Culture-Driven Neural Plasticity and Imprints of Body-Movement Pace on Musical Rhythm Processing

Ségolène M. R. Guérin[1], Emmanuel Coulon[1], Tomas Lenc[1], Rainer Polak[2], Peter E. Keller[3], and Sylvie Nozaradan[1,4]

[1]Institute of Neuroscience (IoNS), Université Catholique de Louvain (UCLouvain), Brussels, Belgium

[2]RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion, University of Oslo, Norway

[3]Center for Music in the Brain, Department of Clinical Medicine, Aarhus University & The Royal Academy of Music Aarhus/Aalborg, Aarhus, Denmark

[4]MARCS Institute for Brain, Behaviour and Development, Western Sydney University, Sydney, Australia

Author Note

Ségolène M. R. Guérin https://orcid.org/0000-0003-0990-9408

Emmanuel Coulon https://orcid.org/0000-0002-8304-2382

Tomas Lenc https://orcid.org/0000-0001-5796-1388

Rainer Polak https://orcid.org/0000-0001-5684-1499

Peter E. Keller https://orcid.org/0000-0001-7579-6515

Sylvie Nozaradan https://orcid.org/0000-0002-5662-3173

The study data and codes will be shared openly as part of the publication of the article. The study is receiving financial support from the European Research Council (ERC Starting Grant Rhythm and Brains, ref. 801872). The authors have no competing financial interests to declare. The ethics committee of the Université Catholique de Louvain, Belgium, approved the proposed study (ref. 2018-353).

Correspondence concerning this article should be addressed to Ségolène M. R. Guérin (segolene.guerin@uclouvain.be).

General Stage 1 Abstract

The proposed programmatic registered report aims at capturing direct neuroscientific evidence for the rhythmic, movement-related shaping of auditory information with a cross-cultural perspective. Specifically, West/Central African- and Western-enculturated individuals will be tested in two distinct studies, to demonstrate the culture-driven neural plasticity in human rhythm processing, and how it is shaped by the pace of rhythmic body movement. Electroencephalography (EEG) and hand clapping will be recorded in separate sessions in response to an auditory rhythm derived from West/Central African music repertoire. These recordings will be conducted both before and after a body movement session where participants will engage in stepping and clapping to the rhythm following a specific metre (three- vs. four-beat metre). We hypothesise that the behavioural and neural representation of metre in the pre-movement session will be distinct in the African vs. Western-enculturated participant groups. Moreover, the representation of metre conveyed by prior movement will be selectively sharpened in the neural and behavioural responses obtained during the post-movement session. This movement effect is expected to be more pronounced for the metrical interpretation that is predominant according to the participant's musical culture. Collectively, these findings are expected to elucidate how prior experience, shaped by long-term cultural background and short-term motor practice, imprint onto rhythm processing in humans.

Keywords: music cognition; cross-cultural; rhythmic entrainment; beat and metre perception; sensorimotor synchronisation; body movements; EEG; frequency tagging

Imprints of Periodic Body Movement Onto Subsequent Processing of Auditory Rhythm

Stage 1 #1 Abstract

While musical rhythms elicit rhythmic behaviours (e.g., dancing), the opposite is also true, and body-movement pace shapes subsequent processing of auditory information. Although this phenomenon is deemed an established principle in music transmission around the globe, clear behavioural and neuroscientific evidence is still lacking. To capture the brain processes underlying this plasticity, electroencephalography (EEG) and hand clapping to an auditory rhythm (derived from West/Central African musical traditions) will be recorded in separate sessions, both before vs. after a body-movement session, in an African-enculturated sample of participants. The movement will consist of stepping and clapping to the rhythm following a specific metrical interpretation (either three-beat metre for one group of participants, or four-beat metre for another group). We predict post-movement enhancement in neural and behavioural entrainment, selective to the periodicity corresponding to the metrical interpretation conveyed by the pace of prior body movements. These findings aim to demonstrate how body-movement pace flexibly imprints onto human sensory processing.

Keywords: music cognition; rhythmic entrainment; beat and meter perception; neural representation; body movements; EEG; active sensing; sensorimotor synchronisation; frequency tagging

Neural Plasticity in Musical Beat Processing Driven by Short-Term Body Movement and Long-Term Cultural Exposure

Stage 1 #2 Abstract

Music compels humans to move with the musical rhythm. In turn, movement pace can shape rhythm perception, and this widely recognised yet understudied effect is likely influenced itself by cultural experience throughout an individual's life. However, clear behavioural and neuroscientific evidence for this short- and long-term shaping of rhythm processing is still lacking. This study aims to capture the brain processes underlying this plasticity, by comparing electroencephalography (EEG) and hand clapping to an auditory rhythm, derived from West/Central African music repertoires, across individuals with specific cultural background from West/Central Africa and a Western convenience sample of individuals. These measurements will be collected both before and after a session of body movement to the rhythm corresponding to a specific metre (three- vs. four-beat metre). First, we predict neural and behavioural differences between the two cultural groups concerning the preferred metric mapping observed before body movement. Moreover, we predict post-movement enhancement in neural and behavioural entrainment, selective to the metre conveyed by prior movement, and magnified for the metre predominant in the participant's culture. Findings are expected to pinpoint the brain processes allowing prior experience of movement and culture to imprint onto rhythm processing in humans.

Keywords: music cognition; cross-cultural; rhythmic entrainment; beat and meter perception; neural representation; sensorimotor synchronisation; body movements; EEG; sensorimotor synchronisation; frenquency tagging

Culture-Driven Neural Plasticity and Imprints of Body-Movement Pace in Musical Rhythm Processing

Moving the body on music can help individuals to internalise the temporal structure of music, making it easier to understand and appreciate the rhythmic complexities of a musical piece as it unfolds over time (Phillips-Silver & Trainor, 2007; Su & Pöppel, 2012; Vuust & Witek, 2014). In addition, prior cultural experience individuals encounter throughout their lives, including stylised ways of moving to musical rhythms (e.g., baby bouncing and children's games, music-accompanied marching and work, dancing to music), could also contribute to the way they perceive and interpret musical rhythms (Hannon & Trehub, 2005; Jacoby & McDermott, 2017; Polak et al., 2018). Together, these short- and long-term factors may thus interact to shape behaviour and neural processing of auditory rhythmic input.

The proposed programmatic registered report aims at capturing direct neuroscientific evidence for the rshaping of auditory information by the pace of previous movements with a cross-cultural perspective. Specifically, West/Central African- and Western-enculturated individuals will be tested in two distinct studies, to demonstrate the culture-driven neural plasticity in rhythm processing in humans. Each Stage 2 output is intended to test a set of specific intra-cultural hypotheses, but the two data sets will also be combined to examine a series of cross-cultural hypotheses. Herein, we provide a theoretical rationale for each of the two studies separately, to clearly identify the content related to each Stage 2 output.

Stage 1 #1 Introduction

Animals commonly rely on rhythmic movements to explore their environment, which facilitates the sampling of sensory information (Zalta et al., 2020; Gibson, 1962). This so-called 'active sensing' process is easily conceivable in the context of vision, somatosensation, or olfaction, where eye, finger, or sniffing movements directly contribute to sensory exploration. In the scope of audition, the way movement might shape perception is less straightforward; this is especially true in species such as humans, who do not use echolocation as a main sensory system, wherein the degree to which such an active sensing process is used to regulate and facilitate sensory inflow, thereby optimising sensitivity to external sounds, remains unclear (Schroeder et al., 2010). The proposed study aims to capture how the pace of body movements leave its imprint on subsequent processing of auditory information in humans, by capitalising on the intrinsic interplay between music and body movement.

Music has accompanied human activities since the dawn of time (Brown, 2022; Garfinkel, 2018; Vander Elst et al., 2023). Specifically, musical rhythm provides an anchor to time movements through its often highly recurrent temporal structure, a process referred to as *sensorimotor synchronisation* (Repp, 2005; Repp & Su, 2013). This temporal coordination between a rhythmic movement and external auditory rhythm is underpinned by anticipatory mechanisms that allow individuals to estimate future acoustic onsets and apply online adjustments if necessary (Cannon, 2021; van der Steen & Keller, 2013; Vuust & Witek, 2014; Vuust et al., 2022).

To be able to form temporal expectancies when listening to music, individuals need to transform complex auditory or other sensory (e.g., visual; Su, 2016) rhythmic inputs into an internal representation of musical-event timing (Cannon, 2021; Large & Palmer, 2002; van der Weij et al., 2017; Vuust et al., 2018). This internal representation typically takes the form of a metre, which corresponds to a nested set of felt pulsations that are often periodic (Lenc et al., 2021; London, 2012; Vuust and Witek, 2014; of note, in the current study, 'metre' is used as a comprehensive term with no explicit specification about the number of pulse layers, thus minimising underlying assumptions). Importantly, the metre perceived when experiencing a given rhythm is not driven by the input in a one-to-one fashion. In other words, the perceptual system does not simply search for an internal periodic template that provides the closest match to periodicities marked by the arrangement of prominent acoustic events over time. Rather, meter perception can be considered a form of perceptual categorisation, thus relying on a flexible mapping between a rhythmic sensory input and an internal representation of periodic pulses (Iversen et al., 2009; Repp, 2010; Schaefer et al., 2011). Arguably, this mapping is far from trivial, especially when the sensory input lacks unambiguous periodic arrangement of salient acoustic features – as in so-called syncopated (Witek, 2017) or contrametric (Kolinski, 1973) rhythms, where rhythmic and metric structures show a degree of incongruency, which are typical for numerous genres of popular, groove-based music around the world (e.g., jazz, funk, breakbeat, Afro-Cuban, and African styles; Huron & Ommen, 2006; London et al., 2017; Temperley, 1999, 2000). In these specific cases, metre perception must rely on internal processes beyond mere detection of acoustic periodicities in the relevant temporal range (Lenc et al., 2021; London, 2012). One of these processes is the learned *association* between contextual cues (e.g., particular rhythmic figure, timbre, tempo, and social setting) and a specific internal metre (Kaplan et al., 2022; London, 2012; London et al., 2017; van der Weij et al., 2017).

Several theoretical models have been proposed to describe the nature of associations between a rhythmic figure (i.e., temporal pattern of sounds) and an internal metre. These models emphasise to different degrees the role of active body movement in learning to map a particular rhythmic stimulus onto an internal representation of a particular metre. For instance, the predictive-coding theory of music claims that when listening to music, the brain deploys a predictive model (based on prior experience) that guides our perception (Vuust et al., 2018, 2022). Movement production would allow to form highly-precise auditory predictions due to the combination of the rhythmic input with multiple sensory information (e.g., proprioceptive and visual inputs; Manning & Schutz, 2015; Wing et al., 2010). Another prominent theory, the neural resonance theory, proposes metre perception to emerge due to synchronisation between a given rhythmic stimulus and the intrinsic dynamics of endogenous oscillatory brain networks (Large & Kolen, 1994; Large & Snyder, 2009; Large et al., 2023). Notably, according to this theoretical model, oscillatory interactions between the auditory and motor areas of the brain would be crucial for metre perception to arise (Large et al., 2015; Tichko et al., 2021).

Also suggesting an effect of movement-related processes on metre perception, the active sensing framework states that the motor system modulates the cortical processing of auditory information by refining attention surrounding relevant sensory information (Morillon et al., 2014, 2015). Specifically, motor delta oscillations (0.5–4 Hz) would sharpen the brain processing of rhythmic sounds by synchronising the temporal fluctuations of attention with the timing of auditory events (Morillon et al., 2019; Zalta et al., 2020). The action simulation for auditory prediction (ASAP) hypothesis proposes that the simulation of periodic movement shapes metre perception (Patel & Iversen, 2014; Proksch et al., 2020). According to this hypothesis, cortical motor planning regions would thus be entrained by an implicit and automatic process of movement simulation triggered by rhythmic sounds, and this oscillatory pattern would propagate to auditory areas, influencing the metric interpretation of rhythm (Iversen et al., 2009). Although these theoretical models of musical rhythm perception diverge in a number of ways (e.g., anatomical substrates, directionality of relationship between movement and meter perception), they can be viewed as mutually reinforcing (e.g., by describing mechanisms at the brain level or at the cognitive level; see Large et al., 2023; Zalta et al., 2024); and importantly, each of them presupposes a strong role of motor production in metre perception.

The effect of body-movement pace on the subsequent internal representation of rhythm has been reported in several empirical studies using behavioural methods. For example, both active and passive body movement coordinated with a rhythmic pattern according to a specific metre was found to bias the way individuals subsequently perceive a rhythm, possibly through vestibular-mediated processes (Phillips-Silver & Trainor, 2008; Trainor et al., 2009). Specifically, both adults and infants have been shown to develop increased expectancy of salient sounds at those positions within a rhythmic pattern that were aligned with the metre the individual had previously moved to (Phillips-Silver & Trainor, 2005, 2007; Su & Pöppel, 2012). Nonetheless, the behavioural measures used in these studies only constitute an indirect way to capture the internal representation of metre elicited by a rhythm (Lenc et al., 2021). Convergent evidence across various forms of measurements (e.g., measurements of both the neural and behavioural responses as recorded in separate sessions in response to rhythmic stimuli) could thus help moving a significant step toward a comprehensive understanding of how movement can shape the internal representation of metre. One neuroimaging study found that the neural responses to a rhythmic pattern were significantly bolstered after body-movement production, selectively at frequencies related to the metre that participants had moved to (Chemin et al., 2014). However, the rhythmic stimulus used in this study contained prominent metre-related periodicities in its acoustic structure, thus making it hard to disentangle effects driven by an actual internal representation of metre from effects related to low-level sensory processing of the rhythmic input.

To move a critical step forward, the aim of the first study of this proposed research project is to determine whether short-term prior experience of rhythmic body movements performed in the time course of an experiment is effective in shaping subsequent neural representation of a rhythm. Body movement will consist of a ~15-min session of stepping and clapping to a rhythm (derived from West/Central African musical traditions) in synchrony with an overlaid drum sound indicating a specific metrical interpretation of the rhythm (three- vs. four-beat metre). The neural responses of non-musician African-enculturated participants will be recorded during pre- and post-movement sessions using an electroencephalogram (EEG). A series of trials in which participants clap along the rhythm will be collected at the end of each session, as an ecological index of behavioural entrainment to the metre periodicities (for a discussion on the importance of using ecological behaviours in timing research, see Rose et al., 2021). Ecological plausibility will also be ensured by matching the cultural validity of the rhythmic input used throughout the experiment and the cultural background of the participants.

The objective of this study is to capture direct neuroscientific evidence for the shaping of auditory information by the pace of previous movement. If significant, this effect would thus likely be intrinsically supported by a number of distinct processes, including motor planning, visual, auditory, somatosensory and vestibular cues combined together (Phillips-Silver & Trainor, 2008; Trainor et al., 2009). Movement-related shaping of auditory information was purposely adopted in the current studies (a) for its ecological validity in music and dance contexts, and (b) to increase the likelihood of eliciting an effect in the listening block subsequent to the movement priming, due to the mixture of multisensory effects expected to strengthen carry-over effects. Hence, our objective is *not* to define the necessary and sufficient mechanism for the effect of movement on rhythm perception to take place, but rather to capture the brain processes underlying this holistic effect, while not precluding mental imagery of beat or priming by auditory inputs (as in Nave et al., 2022) that could also significantly shape auditory information.

Stage 1 #2 Introduction

Listening to music powerfully compels humans to move their body in time with the musical rhythm and with each other (Grahn & Brett, 2007; Janata et al., 2012; Madison, 2006). The production of body movement with rhythmic inputs is generally assumed to rely on an internal time reference often called the *metre*, which refers to a nested set of felt pulsations (Cohn, 2020; Honing and Bouwer, 2019; London, 2012; Polak, 2021; of note, in the current study, 'metre' is used as a comprehensive term with no explicit specification about the number of pulse layers, thus minimising underlying assumptions). Crucially, the internal representation of a metre is not fully driven by the acoustic properties of the rhythmic stimulus. Instead, perception of a metre in music can be seen as a perceptual categorisation process, whereby rhythmic sensory inputs are associated with internal representations of specific meters in a many-to-one manner (Iversen et al., 2009; Repp, 2010; Schaefer et al., 2011). In other words, physically different rhythmic stimuli can lead to the same perceived metre. Conversely, the same rhythmic input can lead to the perception of different metres (e.g., a three-beat metre, as in a waltz, or a two-beat metre, as in a march; Desain & Honing, 2003; Locke, 1982).

The particular metre elicited by an external rhythmic stimulus seems to be determined by various factors operating on a short timescale, for example body movement performed concurrently with the stimulus and following a specific metre (Phillips-Silver & Trainor, 2007). Specifically, over the past decades, a number of theoretical models have proposed that prior and concurrent motor production plays an important role in metre perception (e.g., predictive-coding theory of music, neural resonance theory, active sensing, action simulation for auditory perception; Large et al., 2015; Morillon et al., 2019; Patel & Iversen, 2014; Proksch et al., 2020; Vuust et al., 2018).

In addition to recent sensory-motor experiences, associations between a given rhythmic input and a particular internal metre can develop over lifetime, driven by long-term culture-specific exposure (including exposure to a musical tradition; Cameron et al., 2015; Hannon & Trehub, 2005; Jacoby & McDermott, 2017; Polak et al., 2018). Along this line, a recent wave of computational work has started to integrate culture-specific factors into the theoretical models of rhythm and metre perception, thus accounting for the wide cultural diversity of musical experience (Kaplan et al., 2022; Tichko & Large, 2019; van der Weij et al., 2017). While differing in their biological plausibility and the level of description, these computational models aim to explain how prolonged exposure to a musical material characteristic for a given culture or musical tradition may elicit plastic changes in the system, and how these changes would subsequently shape processing of rhythmic inputs.

Previous studies have reported an effect of body movement on subsequent internal representation of rhythm, but most of these studies employed behavioural measures that represent an *indirect* approach to capturing the internal representation of meter induced by a rhythm (e.g., Phillips-Silver & Trainor, 2005, 2007, 2008; Su & Pöppel, 2012; Trainor et al., 2009). To our knowledge, only one neuroimaging study investigated neural responses to rhythmic input after executing intentional whole-body movements. Using electroencephalography (EEG), the authors provided first evidence for the effect of movement on subsequent brain processing of rhythm, with enhanced neural activity at the frequencies specifically related to the metre to which participants had moved (Chemin et al., 2014). However, this work focused exclusively on Western individuals, limiting the generalisability of the findings with respect to the cultural diversity in rhythm processing.

In the same way, all the previous empirical evidence available so far on cultural variations in rhythm processing was gathered exclusively through behavioural approaches (Hannon & Trehub, 2005; Jacoby & McDermott, 2017). For example, individuals have shown better tapping performance to rhythms derived from familiar musical traditions (Cameron et al., 2015; Toiviainen & Eerola, 2003). Notwithstanding the high relevance of this behavioural work, the brain processes underlying the outstanding plasticity of rhythm processing specific to humans remain largely unknown.

The aim of the second study of this proposed research project is to take an important step forward in this endeavour by providing direct behavioural and neuroscientific evidence on how short-term prior experience of rhythmic body movements, together with long-term cultural background, shapes the subsequent internal representation of rhythm. Specifically, a Western convenience sample of non-musician individuals (referred to as Western-enculturated participants hereafter) will be tested using the exact same experimental protocol used in Stage 1 #1. Their neural and behavioural responses to a context-free version of a rhythm derived from West/Central African musical traditions will be analysed to test a set of intra-cultural hypotheses, but will also be compared with those of West/Central African-enculturated participants (referred to as African-enculturated participants hereafter) as collected in Stage 1 #1 to test a set of cross-cultural hypotheses.

Research Hypotheses

This programmatic Stage 1 registered report proposes two distinct studies that are complementary to answer our broad research questions, and will thus result in two Stage 2 articles. Specifically, Stage 1 #1 will target African-enculturated individuals, while Stage 1 #2 will focus on Western-enculturated individuals and the cross-cultural comparisons (see Table 1). Within each study, one group of individuals will participate in a ~15-min body-movement session consisting of stepping and clapping to a rhythm in synchrony with an overlaid drum sound indicating a three-beat metrical interpretation of the rhythm. Another group of individuals will be engaged in the same protocol but following a four-beat metrical interpretation of the same rhythm. The rhythmic input will consist in a context-free version derived from a rhythmic pattern spanning 12 elements often used in musical traditions from West to Central Africa (Agawu, 2006; Kubik, 2010; Poole, 2018), and frequently referred to as Bembé, bell/clave pattern, or standard timeline. Specifically, this rhythmic pattern serves a key role at indicating the temporal reference in African (and African derived) music (Agawu, 2006; Kubik, 2010; Locke, 1982; Poole, 2018; Toussaint, 2003). While empirical evidence is still lacking, ethnomusicologist work suggests that widespread metric mode among populations enculturated in West and Central African musical environments is to experience 12-element rhythmic patterns as suggesting a four-beat metre (Locke, 1982; Poole, 2018). This mode is relatively less prominent in populations enculturated with Euro-American popular or art music traditions. By contrast, individuals with such backgrounds often carry metric modes that would map the same 12-element rhythms to a three-beat metres (Blacking, 1967).

The neural activity of participants will be recorded using EEG while they stay still and listen to the same rhythmic input in two sessions directly preceding and following the body-movement session. At the end of each EEG session, participants will be asked to clap along with the rhythm as an ecological index of behavioural entrainment to the perceived metre (Rose et al., 2021). A frequency-tagging approach will be used to measure the relative prominence of the periodicity corresponding to the perceived metre in the signal of interest (i.e., acoustic input, EEG response elicited by the acoustic input, clapping movement to the acoustic input; Lenc et al., 2021, 2022). Over the past 10 years, this approach has proven to be useful in objectively measuring the input–output transformation performed by the brain, and how this transformation might relate to metre perception (Lenc et al., 2022; Nave et al., 2022; Nozaradan et al., 2017; Stupacher et al., 2016). Here, we predict that an enhanced representation of the metre will be observed in the post-movement neural and behavioural responses to the rhythmic input. This enhancement is expected to be selective to the metre conveyed by prior movement and magnified for the metre predominant in the participant's culture.

In Stage 1 #1, we hypothesise that the amplitude of neural responses at metre frequencies (i.e., three-beat frequencies in the three-beat condition, and four-beat frequencies in the four-beat condition; see Methods) will be enhanced after vs. before the movement session (H_{1a}). This session effect (pre- vs. post-movement) would confirm that short-term multimodal exposure to a specific metre as induced by active, intentional movement shapes subsequent internal representation of an auditory rhythm, possibly through perceptual learning (Cannon, 2021; Pearce, 2018). As an alternative, an absence of effect would indicate that (a) the metrical interpretation was already strongly associated with this rhythmic pattern before the body-movement session, possibly driven by a mix of biological and cultural factors (see Kaplan et al., 2022; van der Weij et al., 2017); or (b) the movement session did not provide a sufficient combination of cues (e.g., auditory, vestibular, tactile) to subsequently stabilise a metrical interpretation in such a short period of time.

In addition, we hypothesise this session effect on neural responses to be magnified in the four-beat condition (H_{1b}). This interaction effect would indicate that moving to the rhythm is more effective at shaping subsequent neural representation of an auditory rhythm when executed according to a culturally relevant metre (i.e., four-beat metre in the case of African-enculturated individuals). On the other hand, if the session effect is greater in the three-beat condition, this would suggest that, in the culturally familiar condition, the skill level is already relatively high, resulting in a ceiling effect.

We also hypothesise that similar effects will be observed at the behavioural level, namely that the amplitude of metre frequencies will be selectively enhanced in the clapping trials (H_{2a}), and that the four-beat movement condition will yield the most powerful effect (H_{2b}). Consistency between brain and behavioural effects would indicate that the observed improvement at clapping the metre in the post-movement session (assumed to be closely related to the way individuals ‘feel’ the metre, due to explicit instructions) is associated with an increased selective representation of the metre frequencies in neural activity. Conversely, observing a significant effect of session in neural but not behavioural responses would suggest that participants may not necessarily be able to use the internal representation of the metre induced by the movement session to guide overt movement beyond the movement session itself.

In Stage Stage 1 #2, we hypothesise that metre frequencies will be enhanced after vs. before the movement session, both at the neural (H_{3a}) and behavioural level (H_{4a}), exactly as expected in Stage Stage 1 #1. However, we expect this pre vs. post-movement effect to be magnified in the three-beat condition for Western-enculturated individuals (i.e., the opposite of what is expected in African-enculturated participants), again for both the neural (H_{3b}) and behavioural measures (H_{4b}).

Regarding the cross-cultural comparisons, we first hypothesise that a within-group comparison in the pre-movement session will result in higher amplitudes of neural (H_{5a}) and behavioural (H_{5b}) responses at metre frequencies in the four-beat metre condition for African-enculturated individuals (data collected in Stage Stage 1 #1), while Western-enculturated individuals (data collected in Stage Stage 1 #2) will display higher amplitudes in the three-beat metre condition. This pattern of results would indicate enculturated disposition or bias for a certain metric mapping due to long-term musical exposure (Benadon, 2020; Blacking, 1967; Locke, 1982). On the other hand, a lack of significant effect would suggest that the context-free rhythm used in the proposed study does not elicit a culturally-biased metric mapping.

In addition, we hypothesise that African-enculturated individuals will display a stronger pre-movement bias towards the culturally relevant metrical interpretation (i.e., four-beat metre) when compared to Western-enculturated individuals (whose music repertoire does not contain this rhythm), both at the brain (H_{6a}) and behavioural level (H_{6b}). This interaction effect would confirm that long-term musical exposure significantly shapes rhythm processing. Alternatively, an absence of effect would indicate that a richer combination of acoustic cues (e.g., timber), musical context (e.g., instrumentation richness), and/or listening environment (e.g., traditional ceremony) may be critical to activate culture-specific metre representations.

Finally, we will test whether African-enculturated individuals show generally greater flexibility in their metrical interpretations. Body movement was found to affect subsequent internal representation of rhythm in Western-enculturated individuals when performed following a three-beat metrical interpretation, but not when performed following a four-beat metrical interpretation (Chemin et al., 2014). However, based on the higher prevalence of rhythmic patterns that are metrically malleable (i.e., only weakly suggestive of one specific metric mapping to be preferred over musically-plausible alternatives) in African musical traditions, individuals familiar with these musical repertoires should be prone to perceive them according to different metrical interpretations depending on contextual cues (Cameron et al., 2015; Locke, 2011; Temperley, 2000). Therefore, we expect to find that prior movement executed along the metre less predominant in individual's cultural background would have larger effect in the case of African-enculturated individuals compared to Western-enculturated individuals (H_7). Conversely, an absence of significant effect would denote that (a) the learned association of malleable rhythms with a specific meter (i.e., four beat) in African-enculturated participants is stable (Agawu, 2006; London et al., 2017; Polak, 2010) and flexibility to override it is not part of the perceptual learning processes; or (b) high musical expertise in African-derived music genres is key to switch from one metric interpretation to another (Benadon, 2020; Locke, 1982).

Methods

Ethical Clearance

The ethics committee of the Université Catholique de Louvain, Belgium, approved the proposed study (ref. 2018-353). Informed consent will be obtained from all the participants prior to inclusion in the proposed study. Participants will be compensated for their time.

Participants

Adult volunteers considered eligible to participate in the study will be aged between 18 and 45 years, non-musicians and non-dancers, free of sensory (i.e., no auditory impairment or uncorrected visual impairment) and motor dysfunctions (i.e., no upper- and/or lower-limb disorders), and not self-identify as having psychiatric or neurological disorders. In the present research project, non-musicians or non-dancers are 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.

Participants will be included in the African-enculturated group if they 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: Mali, Côte d'Ivoire, Togo, Benin, Cameroon, Gabon, Republic of Congo, or Democratic Republic of Congo; and (b) they speak fluently and at least 1h/week one of the idioms (i.e., languages, dialects) from the above-mentioned countries. For participants to be included in the Western-enculturated group, they will need to self-report that (a) they do not meet the two criteria described above for the African-enculturated group, (b) 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 (c) they speak fluently and at least 1h/week one of the idioms (i.e., languages, dialects) from the above-mentioned countries. The two screening questionnaires are available for consultation in Supplementary File 1.

The sample size for the critical statistical test of each research hypothesis was calculated using R with the 'pwr' and 'WebPower' packages (code is available here: https://zenodo.org/doi/10.5281/zenodo.10221480). The EEG and behavioural results of Chemin et al. (2014) were used as a parameter for H_1–H_7, with one-tailed tests. For H_1 and H_3, the power analysis indicated that eight participants would be required for the sesion effect (d = 1.53; α = .02; 1-β = .90) and 20 participants per movement condition would be necessary for the interaction effect between movement condition and session (f = 0.89; α = .02; 1-β = .90). For H_2 and H_4, six participants would be required for the session effect (d = 1.77; α = .02; 1-β = .90) and 20 participants per movement condition would be necessary for the interaction effect between movement condition and session ($f = 0.89$; $\alpha = .02$; 1-$\beta = .90$). In addition, 20 participants per group would be needed for the interaction effects of H_5–H_7 ($f = 0.89$; $\alpha = .02$; 1-$\beta = .90$). Therefore, a total sample of 40 participants (i.e., 20 per movement condition) will be recruited for each of the two proposed studies, which means a total of 80 participants for the whole research project (see see Table 1).

The small telescopes approach was used to determine the smallest effect size of interest (SESOI; i.e., the difference that is considered large enough to be meaningful; Simonsohn, 2015). Accordingly, the SESOI was set to the effect size that an earlier study would have had 33% power to detect (Lakens et al., 2018). Here again, the behavioural and EEG results of Chemin et al. (2014) were used as parametres for H_1–H_7, with one-tailed tests. The SESOI computations were performed using R (code is available as supplementary material here: https://zenodo.org/doi/10.5281/zenodo.10221480) and the outputs are displayed in Table 1.

Experimental Procedure and Tasks

Both groups of participants (i.e., African- and Western-enculturated individuals) will complete the same experimental procedure and tasks describe below, in order to offer a valid cross-cultural comparison in Stage 2 #2.

Experimental Procedure

Each participant will be administered three sessions (~20 min each) on the same day. In the pre- and post-movement sessions, the participant will be asked to perform a separate listening and hand-clapping task in a fixed order (see Figure 1). Brain activity of the participant will be recorded with EEG during the listening task and behavioural data will be collected during the hand-clapping task. In the movement session, half of the participants will engage in the three-beat movement condition while the other half will participate in the four-beat movement condition (i.e., between-subjects study design with repeated measures). EEG data will not be collected during the movement session. To verify effective behavioural synchronisation in the movement session, an accelerometer will be attached to the right foot of the participant and hand-clapping sounds will be collected through a microphone. To control for the absence of body movement during the pre- and post-movement sessions, the accelerometer will be placed on the participant's head.

In the pre- and post-movement sessions, the participant will be seated in a comfortable chair, with their head resting against the back of the chair. In these sessions, the participant will be 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 minimise large eye movements). During the movement session, the EEG electrode cables will be unplugged from the amplifier and attached on the participant's shoulders to free their movements.

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 will have a duration of 2.4 s and will be seamlessly repeated 17 times to form a long sequence, with a total duration of 40.8 s (see Figure 2, Panel A). Its 'x.x.xx.x.x.x' structure is based on a 12-intervals grid (200 ms $\times$ 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 '.').

This rhythmic stimulus is particularly relevant to the proposed study for several reasons. Firstly, the rhythmic pattern is culturally valid due to its wide use across musical traditions in Central and West Africa (Locke, 1982; Temperley, 2000). Yet, the pattern can be presented in a decontextualized fashion for the purposes of the current study (e.g., by using pure tones instead of a clave sound that typically delivers the pattern in stylistically valid contexts), thus minimising the interference caused by non-rhythmic contextual cues in participants familiar with musical repertoires containing this pattern. Unlike stimuli used in the majority of prior studies (e.g., 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 metre 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 movement session, a metronome-like acoustic pulse will be added to the auditory stimulus and will serve as a cue to the beat from the targeted metre. This pulse consists of a low-pitched drum sound presented isochronously with an inter-onset interval of 800 ms in the three-beat metre condition and 600 ms in the four-beat metre condition, thus yielding three or four drum cues per repetition of the 2.4-s rhythmic pattern, respectively. In the three-beat metre condition, the pulses are aligned with the first, fifth, and ninth time point on the grid used to generate the rhythmic pattern. In the four-beat metre condition, the pulses occur at the first, fourth, seventh, and tenth grid point (see Figure 1, Panel B). The drum sound coinciding with the first grid point is accented (sound intensity increased by 2.5 dB) to emphasise the onset of each repetition of the pattern. Three additional repetitions of the rhythmic pattern without the overlaid pulse will be 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 1, Panel A). The three auditory stimuli will be generated using MATLAB (version R2022a; MathWorks, Portola Valley, CA).

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 et al., 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 2, 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 analysis of the EEG signals (see below 'EEG Data' subsection), the first and last frequency of the spectrum were discarded from further computation.

To assess the relative prominence of frequencies considered as related to the metre vs. the other, metre-unrelated frequencies, the magnitudes of responses at the 10 frequencies of interest were then converted into z scores following Equation 1 (see Figure 2, Panel B; Lenc et al., 2018):

$$z_i = \frac{A_i - \bar{A}_{\text{all}}}{s_{\text{all}}} \tag{1}$$

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 metre frequencies (i.e., the frequency corresponding to the metre 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 2 (right part), the stimulus contains a virtually equivalent low acoustic energy (z scores < 0) at either of the two metre periodicities considered here, when compared to the remaining frequencies constituting the envelope spectrum of the rhythm.

Tasks Description

The auditory stimuli will be 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 will be collected), the auditory stimulus will be played to the participant while they will be required to perform an orthogonal task to encourage attentive listening. More precisely, the participant will be 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 will be 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 s. There will be a total of two trials per session containing this deviant period (with those trials being randomly positioned across participants), and these trials will be discarded from further analyses. In the hand-clapping task (i.e., which will directly follow the listening task in both the pre- and post-movement sessions; see Figure 1), the participant will be instructed to clap along with the beat they perceive in the auditory stimulus ('Clap your hands as you would clap in sync with the music at a concert').

During the movement session (i.e., without EEG recordings), the participant will be asked to step on-the-spot and clap with their hands (i.e., whole-body movements) in synchrony with the beat according to a specific metrical interpretation of the rhythmic pattern, as indicated with the drum cue. In the last three repetitions of the rhythmic pattern, the pulse prompter will stop, and the participant will thus need to continue synchronising to the same metrical interpretation without the pulse prompter (i.e., synchronisation-continuation task; see e.g., Repp, 2001; Rose et al., 2021). Detailed task instructions can be found in Supplementary File 1.

Experimental Design

The experiment will use a fixed block-design procedure (see Figure 1), with each trial lasting 40.8 s in the pre- and post-movement sessions and 48 s in the movement session. The pre- and post-movement sessions will be 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 movement session will consist of 18 trials. To assess the participant's familiarity with the stimulus, they will be asked during the debriefing session at the end of the experiment whether they recognised the rhythmic pattern. The total duration of the experimental procedure will be ~1 hr.

Data Acquisition and Pre-Processing Analyses

Data acquisition will be performed using an ActiveTwo system (BioSemi, Amsterdam, Netherlands) and facilitated by the ActiView software (version 8.13). All the pre-processing analyses will be performed using MATLAB (version R2022a). Data collection and analysis will not be performed blind to the conditions of the study. To avoid a confounding effect of the experimenter, the first and second authors of this Stage 1 manuscript (who will each lead one of the two Stage 2 manuscripts) will each collect data from half of the two groups. Pilot tests were run ($n = 1$ in the three- and four-beat movement condition) to confirm that the proposed experimental protocol and data collection are logistically feasible and that planned analyses will allow us to test the research hypotheses (see Supplementary File 2).

EEG Data

The EEG data will be 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 will be located over the left and right mastoids. Signals will be referenced to the common-mode sense electrode and digitised at a 1024-Hz sampling rate. Electrodes offset relative to the common mode sense (CMS) and driven leg (DRL) electrode loop will be kept below ± 50 mV.

The EEG data will be pre-processed using Letswave6 built-in functions (https://github.com/NOCIONS/letswave6) and custom MATLAB scripts. The raw data will be 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 proposed study (while also allowing further down sampling of the data if necessary). The filtered signals will be 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 will be linearly interpolated using the three closest channels (based on Cartesian coordinates). Note that a channel that will be interpolated in one EEG session will also be interpolated in the other EEG session of the same participant to prevent confounds. In addition, trials showing excessive artefacts will be rejected. The full data set of a participant will be removed prior to further analyses if $> 15\%$ of the channels are interpolated and/or > 3 trials per session are rejected (see Figure 3). Any excluded participants will be replaced to ensure that $n = 20$ per group.

Independent component analysis will be 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 will be identified through visual inspection of the first 10 independent components' waveform and topography, and removed from the EEG signals. Data will then be 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 will be 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 will minimised by subtracting, at each frequency bin, the mean amplitude of the four neighbouring bins (2nd to 5th on both sides; see Bouvet et al., 2020; Lenc et al., 2022). The frequencies will then be 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).

For each participant and session, the amplitude will be measured at frequencies of interest that are defined based on the temporal structure of the rhythmic pattern. Specifically, these frequencies of interest will correspond 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 is determined based on previous studies (see e.g., Lenc et al., 2020, 2022), showing that surface EEG responses to rhythmic acoustic patterns – similar to the one that will be used in the proposed study – mainly project onto this frequency range. From the resulting set of 12 harmonic frequencies, the first frequency (i.e., 0.42 Hz) will be 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., 2022). The last harmonic frequency (i.e., 5 Hz) will also be dismissed, as its amplitude is likely driven by the shape of the individual 200-ms sounds composing the rhythmic pattern (see Figure 2, left part, for depiction of these frequencies as identified in the modulation spectrum of the stimulus).

From this set, the purpose of the study is to assess the relative prominence of frequencies considered as related to the metre periodicity vs. the other, metre-unrelated frequencies (Lenc et al., 2018). To this aim, the amplitude at each of these 10 frequencies of interest will be converted into z scores (see Equation 1). Finally, the obtained z scores will be averaged across metre frequencies (i.e., 1.25 and 3.75 Hz in the three-beat condition [i.e., $\bar{z}_{\text{EEG,3-beat}}$], and 0.83, 1.67, 3.33, and 4.17 Hz in the four-beat condition [i.e., $\bar{z}_{\text{EEG,4-beat}}$]). Along the lines of the sound analysis, the sixth frequency (i.e., 2.5 Hz) will be dismissed as it is found in both metrical interpretations. In each condition, Δ_{EEG} will also be computed as the difference between $\bar{z}_{\text{EEG,3-beat}}$ and $\bar{z}_{\text{EEG,4-beat}}$ (i.e., a positive value indicates more activity at three-beat frequencies when compared to four-beat frequencies).

Behavioural Data

Hand Clapping. Hand clapping will be collected using a microphone (ATR20; Audio-Technica, Machida, Japan) and digitised through the Fireface UC audio interface (sampling rate = 44100 Hz).

Pre- and Post-Movement Sessions. The continuous sound signal recorded during the pre- and post-movement sessions will be 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 will be removed to match epoching of the EEG data. Claps will be detected in the sound signal using the 'findpeaks' function and IRIs will be computed for each trial.

The recorded clapping signal will also be analysed in the frequency domain, similarly to the EEG and sound signals. The continuous sound signal will be averaged across trials. The amplitude envelope of this mean signal will be 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 will also be applied to the obtained spectra. Finally, $\bar{z}_{\text{clapping}}$ and Δ_{clapping} will be computed following the same method described for the EEG data (see Equation 1), with the difference that the frequency range of interest will be adjusted based on visual inspection – the shape of clap events could project onto a larger frequency range than the one typically observed for EEG responses (i.e., slightly beyond 5 Hz).

Movement Session. The continuous audio signal of clapping obtained from participants instructed to synchronise clapping to the drum cue will be segmented into epochs lasting 45.6 s (from 2.4 to 48 s with respect to trial onset). Claps will be detected using a find peaks function applied onto the envelope extracted from the recording signals. The signed asynchrony will be computed as the difference between each clap and its associated pulse. Signed asynchrony will be negative when the clap will be preceding the targeted drum cue, and positive when the clap will be following the targeted drum cue. The mean signed asynchrony within a trial will be calculated as a measure of synchrony with the pulse prompter.

Stepping. Stepping performed during the movement session will be recorded using an accelerometer placed on the participant's right foot (ADXL335; Adafruit, New York, USA), and digitised through the BioSemi analog input box (sampling rate = 1024 Hz). As for the hand-clapping data, the obtained continuous acceleration signal will be segmented into epochs lasting 45.6 s (from 2.4 to 48 s with respect to trial onset), steps will be detected using a find peaks function (the detected peaks will correspond to the initial-contact phase; Buckley et al., 2019; Sant'Anna & Wickström, 2010), and inter-response intervals (IRIs) will be computed. The IRIs time series will then be divided by two, to account for data recorded from one foot only. The asynchrony indices will be computed following the same method described for the hand-clapping data.

Control Measures

Effectiveness of Auditory Stimulation. A prerequisite to our hypotheses is 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 standardised signal-to-noise ratio ($z_{\text{SNR,EEG}}$) of the frequencies of interest will be computed from the raw, non-subtracted amplitude spectrum of EEG data averaged across the fronto-central channels (see Figure 3; Bottari et al., 2020; Vettori et al., 2020).

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

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

where A is the amplitude and s is the standard deviation. This index will serve 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 proposed study is that the selective enhancement of EEG responses at metre-related frequencies are not due to neural responses per so 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 will be recorded using the accelerometer during the listening trials of the pre- and post-training sessions. The $z_{\text{SNR,head}}$ of metre-related frequencies (i.e., 1.25, 2.50, and 3.75 Hz) will be computed following the same method described for the EEG data (see Equation 2). This index will serve as an indicator of head synchronisation with metre-related frequencies.

Statistical Analyses

Data Eligible for Analysis

Note that participants failing to meet the criteria mentioned below will be replaced to ensure that $n = 20$ per group.

Outcome-Neutral Criteria. As described in more details above, only data coming from participants with $\leq 15\%$ of interpolated channels and ≤ 3 rejected trials per session will be analysed (see Figure 3).

Positive Control. A participant's data set will excluded from the analyses if $z_{\text{SNR,EEG}} < 1.96$ (i.e., $\alpha > .02$), which would indicate an absence of neural responses elicited by the rhythmic stimulus.

Planned Analyses

R will be used for the statistical analyses, with alpha set at $p < .020$ (i.e., in accord with the strictest available stipulations from the list of *PCI RR*-friendly journals). For each statistical comparison, the effect sizes (i.e., η^2_{p}, Cohen's d) will be reported as a quantification of the experimental-effect magnitude and interpreted in accord with Cohen (1988)'s guidelines. For effect sizes that will be presented as Cohen's d, $d < 0.5$ will be considered as small, $d \geq 0.5$ as medium, and $d \geq 0.8$ as large. Where effect sizes will be presented as η^2_{p}, $\eta^2_{\text{p}} \geq .01$ will be considered as small, $\eta^2_{\text{p}} \geq .06$ as medium, and $\eta^2_{\text{p}} \geq .14$ as large. To test the robustness of our statistical outcomes (for the importance of conducting multiverse analyses, see Wagenmakers et al., 2023), linear mixed models will also be used to test each hypothesis (with the 'lme4' and 'emmeans' packages), and the results will be reported in a supplementary file.

To examine H_1–H_4, a two-way mixed-model analysis of variance (ANOVA; Session [pre vs. post movement] × Movement Condition [three- vs. four-beat metre]) will be applied on the two dependent variables, $\bar{z}_{\text{EEG}}$ and $\bar{z}_{\text{clapping}}$. To demonstrate that periodic head movements do not contribute significantly to the effects found in the EEG (if any), an identical ANOVA model will be applied on $z_{\text{SNR,head}}$. H_5 and H_6 will be examined by means of a two-way mixed-model Group (African- vs. Western-enculturated group) × Metre Frequency (three- vs. four-beat metre) mixed-model ANOVA. In addition, a two-way ANOVA (Group × Movement Condition) will be considered to examine H_7 (see Table 1).

Normality of residuals will be checked using the R 'performance' package (Lüdecke et al., 2021); if violated, the data will be normalised using a transformation that will be contingent on data distribution curves (e.g., log10, cube root). Where Mauchly's tests will indicate violations of the sphericity assumption, Greenhouse–Geisser corrections will be applied. Independent and pairwise post hoc t tests with Bonferroni adjustments for multiple comparisons will used where necessary to identify where differences lie.

Open Practices

Data Availability

Pilot data are available on a public Zenodo repository (https://zenodo.org/doi/10.5281/zenodo.10221480). All anonymised raw and processed data supporting the reported analyses will be archived in this repository at the point of Stage 2 submission.

Code Availability

The scripts used to conduct the power analysis are available on a public Zenodo repository (https://zenodo.org/doi/10.5281/zenodo.10221480). All scripts supporting the reported analyses will also be archived in this repository at the point of Stage 2 submission.

Acknowledgements

Sylvie Nozaradan is receiving financial support from the European Research Council (ERC Starting Grant Rhythm and Brains, ref. 801872). The founder will have no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

CRediT Author Statement

S. M. R. G.: Conceptualisation; Methodology; Formal analysis; Investigation; Data curation; Software; Visualisation; Project Administration; Writing – original draft; Writing – review & editing. E. C.: Conceptualisation; Methodology; Writing – original draft; Writing – review & editing. T. L.: Conceptualisation; Methodology; Writing – review & editing. R. P.: Methodology; Writing – review & editing. P. E. K.: Writing – review & editing. S. N.: Conceptualisation; Methodology; Formal analysis; Funding acquisition; Resources; Project Administration; Supervision; Writing – review & editing.

Competing Interests

The authors have no competing financial interests to declare.

References

Agawu, K. (2006). Structural analysis or cultural analysis? Competing perspectives on the "standard pattern" of West African rhythm. *Journal of the American Musicological Society, 59*(1), 1–46. https://doi.org/10.1525/jams.2006.59.1.1

Benadon, F. (2020). Meter isn't everything: The case of a timeline-oriented Cuban polyrhythm. *New Ideas in Psychology, 56,* Article 100735. https://doi.org/10.1016/j.newideapsych.2019.03.002

Blacking, J. (1967). *Venda children's songs.* Witwatersrand University Press.

Bottari, D., Bednaya, E., Dormal, G., Villwock, A., Dzhelyova, M., Grin, K., Pietrini, P., Ricciardi, E., Rossion, B., & Röder, B. (2020). EEG frequency-tagging demonstrates increased left hemispheric involvement and crossmodal plasticity for face processing in congenitally deaf signers. *NeuroImage, 223,* Article 117315. https://doi.org/10.1016/j.neuroimage.2020.117315

Bouvet, C. J., Bardy, B. G., Keller, P. E., Dalla Bella, S., Nozaradan, S., & Varlet, M. (2020). Accent-induced modulation of neural and movement patterns during spontaneous synchronization to auditory rhythms. *Journal of Cognitive Neuroscience, 32*(12), 2260–2271. https://doi.org/10.1162/jocn_a_01605

Brown, S. (2022). Group dancing as the evolutionary origin of rhythmic entrainment in humans. *New Ideas in Psychology, 64,* Article 100902. https://doi.org/10.1016/j.newideapsych.2021.100902

Buckley, C., Micó-Amigo, M. E., Dunne-Willows, M., Godfrey, A., Hickey, A., Lord, S., Rochester, L., Del Din, S., & Moore, S. A. (2019). Gait asymmetry post-stroke: Determining valid and reliable methods using a single accelerometer located on the trunk. *Sensors, 20*(1), Article 37. https://doi.org/10.3390/s20010037

Cameron, D. J., Bentley, J., & Grahn, J. A. (2015). Cross-cultural influences on rhythm processing: Reproduction, discrimination, and beat tapping. *Frontiers in Psychology, 6,* Article 366. https://doi.org/10.3389/fpsyg.2015.00366

Cannon, J. (2021). Expectancy-based rhythmic entrainment as continuous Bayesian inference. *PLoS Computational Biology, 17*(6), Article e1009025. https://doi.org/10.1371/journal.pcbi.1009025

Chemin, B., Mouraux, A., & Nozaradan, S. (2014). Body movement selectively shapes the neural representation of musical rhythms. *Psychological Science, 25*(12), 2147–2159. https://doi.org/10.1177/0956797614551161

Cirelli, L. K., Spinelli, C., Nozaradan, S., & Trainor, L. J. (2016). Measuring neural entrainment to beat and meter in infants: Effects of music background. *Frontiers in Neuroscience, 10,* Article 229. https://doi.org/10.3389/fnins.2016.00229

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* Routledge.

Cohn, R. (2020). Meter. In A. Rehding & S. Rings (Eds.), *The Oxford handbook of critical concepts in music theory* (pp. 207–233). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780190454746.013.9

Desain, P., & Honing, H. (2003). The formation of rhythmic categories and metric priming. *Perception, 32*(3), 341–365. https://doi.org/10.1068/p3370

Garfinkel, Y. (2018). The evolution of human dance: Courtship, rites of passage, trance, calendrical ceremonies and the professional dancer. *Cambridge Archaeological Journal, 28*(2), 283–298. https://doi.org/10.1017/S0959774317000865

Gibson, J. J. (1962). Observations on active touch. *Psychological Review, 69*(6), 477–491. https://doi.org/10.1037/h0046962

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

Hannon, E. E., & Trehub, S. E. (2005). Metrical categories in infancy and adulthood. *Psychological Science, 16*(1), 48–55. https://doi.org/10.1111/j.0956-7976.2005.0077

Honing, H., & Bouwer, F. L. (2019). Rhythm. In P. J. Rentfrow & D. J. Levitin (Eds.), *Foundations in music psychology: Theory and research* (pp. 33–69). The MIT Press.

Huron, D., & Ommen, A. (2006). An empirical study of syncopation in American popular music, 1890–1939. *Music Theory Spectrum, 28*(2), 211–231. https://doi.org/10.1525/mts.2006.28.2.211

Iversen, J. R., Repp, B. H., & Patel, A. D. (2009). Top-down control of rhythm perception modulates early auditory responses. *Annals of the New York Academy of Sciences, 1169*(1), 58–73. https://doi.org/10.1111/j.1749-6632.2009.04579.x

Jacoby, N., & McDermott, J. H. (2017). Integer ratio priors on musical rhythm revealed cross-culturally by iterated reproduction. *Current Biology, 27*(3), 359–370. https://doi.org/10.1016/j.cub.2016.12.031

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

Jasper, H. H. (1958). Report of the committee on methods of clinical examination in electroencephalography. *Electroencephalography and Clinical Neurophysiology, 10,* 370–375. https://doi.org/10.1016/0013-4694(58)90053-1

Kaplan, T., Cannon, J., Jamone, L., & Pearce, M. (2022). Modeling enculturated bias in entrainment to rhythmic patterns. *PLOS Computational Biology, 18*(9), Article e1010579. https://doi.org/10.1371/journal.pcbi.1010579

Kolinski, M. (1973). A cross-cultural approach to metro-rhythmic patterns. *Ethnomusicology, 17*(3), 494–506. https://doi.org/10.2307/849962

Kubik, G. (2010). *Theory of african music* (Vol. 2). University of Chicago Press.

Lakens, D., Scheel, A. M., & Isager, P. M. (2018). Equivalence testing for psychological research: A tutorial. *Advances in Methods and Practices in Psychological Science, 1,* 259–269. https://doi.org/10.1177/2515245918770963

Large, E. W., Herrera, J. A., & Velasco, M. J. (2015). Neural networks for beat perception in musical rhythm. *Frontiers in Systems Neuroscience, 9,* Article 159. https://doi.org/10.3389/fnsys.2015.00159

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

Large, E. W., & Palmer, C. (2002). Perceiving temporal regularity in music. *Cognitive Science, 26*(1), 1–37. https://doi.org/10.1207/s15516709cog2601_1

Large, E. W., Roman, I., Kim, J. C., Cannon, J., Pazdera, J. K., Trainor, L. J., Rinzel, J., & Bose, A. (2023). Dynamic models for musical rhythm perception and coordination. *Frontiers in Computational Neuroscience, 17,* Article 1151895. https://doi.org/10.3389/fncom.2023.1151895

Large, E. W., & Snyder, J. S. (2009). Pulse and meter as neural resonance. *Annals of the New York Academy of Sciences, 1169*(1), 46–57. https://doi.org/10.1111/j.1749-6632.2009.04550.x

Lenc, T., Keller, P. E., Varlet, M., & Nozaradan, S. (2018). Neural tracking of the musical beat is enhanced by low-frequency sounds. *Proceedings of the National Academy of Sciences, 115*(32), 8221–8226. https://doi.org/10.1073/pnas.1801421115

Lenc, T., Keller, P. E., Varlet, M., & Nozaradan, S. (2020). Neural and behavioral evidence for frequency-selective context effects in rhythm processing in humans. *Cerebral Cortex Communications, 1*(1), Article tgaa037. https://doi.org/10.1093/texcom/tgaa037

Lenc, T., Merchant, H., Keller, P. E., Honing, H., Varlet, M., & Nozaradan, S. (2021). Mapping between sound, brain and behaviour: Four-level framework for understanding rhythm processing in humans and non-human primates. *Philosophical Transactions of the Royal Society B, 376*(1835), Article 20200325. https://doi.org/10.1098/rstb.2020.0325

Lenc, T., Peter, V., Hooper, C., Keller, P. E., Burnham, D., & Nozaradan, S. (2022). Infants show enhanced neural responses to musical meter frequencies beyond low-level features. *Developmental Science,* Article e13353. https://doi.org/10.1111/desc.13353

Locke, D. (1982). Principles of offbeat timing and cross-rhythm in southern Eve dance drumming. *Ethnomusicology, 26*(2), 217–246. https://doi.org/10.2307/851524

Locke, D. (2011). The metric matrix: Simultaneous multidimensionality in African music. *Analytical Approaches to World Music, 1*(1), 48–72. https://iftawm.org/journal/oldsite/articles/2011a/Locke_AAWM_Vol_1_1.pdf

London, J. (2012). *Hearing in time: Psychological aspects of musical meter* (2nd ed.). Oxford University Press.

London, J., Polak, R., & Jacoby, N. (2017). Rhythm histograms and musical meter: A corpus study of malian percussion music. *Psychonomic Bulletin & Review, 24,* 474–480. https://doi.org/10.3758/s13423-016-1093-7

Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., & Makowski, D. (2021). performance: An R package for assessment, comparison and testing of statistical models. *Journal of Open Source Software, 6*(60), Article 3139. https://doi.org/10.21105/joss.03139

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

Manning, F. C., & Schutz, M. (2015). Movement enhances perceived timing in the absence of auditory feedback. *Timing & Time Perception, 3*(1–2), 3–12. https://doi.org/10.1163/22134468-03002037

Morillon, B., Arnal, L. H., Schroeder, C. E., & Keitel, A. (2019). Prominence of delta oscillatory rhythms in the motor cortex and their relevance for auditory and speech perception. *Neuroscience & Biobehavioral Reviews, 107,* 136–142. https://doi.org/10.1016/j.neubiorev.2019.09.012

Morillon, B., Hackett, T. A., Kajikawa, Y., & Schroeder, C. E. (2015). Predictive motor control of sensory dynamics in auditory active sensing. *Current Opinion in Neurobiology, 31,* 230–238. https://doi.org/10.1016/j.conb.2014.12.005

Morillon, B., Schroeder, C. E., & Wyart, V. (2014). Motor contributions to the temporal precision of auditory attention. *Nature Communications, 5*(1), Article 5255. https://doi.org/10.1038/ncomms6255

Nave, K. M., Hannon, E. E., & Snyder, J. S. (2022). Steady state-evoked potentials of subjective beat perception in musical rhythms. *Psychophysiology, 59*(2), Article e13963. https://doi.org/10.1111/psyp.13963

Nozaradan, S. (2014). Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1658), Article 20130393. https://doi.org/10.1098/rstb.2013.0393

Nozaradan, S., Keller, P. E., Rossion, B., & Mouraux, A. (2018). EEG frequency-tagging and input–output comparison in rhythm perception. *Brain Topography, 31,* 153–160. https://doi.org/10.1007/s10548-017-0605-8

Nozaradan, S., Mouraux, A., & Cousineau, M. (2017). Frequency tagging to track the neural processing of contrast in fast, continuous sound sequences. *Journal of Neurophysiology, 118*(1), 243–253. https://doi.org/10.1152/jn.00971.2016

Nozaradan, S., Peretz, I., & Mouraux, A. (2012). Steady-state evoked potentials as an index of multisensory temporal binding. *NeuroImage, 60*(1), 21–28. https://doi.org/10.1016/j.neuroimage.2011.11.065

Nozaradan, S., Schönwiesner, M., Caron-Desrochers, L., & Lehmann, A. (2016). Enhanced brainstem and cortical encoding of sound during synchronized movement. *NeuroImage, 142,* 231–240. https://doi.org/10.1016/j.neuroimage.2016.07.015

Patel, A. D., & Iversen, J. R. (2014). The evolutionary neuroscience of musical beat perception: The Action Simulation for Auditory Prediction (ASAP) hypothesis. *Frontiers in Systems Neuroscience, 8,* Article 57. https://doi.org/10.3389/fnsys.2014.00057

Pearce, M. T. (2018). Statistical learning and probabilistic prediction in music cognition: Mechanisms of stylistic enculturation. *Annals of the New York Academy of Sciences, 1423*(1), 378–395. https://doi.org/10.1111/nyas.13654

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

Phillips-Silver, J., & Trainor, L. J. (2007). Hearing what the body feels: Auditory encoding of rhythmic movement. *Cognition, 105*(3), 533–546. https://doi.org/10.1016/j.cognition.2006.11.006

Phillips-Silver, J., & Trainor, L. J. (2008). Vestibular influence on auditory metrical interpretation. *Brain and Cognition, 67*(1), 94–102. https://doi.org/10.1016/j.bandc.2007.11.007

Polak, R. (2010). Rhythmic feel as meter: Non-isochronous beat subdivision in jembe music from Mali. *Music Theory Online, 16*(4). https://www.mtosmt.org/issues/mto.10.16.4/mto.10.16.4.polak.html#Beginning

Polak, R. (2021). Non-isochronous metre in music from Mali. In M. Doffman, E. Payne, & T. Young (Eds.), *The Oxford handbook of time in music* (pp. 253–274). Oxford University Press.

Polak, R., Jacoby, N., Fischinger, T., Goldberg, D., Holzapfel, A., & London, J. (2018). Rhythmic prototypes across cultures: A comparative study of tapping synchronization. *Music Perception: An Interdisciplinary Journal, 36*(1), 1–23. https://doi.org/10.1525/mp.2018.36.1.1

Poole, A. (2018). Comparing timeline rhythms in Pygmy and Bushmen music. *Empirical Musicology Review, 12*(3-4), 172–193. https://doi.org/10.18061/emr.v12i3-4.5823

Proksch, S., Comstock, D. C., Médé, B., Pabst, A., & Balasubramaniam, R. (2020). Motor and predictive processes in auditory beat and rhythm perception. *Frontiers in Human Neuroscience, 14,* Article 375. https://doi.org/10.3389/fnhum.2020.578546

Repp, B. H. (2001). Processes underlying adaptation to tempo changes in sensorimotor synchronization. *Human Movement Science, 20*(3), 277–312. https://doi.org/10.1016/S0167-9457(01)00049-5

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review, 12,* 969–992. https://doi.org/10.3758/BF03206433

Repp, B. H. (2010). Do metrical accents create illusory phenomenal accents? *Attention, Perception, & Psychophysics, 72*(5), 1390–1403. https://doi.org/10.3758/APP.72.5.1390

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

Rose, D., Ott, L., Guérin, S. M. R., Annett, L. E., Lovatt, P., & Delevoye-Turrell, Y. N. (2021). A general procedure to measure the pacing of body movements timed to music and metronome in younger and older adults. *Scientific Reports, 11*(1), Article 3264. https://doi.org/10.1038/s41598-021-82283-4

Sant'Anna, A., & Wickström, N. (2010). A linguistic approach to the analysis of accelerometer data for gait analysis. *Proceedings of the 7th IASTED International Conference on Biomedical Engineering.* https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A345707&dswid=7883

Schaefer, R. S., Vlek, R. J., & Desain, P. (2011). Decomposing rhythm processing: Electroencephalography of perceived and self-imposed rhythmic patterns. *Psychological Research, 75,* 95–106. https://doi.org/10.1007/s00426-010-0293-4

Schroeder, C. E., Wilson, D. A., Radman, T., Scharfman, H., & Lakatos, P. (2010). Dynamics of active sensing and perceptual selection. *Current Opinion in Neurobiology, 20*(2), 172–176. https://doi.org/10.1016/j.conb.2010.02.010

Simonsohn, U. (2015). Small telescopes: Detectability and the evaluation of replication results. *Psychological Science, 26,* 559–569. https://doi.org/10.1177/0956797614567341

Stupacher, J., Witte, M., Hove, M. J., & Wood, G. (2016). Neural entrainment in drum rhythms with silent breaks: Evidence from steady-state evoked and event-related potentials. *Journal of Cognitive Neuroscience, 28*(12), 1865–1877. https://doi.org/10.1162/jocn_a_01013

Su, Y.-H. (2016). Visual tuning and metrical perception of realistic point-light dance movements. *Scientific Reports, 6*(1), 22774. https://doi.org/10.1038/srep22774

Su, Y.-H., & Pöppel, E. (2012). Body movement enhances the extraction of temporal structures in auditory sequences. *Psychological Research, 76,* 373–382. https://doi.org/10.1007/s00426-011-0346-3

Temperley, D. (1999). Syncopation in rock: A perceptual perspective. *Popular Music, 18*(1), 19–40. https://doi.org/10.1017/S0261143000008710

Temperley, D. (2000). Meter and grouping in African music: A view from music theory. *Ethnomusicology, 44*(1), 65–96. https://doi.org/10.2307/852655

Tichko, P., Kim, J. C., & Large, E. W. (2021). Bouncing the network: A dynamical systems model of auditory–vestibular interactions underlying infants' perception of musical rhythm. *Developmental Science, 24*(5), Article e13103. https://doi.org/10.1111/desc.13103

Tichko, P., & Large, E. W. (2019). Modeling infants' perceptual narrowing to musical rhythms: Neural oscillation and hebbian plasticity. *Annals of the New York Academy of Sciences, 1453*(1), 125–139. https://doi.org/10.1111/nyas.14050

Toiviainen, P., & Eerola, T. (2003). Where is the beat? Comparison of Finnish and South African listeners. In R. Kopiez, A. C. Lehmann, I. Wolther, & C. Wolf (Eds.), *Proceedings of the 5th triennial ESCOM conference* (pp. 501–504).

Toussaint, G. (2003). Classification and phylogenetic analysis of African ternary rhythm timelines. *Meeting Alhambra, ISAMA-BRIDGES Conference Proceedings,* 25–36. https://archive.bridgesmathart.org/2003/bridges2003-25.pdf

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

van der Steen, M. C., & Keller, P. E. (2013). The adaptation and anticipation model (ADAM) of sensorimotor synchronization. *Frontiers in Human Neuroscience, 7,* Article 253. https://doi.org/10.3389/fnhum.2013.00253

van der Weij, B., Pearce, M. T., & Honing, H. (2017). A probabilistic model of meter perception: Simulating enculturation. *Frontiers in Psychology, 8,* Article 824. https://doi.org/10.3389/fpsyg.2017.00824

Vander Elst, O. F., Foster, N. H., Vuust, P., Keller, P. E., & Kringelbach, M. L. (2023). The neuroscience of dance: A conceptual framework and systematic review. *Neuroscience & Biobehavioral Reviews, 150,* Article 105197. https://doi.org/10.1016/j.neubiorev.2023.105197

Vettori, S., Dzhelyova, M., Van der Donck, S., Jacques, C., Van Wesemael, T., Steyaert, J., Rossion, B., & Boets, B. (2020). Combined frequency-tagging EEG and eye tracking reveal reduced social bias in boys with autism spectrum disorder. *Cortex, 125,* 135–148. https://doi.org/10.1016/j.cortex.2019.12.013

Vuust, P., Dietz, M. J., Witek, M., & Kringelbach, M. L. (2018). Now you hear it: A predictive coding model for understanding rhythmic incongruity. *Annals of the New York Academy of Sciences, 1423,* 19–29. https://doi.org/10.1111/nyas.13622

Vuust, P., Heggli, O. A., Friston, K. J., & Kringelbach, M. L. (2022). Music in the brain. *Nature Reviews Neuroscience, 23*(5), 287–305. https://doi.org/10.1038/s41583-022-00578-5

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

Wagenmakers, E.-J., Sarafoglou, A., & Aczel, B. (2023). Facing the unknown unknowns of data analysis. *Current Directions in Psychological Science, 32*(5), 362–368. https://doi.org/10.1177/09637214231168565

Wing, A. M., Doumas, M., & Welchman, A. E. (2010). Combining multisensory temporal information for movement synchronisation. *Experimental Brain Research, 200,* 277–282. https://doi.org/10.1007/s00221-009-2134-5

Witek, M. A. (2017). Filling in: Syncopation, pleasure and distributed embodiment in groove. *Music Analysis, 36*(1), 138–160. https://doi.org/10.1111/musa.12082

Zalta, A., Large, E. W., Schön, D., & Morillon, B. (2024). Neural dynamics of predictive timing and motor engagement in music listening. *Science Advances, 10*(10), Article eadi2525. https://doi.org/10.1126/sciadv.adi2525

Zalta, A., Petkoski, S., & Morillon, B. (2020). Natural rhythms of periodic temporal attention. *Nature Communications, 11*(1), Article 1051. https://doi.org/10.1038/s41467-020-14888-8

Table 1

Estimated Required Sample and Effect Sizes

Question	**Hypothesis**	**Analysis plan**	**Sampling plan**	**Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis**	**Interpretation given to different outcomes**
Stage 1 #1 (African-enculturated individuals)					
The amplitude of neural responses at metre-related frequencies will be enhanced after vs. before the movement session, and this effect will be magnified in the four-beat metre condition.	$\bar{z}_{\text{EEG}}$ will be larger after when compared to before movement (H_{1a}).	Pairwise t test	$N = 8$ ($d = 1.53$; $\alpha = .020$; 1-β = .90)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	The hypotheses will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\text{SESOI}}$.
	$\bar{z}_{\text{EEG}}$ post movement will be larger for the four-beat metre condition when compared to the three-beat metre condition (H_{1b}).	Mixed-model ANOVA (Movement Condition × Session) followed by pairwise t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; 1-$\beta = .90$) and $N = 6$ for the simple effect ($d = 1.77$; $\alpha = .020$; 1-$\beta = .90$)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	

(*Continued*)

Movement will enhance the amplitude of metre frequencies in the clapping signal, and the four-beat metre condition will yield the most powerful effect.	$\bar{z}_{\text{clapping}}$ will be larger after when compared to before the movement (H_{2a}).	Pairwise t test	$N = 6$ ($d = 1.77$; $\alpha = .020$; 1-β = .90)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	The hypothesis will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\text{SESOI}}$.
	$\bar{z}_{\text{clapping}}$ post movement will be larger for the four-beat metre condition when compared to the three-beat metre condition (H_{2b}).	Mixed-model ANOVA (Movement Condition × Session) followed by pairwise t test	$N = 20$ for the interaction effect ($f = 0.89$; α = .02; 1-β = .90) and $N = 6$ for the simple effect (d = 1.77; $\alpha = .020$; 1-β = .90)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	
Stage 1 #2 (Western-enculturated individuals and cross-cultural comparisons)					
The amplitude of neural responses at metre-related frequencies will be enhanced after vs. before the movement session, and this effect will be magnified in the three-beat metre condition.	$\bar{z}_{\text{EEG}}$ will be larger after when compared to before movement (H_{3a}).	Pairwise t test	$N = 8$ ($d = 1.53$; $\alpha = .020$; 1-β = .90)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	The hypotheses will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\text{SESOI}}$.
	$\bar{z}_{\text{EEG}}$ post movement will be larger for the three-beat metre condition when compared to the four-beat metre condition (H_{3b}).	Mixed-model ANOVA (Movement Condition × Session) followed by pairwise t test	$N = 20$ for the interaction effect ($f = 0.89$; α = .020; 1-β = .90) and $N = 6$ for the simple effect (d = 1.77; $\alpha = .020$; 1-β = .90)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	

(*Continued*)

Movement will enhance the amplitude of metre frequencies in the clapping signal, and the three-beat metre condition will yield the most powerful effect.	$\bar{z}_{\text{clapping}}$ will be larger after when compared to before the movement (H_{4a}).	Pairwise t test	$N = 6$ ($d = 1.77$; $\alpha = .020$; 1-β = .90)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	The hypothesis will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\text{SESOI}}$.
	$\bar{z}_{\text{clapping}}$ post movement will be larger for the three-beat metre condition when compared to the four-beat metre condition (H_{4b}).	Mixed-model ANOVA (Movement Condition × Session) followed by pairwise t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; 1-β = .90) and $N = 6$ for the simple effect ($d = 1.77$; $\alpha = .020$; 1-β = .90)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	

(*Continued*)

The behavioural and neural representation of metre in the pre-movement session will be distinct in the African- vs. Western-enculturated participants.	During the pre-movement session, $\bar{z}_{\mathrm{EEG}}$ of four-beat frequencies will be more important than $\bar{z}_{\mathrm{EEG}}$ of three-beat frequencies in the African-enculturated group, and vice-versa in the Western-enculturated group (H_{5a}).	Mixed-model ANOVA (Group × Metre Frequency) followed by pairwise t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1\text{-}\beta = .90$) and $N = 6$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1\text{-}\beta = .90$)	Small telescopes approach ($d_{\mathrm{SESOI}} = 0.47$).	The hypotheses will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\mathrm{SESOI}}$.
	During the pre-movement session, $\bar{z}_{\mathrm{clapping}}$ of four-beat frequencies will be more important than $\bar{z}_{\mathrm{clapping}}$ of three-beat frequencies in the African-enculturated group, and vice-versa in the Western-enculturated group (H_{5b}).	Mixed-model ANOVA (Group × Metre Frequency) followed by pairwise t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1\text{-}\beta = .90$) and $N = 6$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1\text{-}\beta = .90$)	Small telescopes approach ($d_{\mathrm{SESOI}} = 0.47$).	

(*Continued*)

The pre-movement bias toward a specific metrical interpretation will be more important among African-enculturated individuals.	During the pre-movement session, $\bar{z}_{\mathrm{EEG}}$ of four-beat frequencies in the African-enculturated group will be more important than $\bar{z}_{\mathrm{EEG}}$ of three-beat frequencies in the Western-enculturated group (H_{6a}).	Mixed-model ANOVA (Group × Metre Frequency) followed by independent t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1\text{-}\beta = .90$) and $N = 9$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1\text{-}\beta = .90$)	Small telescopes approach ($d_{\mathrm{SESOI}} = 0.47$).	The hypotheses will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\mathrm{SESOI}}$.
	During the pre-movement session, $\bar{z}_{\mathrm{clapping}}$ of four-beat frequencies in the African-enculturated group will be more important than $\bar{z}_{\mathrm{clapping}}$ of three-beat frequencies in the Western-enculturated group (H_{6b}).	Mixed-model ANOVA (Group × Metre Frequency) followed by independent t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1\text{-}\beta = .90$) and $N = 6$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1\text{-}\beta = .90$)	Small telescopes approach ($d_{\mathrm{SESOI}} = 0.47$).	

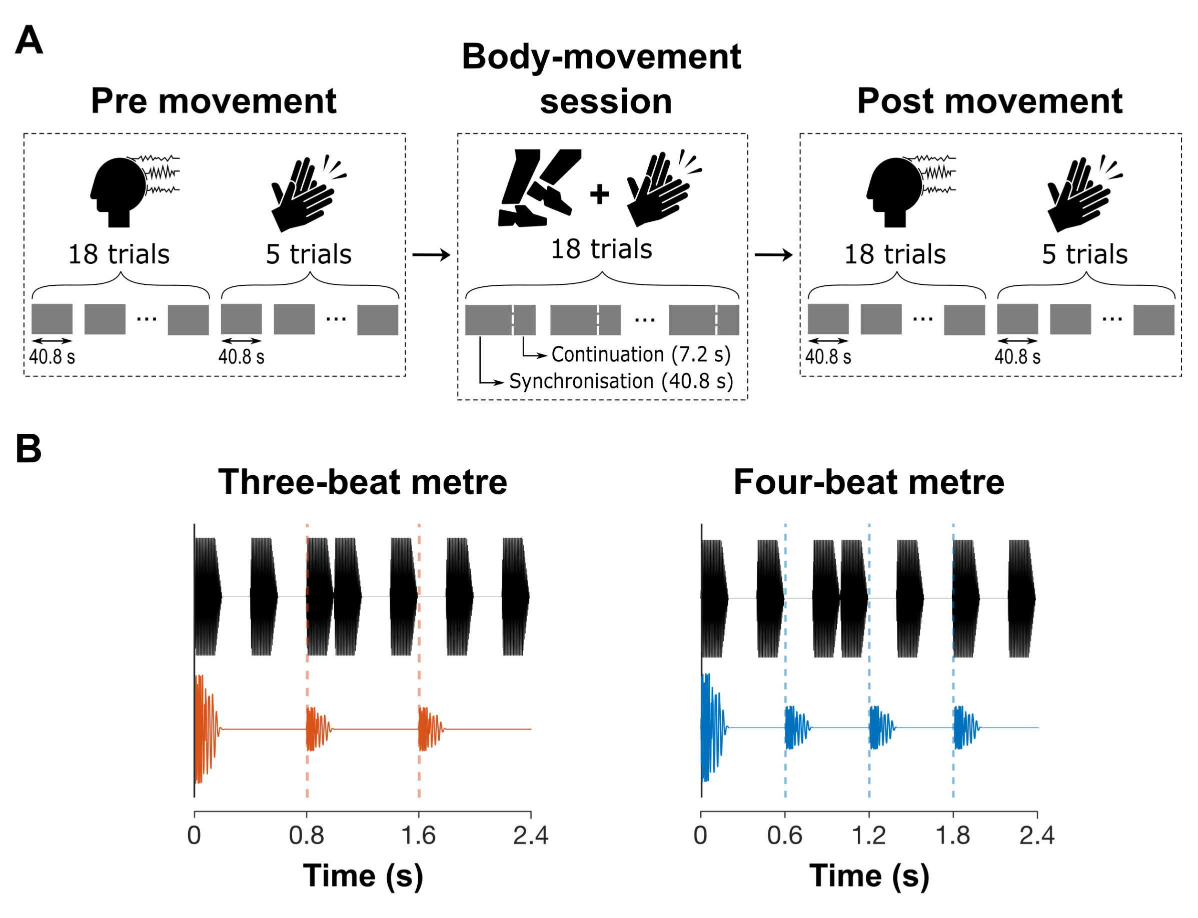
(*Continued*)

African-enculturated individuals will display larger learning effect for metrical interpretation that is less predominant in their traditional, cultural background.	During the post-movement session, Δ_{EEG} of the African-enculturated group in the three-beat metre condition will be more important than Δ_{EEG} in the Western-enculturated group in the four-beat metre condition (H_{7a}).	ANOVA (Group × Movement Condition) followed by independent t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1\text{-}\beta = .90$) and $N = 9$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1\text{-}\beta = .90$)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	The hypotheses will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\text{SESOI}}$.
	During the post-movement session, Δ_{clapping} of the African-enculturated group in the three-beat metre condition will be more important than Δ_{clapping} in the Western-enculturated group in the four-beat metre condition (H_{7b}).	ANOVA (Group × Movement Condition) followed by independent t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1\text{-}\beta = .90$) and $N = 6$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1\text{-}\beta = .90$)	Small telescopes approach ($d_{\text{SESOI}} = 0.47$).	

Note. Statistical power, planned analyses, and critical statistical tests for each research hypothesis. H = Hypothesis; RM ANOVA = Repeated-measures analysis of variance; SESOI = smallest effect size of interest.

Figure 1

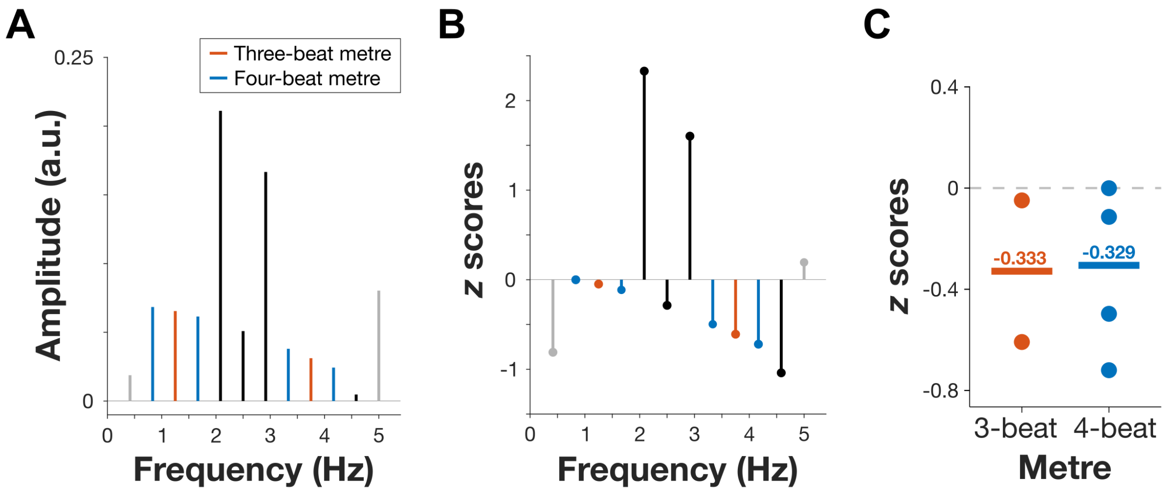
Experimental Design and Material



Note. Panel A: Diagrammatic representation of the experimental design. Panel 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.

Figure 2

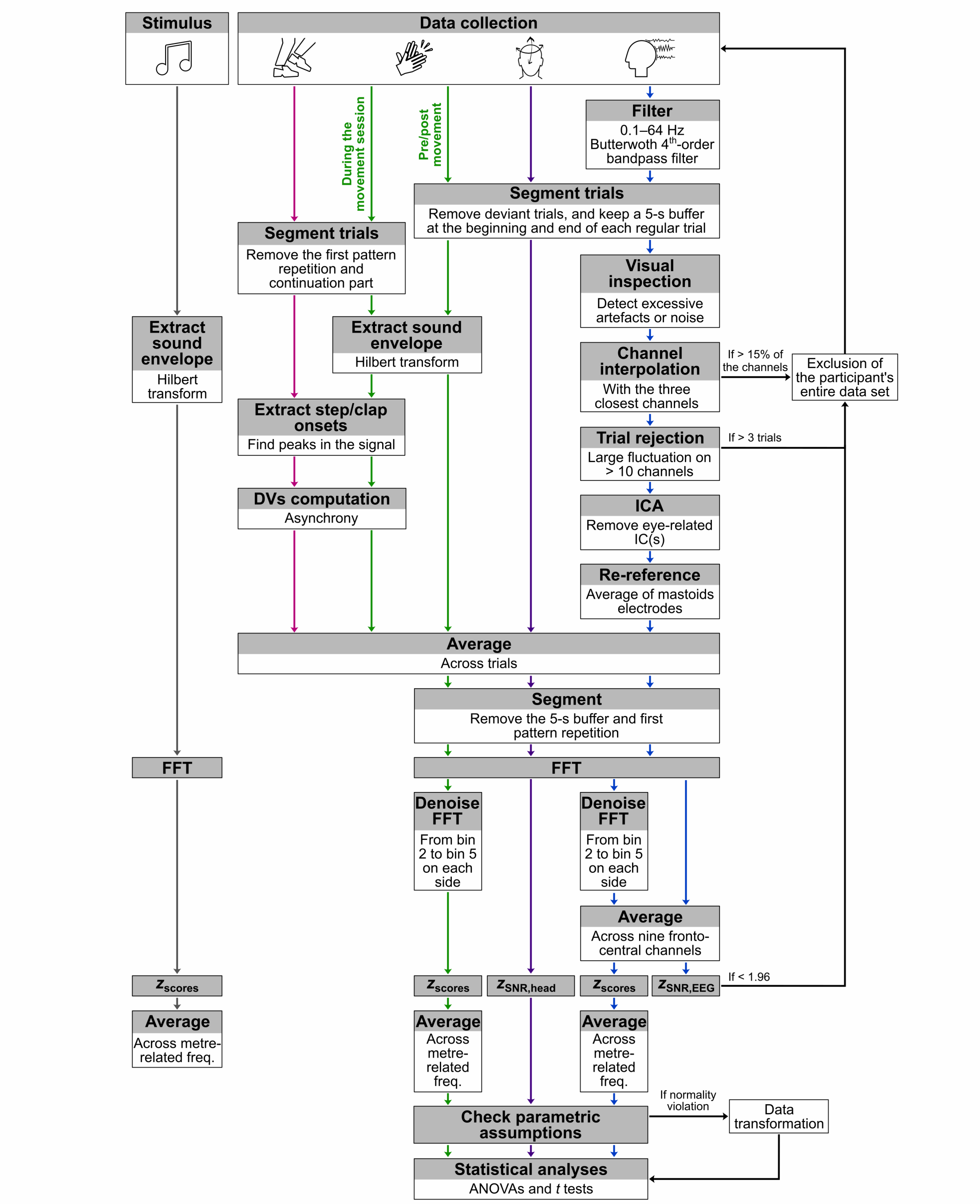
Auditory Stimulus Analyses



Note. Three-beat metre related frequencies (i.e., 1.25 and 3.75 Hz) are highlighted in orange and four-beat metre 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.

Figure 3

Data-Processing Pipeline



Note. ICA = independent component analysis; FFT = fast-Fourier transform; freq. = frequency; ANOVA = analysis of variance. Icon sources: 'Music and multimedia' by Colourcreatype (modified), 'Dancing' by Jack (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.