (vous l'avez trouvé extrêmement étrange), et les niveaux intermédiaires de 25%, 50% et 75%

☐ 0% ☐ 25% ☐ 50% ☐ 75% ☐ 100%

Q15 : Le rythme vous a-t-il rappelé quelque chose ? ☐ Oui ☐ Non

<u>Si oui</u>, à quoi vous a-t-il fait penser ? Ici, vous pouvez répondre par tout ce qui vous vient à l'esprit, que ce soit le nom d'un style de musique, d'un morceau ou d'un genre musical, des activités ou des événements que vous connaissez dans votre vie de tous les jours ou tout autre chose que le rythme vous a rappelé.

____

____

____

Appendix 4: Consent form

FORMULAIRE DE CONSENTEMENT ECLAIRE AU PARTICIPANT

1. Je soussigné(e), ...

   déclare avoir lu l'information qui précède (formulaire daté du 24/09/2018; v1) et accepter de participer à l'étude intitulée «*How musical rhythm moves humans: functional mechanisms of entrainment and perception-action coupling*». Cette étude comporte plusieurs expériences.

   Ma participation à l'expérience comportera les procédures suivantes :

	OUI	NON
Enregistrement électroencéphalographique de surface	☐	☐
Stimulation magnétique trancrânienne (SMT)	☐	☐
Stimulation auditive	☐	☐
Stimulation visuelle	☐	☐
Production de mouvements	☐	☐

2. On m'a remis une copie de ce formulaire de consentement éclairé signé et daté, ainsi que de la note d'information destinée au patient. J'ai reçu une explication concernant la nature, le but, la durée et les effets prévisibles de l'étude et j'ai été informé(e) de ce qu'on attend de ma part. Les risques et avantages éventuels de l'étude m'ont été expliqués. On m'a donné le temps et l'occasion de poser des questions sur l'étude; toutes mes questions ont reçu une réponse satisfaisante.

3. Au cas (exceptionnel) où une observation qui nécessiterait un suivi médical serait détectée, il m'est demandé de préciser la démarche que l'investigateur suivra (cocher la démarche choisie):
   - ☐ Je souhaite ne pas en être informé(e)
   - ☐ Je souhaite que le responsable de l'étude m'en informe
   - ☐ Je souhaite que le responsable de l'étude en informe le médecin dont j'inscris les coordonnées complètes ci-après:

     ....

     ....

4. J'ai été informé(e) de l'existence d'une assurance couvrant les cas éventuels de lésions imputables aux procédures de l'étude.

5. Je sais que cette étude a été soumise à l'approbation de la Commission d'Éthique Biomédicale Hospitalo-Facultaire de l'UCL.

6. Je suis libre de participer ou non, de même que quitter l'étude à tout moment sans qu'il soit nécessaire de justifier ma décision et sans que cela n'entraîne le moindre désavantage pour mon traitement médical ultérieur.

7. Je sais que les représentants du commanditaire, du Comité d'Éthique ou des autorités d'enregistrement peuvent souhaiter inspecter mes données médicales pour vérifier l'information recueillie. En signant ce document, j'autorise cette inspection de mes données dans le respect de la

loi belge du 8 décembre 1992 relative à la protection de la vie privée, de la loi du 22 août 2002 relative aux droits du patient et de la loi du 7 mai 2004 relative à l'expérimentation humaine.

8. Je consens de mon plein gré à participer à cette étude.

_______________________________________ ______________________

Nom, prénom et signature du/de la volontaire/patient(e) Date (jour/mois/année)

Je confirme que j'ai expliqué la nature, le but et les effets prévisibles de l'étude au/à la volontaire/patient(e) mentionné(e) ci-dessus. Le/la volontaire confirme son accord de participation par sa signature personnellement datée.

_______________________________________ ______________________

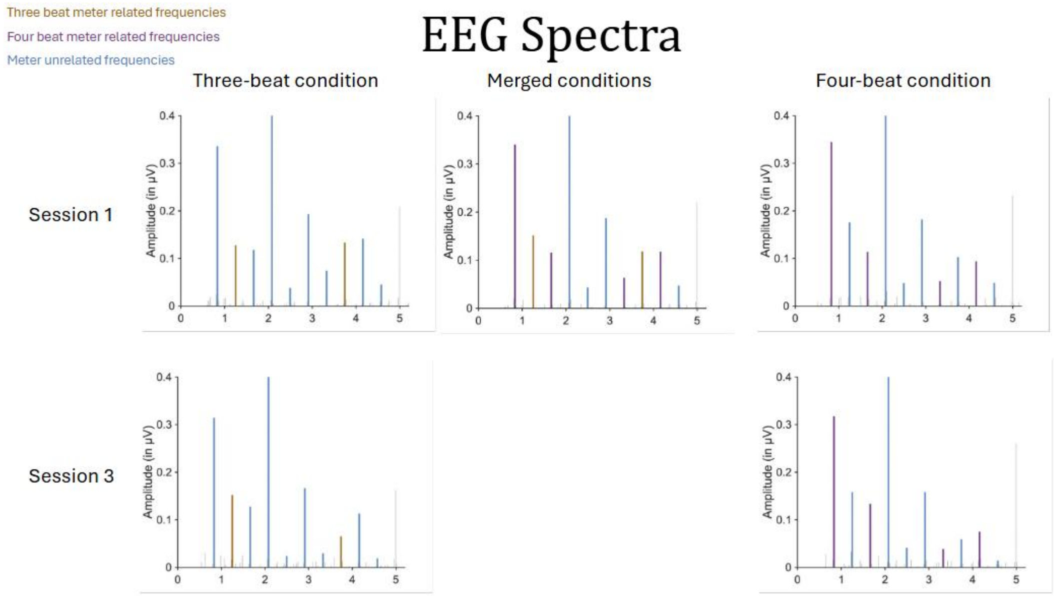
Signature de la personne qui procure l'information Date (jour/mois/année)

____

Nom et Prénom en lettres capitales de la personne qui procure l'information

Appendix 5 : EEG and clapping spectra

A



B

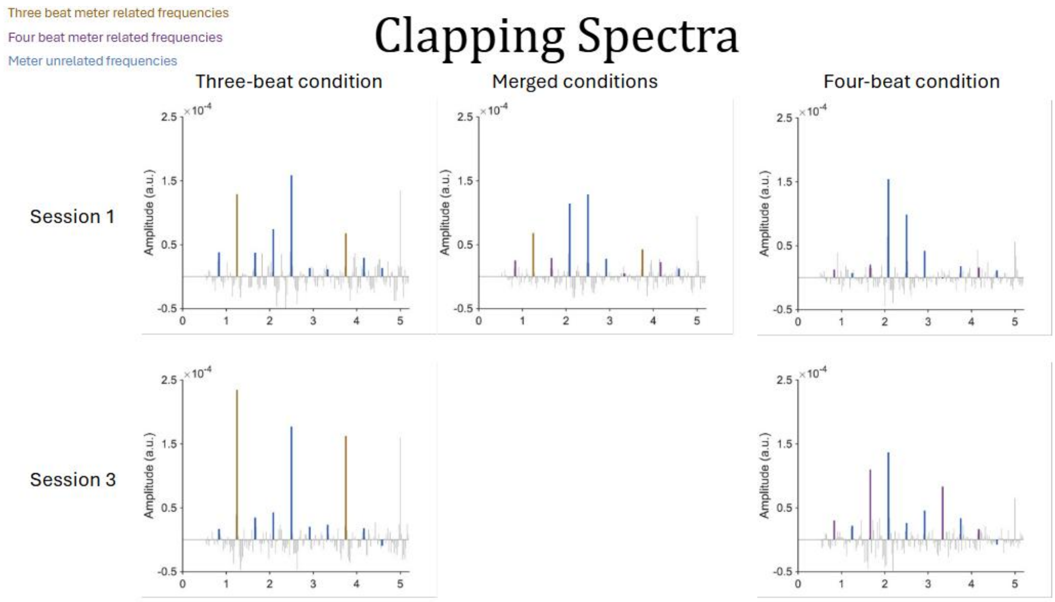


Fig.12. *(A) EEG spectra, (B) Clapping spectra. Frequency domain representation of three-beat and four-beat condition meter-related frequencies in session one and session three. Merged conditions is the association of three-beat condition and four-beat condition. Three-beat meter related frequencies are represented in brown, four-beat meter related frequencies are represented in purple, the unrelated meter frequencies are represented in light blue.*

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Summary

Introduction: Music makes us move. To coordinate movements with rhythmic inputs, an internal representation of time is required. Interpretation of a specific rhythm input is highly flexible and may depend on a multitude of factors. Body movement is known to enhance rhythm perception. But it is still unclear which component of movement is the principal actor of this enhancement.

Method: Forty participants took part in an audio-visual training of a syncopated rhythm which could be interpreted in three-beat or four-beat. Half of the participant took part in a three-beat training while the other half took part in a four-beat training. We used electroencephalography to capture the neural responses, and we asked participants to clap in their hands to capture the behavioral responses. We then used statistical methods to evaluate the effect of the training, of training condition and the interaction between both.

Results: Results showed no significant results of the neural response in any of the component analyzed. However, the behavioral data showed a significant effect of session after the audiovisual-training session (p = .008).

Conclusion: We hypothesize that the effect of the behavioral response could be linked to another brain area such as motor or associative area instead of the auditory cortex.

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