

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

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27

General Stage 1 Abstract

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

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

49 **Imprints of Periodic Body Movement Onto Subsequent Processing of**
50 **Auditory Rhythm**

51 **Stage 1 #1 Abstract**

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

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

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

71 **Stage 1 #2 Abstract**

72 Music compels humans to move with the musical rhythm. In turn, movement [pace](#) can
73 shape rhythm perception, and this widely recognised yet understudied effect is likely
74 influenced itself by cultural experience throughout an individual's life. However, clear
75 behavioural and neuroscientific evidence for this short- and long-term shaping of
76 rhythm processing is still lacking. This study aims to capture the brain processes

77 underlying this plasticity, by comparing electroencephalography (EEG) and hand
78 clapping to an auditory rhythm, derived from West/Central African music repertoires,
79 across individuals with specific cultural background from West/Central Africa and a
80 Western convenience sample of individuals. These measurements will be collected both
81 before and after a session of body movement to the rhythm corresponding to a specific
82 metre (three- vs. four-beat metre). First, we predict neural and behavioural differences
83 between the two cultural groups concerning the preferred metric mapping observed
84 before body movement. Moreover, we predict post-movement enhancement in neural
85 and behavioural entrainment, selective to the metre conveyed by prior movement, and
86 magnified for the metre predominant in the participant's culture. Findings are expected
87 to pinpoint the brain processes allowing prior experience of movement and culture to
88 imprint onto rhythm processing in humans.

89 *Keywords:* music cognition; cross-cultural; rhythmic entrainment; beat and meter
90 perception; neural representation; sensorimotor synchronisation; body movements;
91 EEG; sensorimotor synchronisation; frequency tagging

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

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

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

113 **Stage 1 #1 Introduction**

114 Animals commonly rely on rhythmic movements to explore their environment,
115 which facilitates the sampling of sensory information (Zalta et al., 2020; [Gibson, 1962](#)).
116 This so-called 'active sensing' process is easily conceivable in the context of vision,
117 somatosensation, or olfaction, where eye, finger, or sniffing movements directly
118 contribute to sensory exploration. In the scope of audition, the way movement might
119 shape perception is less straightforward; [this is especially true in species such as](#)
120 [humans, who do not use echolocation as a main sensory system, wherein the degree to](#)

121 which such an active sensing process is used to regulate and facilitate sensory inflow,
122 thereby optimising sensitivity to external sounds, remains unclear (Schroeder et al.,
123 2010). The proposed study aims to capture how the pace of body movements leave its
124 imprint on subsequent processing of auditory information in humans, by capitalising on
125 the intrinsic interplay between music and body movement.

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

134 To be able to form temporal expectancies when listening to music, individuals
135 need to transform complex auditory or other sensory (e.g., visual; Su, 2016) rhythmic
136 inputs into an internal representation of musical-event timing (Cannon, 2021; Large &
137 Palmer, 2002; van der Weij et al., 2017; Vuust et al., 2018). This internal representation
138 typically takes the form of a metre, which corresponds to a nested set of felt pulsations
139 that are often periodic (Lenc et al., 2021; London, 2012; Vuust and Witek, 2014; of
140 note, in the current study, ‘metre’ is used as a comprehensive term with no explicit
141 specification about the number of pulse layers, thus minimising underlying
142 assumptions). Importantly, the metre perceived when experiencing a given rhythm is
143 not driven by the input in a one-to-one fashion. In other words, the perceptual system
144 does not simply search for an internal periodic template that provides the closest match
145 to periodicities marked by the arrangement of prominent acoustic events over time.
146 Rather, meter perception can be considered a form of perceptual categorisation, thus
147 relying on a flexible mapping between a rhythmic sensory input and an internal
148 representation of periodic pulses (Iversen et al., 2009; Repp, 2010; Schaefer et al., 2011).
149 Arguably, this mapping is far from trivial, especially when the sensory input lacks

150 unambiguous periodic arrangement of salient acoustic features – as in so-called
151 syncopated (Witek, 2017) or contrametric (Kolinski, 1973) rhythms, where rhythmic
152 and metric structures show a degree of incongruency, which are typical for numerous
153 genres of popular, groove-based music around the world (e.g., jazz, funk, breakbeat,
154 Afro-Cuban, and African styles; Huron & Ommen, 2006; London et al., 2017;
155 Temperley, 1999, 2000). In such scenarios, metre perception must rely on internal
156 processes beyond mere detection of acoustic periodicities in the relevant temporal range
157 (Lenc et al., 2021; London, 2012). One of these processes is the learned *association*
158 between contextual cues (e.g., particular rhythmic figure, timbre, tempo, and social
159 setting) and a specific internal metre (Kaplan et al., 2022; London, 2012; London et al.,
160 2017; van der Weij et al., 2017).

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

177 Suggesting a more direct effect of movement-related processes on metre
178 perception, the active sensing framework states that the motor system modulates the

179 cortical processing of auditory information by refining attention surrounding relevant
180 sensory information (Morillon et al., 2014, 2015). Specifically, motor delta oscillations
181 (0.5–4 Hz) would sharpen the brain processing of rhythmic sounds by synchronising the
182 temporal fluctuations of attention with the timing of auditory events (Morillon et al.,
183 2019; Zalta et al., 2020). More radically, the action simulation for auditory prediction
184 (ASAP) hypothesis proposes that the simulation of periodic movement shapes metre
185 perception (Patel & Iversen, 2014; Proksch et al., 2020). According to this hypothesis,
186 cortical motor planning regions would thus be entrained by an implicit and automatic
187 process of movement simulation triggered by rhythmic sounds, and this oscillatory
188 pattern would propagate to auditory areas, influencing the metric interpretation of
189 rhythm (Iversen et al., 2009). Although these theoretical models of musical rhythm
190 perception diverge in a number of ways (e.g., anatomical substrates, directionality of
191 relationship [between movement and meter perception](#)), [they can be viewed as mutually](#)
192 [reinforcing \(e.g., by describing mechanisms at the brain level or at the cognitive level;](#)
193 [see Large et al., 2023; Zalta et al., 2024\)](#); and importantly, each of them presupposes a
194 strong role of motor production in metre perception.

195 The effect of body-movement [pace](#) on the subsequent internal representation of
196 rhythm has been reported in several empirical studies using behavioural methods. For
197 example, body movement coordinated with a rhythmic pattern according to a specific
198 metre was found to bias the way individuals subsequently perceive a rhythm, possibly
199 through vestibular-mediated processes (Phillips-Silver & Trainor, 2008; Trainor et al.,
200 2009). Specifically, both adults and infants have been shown to develop increased
201 expectancy of salient sounds at those positions within a rhythmic pattern that were
202 aligned with the metre the individual had previously moved to (Phillips-Silver &
203 Trainor, 2005, 2007; Su & Pöppel, 2012). Nonetheless, the behavioural measures used in
204 these studies only constitute an indirect way to capture the internal representation of
205 metre elicited by a rhythm (Lenc et al., 2021). [To date](#), little work has been done using
206 more direct methods ([e.g., measurements of both the neural and behavioural responses](#)
207 [as recorded in separate sessions in response to rhythmic stimuli](#)) [with the aim to](#)

208 capture the internal representation of metre elicited by a rhythm. One neuroimaging
209 study found that the neural responses to a rhythmic pattern were significantly bolstered
210 after body-movement production, selectively at frequencies related to the metre that
211 participants had moved to (Chemin et al., 2014). However, the rhythmic stimulus used
212 in this study contained prominent metre-related periodicities in its acoustic structure,
213 thus making it hard to disentangle effects driven by an actual internal representation of
214 metre from effects related to low-level sensory processing of the rhythmic input.

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

230 The objective of this study is to capture direct neuroscientific evidence for the
231 shaping of auditory information by the pace of previous movement. If significant, this
232 effect would thus likely be intrinsically supported by a number of distinct processes,
233 including motor planning, visual, auditory, somatosensory and vestibular cues combined
234 together (Phillips-Silver & Trainor, 2008; Trainor et al., 2009). Movement-related
235 shaping of auditory information was purposely adopted in the current studies (a) for its
236 ecological validity in music and dance contexts, and (b) to increase the likelihood of

237 eliciting an effect in the listening block subsequent to the movement priming, due to the
238 mixture of multisensory effects expected to strengthen carry-over effects. Hence, our
239 objective is *not* to define the necessary and sufficient mechanism for the effect of
240 movement on rhythm perception to take place, but rather to capture the brain
241 processes underlying this holistic effect, while not precluding mental imagery of beat or
242 priming by auditory inputs (as in Nave et al., 2022) that could also significantly shape
243 auditory information.

244 Stage 1 #2 Introduction

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

260 The particular metre elicited by an external rhythmic stimulus seems to be
261 determined by various factors operating on a short timescale, for example body
262 movement performed concurrently with the stimulus and following a specific metre
263 (Phillips-Silver & Trainor, 2007). Specifically, over the past decades, a number of
264 theoretical models have proposed that prior and concurrent motor production plays an
265 important role in metre perception (e.g., predictive-coding theory of music, neural

266 resonance theory, active sensing, action simulation for auditory perception; Large et al.,
267 2015; Morillon et al., 2019; Patel & Iversen, 2014; Proksch et al., 2020; Vuust et al.,
268 2018).

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

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

293 In the same way, all the previous empirical evidence available so far on cultural
294 variations in rhythm processing was gathered exclusively through behavioural

295 approaches (Hannon & Trehub, 2005; Jacoby & McDermott, 2017). For example,
296 individuals have shown better tapping performance to rhythms derived from familiar
297 musical traditions (Cameron et al., 2015; Toiviainen & Eerola, 2003). Notwithstanding
298 the high relevance of this behavioural work, the brain processes underlying the
299 outstanding plasticity of rhythm processing specific to humans remain largely unknown.

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

312 **Research Hypotheses**

313 This programmatic Stage 1 registered report proposes two distinct studies that
314 are complementary to answer our broad research questions, and will thus result in two
315 Stage 2 articles. Specifically, Stage 1 #1 will target African-enculturated individuals,
316 while Stage 1 #2 will focus on Western-enculturated individuals and the cross-cultural
317 comparisons (see Table 1). Within each study, one group of individuals will participate
318 in a ~15-min body-movement session consisting of stepping and clapping to a rhythm in
319 synchrony with an overlaid drum sound indicating a three-beat metrical interpretation
320 of the rhythm. Another group of individuals will be engaged in the same protocol but
321 following a four-beat metrical interpretation of the same rhythm. The rhythmic input
322 will consist in a context-free version derived from a rhythmic pattern spanning 12
323 elements often used in musical traditions from West to Central Africa (Agawu, 2006;

324 Kubik, 2010; Poole, 2018), and frequently referred to as Bembé, bell/clave pattern, or
325 standard timeline. Specifically, this rhythmic pattern serves a key role at indicating the
326 temporal reference in African (and African derived) music (Agawu, 2006; Kubik, 2010;
327 Locke, 1982; Poole, 2018; Toussaint, 2003). While empirical evidence is still lacking,
328 ethnomusicologist work suggests that widespread metric mode among populations
329 enculturated in West and Central African musical environments is to experience
330 12-element rhythmic patterns as suggesting a four-beat metre (Locke, 1982; Poole,
331 2018). This mode is relatively less prominent in populations enculturated with
332 Euro-American popular or art music traditions. By contrast, individuals with such
333 backgrounds often carry metric modes that would map the same 12-element rhythms to
334 a three-beat metres (Blacking, 1967).

335 The neural activity of participants will be recorded using EEG while they stay
336 still and listen to the same rhythmic input in two sessions directly preceding and
337 following the body-movement session. At the end of each EEG session, participants will
338 be asked to clap along with the rhythm as an ecological index of behavioural
339 entrainment to the perceived metre (Rose et al., 2021). A frequency-tagging approach
340 will be used to measure the relative prominence of the periodicity corresponding to the
341 perceived metre in the signal of interest (i.e., acoustic input, EEG response elicited by
342 the acoustic input, clapping movement to the acoustic input; Lenc et al., 2021, 2022).
343 Over the past 10 years, this approach has proven to be useful in objectively measuring
344 the input–output transformation performed by the brain, and how this transformation
345 might relate to metre perception (Lenc et al., 2022; Nave et al., 2022; Nozaradan et al.,
346 2017; Stupacher et al., 2016). Here, we predict that an enhanced representation of the
347 metre will be observed in the post-movement neural and behavioural responses to the
348 rhythmic input. This enhancement is expected to be selective to the metre conveyed by
349 prior movement and magnified for the metre predominant in the participant’s culture.

350 In Stage 1 #1, we hypothesise that the amplitude of neural responses at metre
351 frequencies (i.e., three-beat frequencies in the three-beat condition, and four-beat
352 frequencies in the four-beat condition; see Methods) will be enhanced after vs. before

353 the movement session (H_{1a}). This session effect (pre- vs. post-movement) would confirm
354 that short-term multimodal exposure to a specific metre as induced by active,
355 intentional movement shapes subsequent internal representation of an auditory rhythm,
356 possibly through [perceptual](#) learning (Cannon, 2021; Pearce, 2018). As an alternative,
357 an absence of effect would indicate that (a) the metrical interpretation was already
358 strongly associated with this rhythmic pattern before the body-movement session,
359 possibly driven by a mix of biological and cultural factors (see Kaplan et al., 2022;
360 van der Weij et al., 2017); or (b) the movement session did not provide a sufficient
361 combination of cues ([e.g., auditory, vestibular, tactile](#)) to subsequently stabilise a
362 metrical interpretation in such a short period of time.

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

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

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

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

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

407 Finally, we will test whether African-enculturated individuals show generally
408 greater flexibility in their metrical interpretations. Body movement was found to affect
409 subsequent internal representation of rhythm in Western-enculturated individuals when

410 performed following a three-beat metrical interpretation, but not when performed
411 following a four-beat metrical interpretation (Chemin et al., 2014). However, based on
412 the higher prevalence of rhythmic patterns that are metrically malleable (i.e., only
413 weakly suggestive of one specific metric mapping to be preferred over
414 musically-plausible alternatives) in African musical traditions, individuals familiar with
415 these musical repertoires should be prone to perceive them according to different
416 metrical interpretations depending on contextual cues (Cameron et al., 2015; Locke,
417 2011; Temperley, 2000). Therefore, we expect to find that prior movement executed
418 along the metre less predominant in individual's cultural background would have larger
419 effect in the case of African-enculturated individuals compared to Western-enculturated
420 individuals (H_7). Conversely, an absence of significant effect would denote that (a) the
421 learned association of malleable rhythms with a specific meter (i.e., four beat) in
422 African-enculturated participants is stable (Agawu, 2006; London et al., 2017; Polak,
423 2010) and flexibility to override it is not part of the statistical perceptual learning
424 processes; or (b) high musical expertise in African-derived music genres is key to switch
425 from one metric interpretation to another (Benadon, 2020; Locke, 1982).

426

Methods

427 Ethical Clearance

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

432 Participants

433 Adult volunteers considered eligible to participate in the study will be aged
434 between 18 and 45 years, non-musicians and non-dancers, and free of sensory (i.e., no
435 auditory impairment or uncorrected visual impairment) and motor dysfunctions (i.e., no
436 upper- and/or lower-limb disorders). In the present research project, non-musicians or
437 non-dancers are defined as those meeting at least two out of the three following criteria:
438 (a) not considering themselves as such, (b) not having more than four years of practice,

439 and (c) not having played an instrument/danced in a concert or performance on stage
440 in front of an audience.

441 Participants will be included in the African-enculturated group if they self-report
442 that (a) themselves or both their parents have lived, at least for the first 15 years of
443 their lives, in one of the following countries: Mali, Côte d'Ivoire, Togo, Benin,
444 Cameroon, Gabon, Republic of Congo, or Democratic Republic of Congo; and (b) they
445 speak fluently and at least 1h/week one of the idioms (i.e., languages, dialects) from the
446 above-mentioned countries (French and English excluded). For participants to be
447 included in the Western-enculturated group, they will need to self-report that (a) they
448 do not meet the two criteria described above for the African-enculturated group, (b)
449 themselves or both their parents have lived, at least for the first 15 years of their lives,
450 in one of the following countries: Belgium, France, United Kingdom, Netherlands,
451 Luxembourg, Germany, Spain, Portugal, Italy, or Switzerland; and (c) they speak
452 fluently and at least 1h/week one of the idioms (i.e., languages, dialects) from the
453 above-mentioned countries. The two screening questionnaires are available for
454 consultation in Supplementary File 1.

455 The sample size for the critical statistical test of each research hypothesis was
456 calculated using R with the 'pwr' and 'WebPower' packages (code is available here:
457 <https://zenodo.org/doi/10.5281/zenodo.10221480>). The EEG and behavioural results of
458 Chemin et al. (2014) were used as a parameter for H_1-H_7 , with one-tailed tests. For H_1
459 and H_3 , the power analysis indicated that eight participants would be required for the
460 session effect ($d = 1.53$; $\alpha = .02$; $1-\beta = .90$) and 20 participants per movement condition
461 would be necessary for the interaction effect between movement condition and session (f
462 $= 0.89$; $\alpha = .02$; $1-\beta = .90$). For H_2 and H_4 , six participants would be required for the
463 session effect ($d = 1.77$; $\alpha = .02$; $1-\beta = .90$) and 20 participants per movement
464 condition would be necessary for the interaction effect between movement condition and
465 session ($f = 0.89$; $\alpha = .02$; $1-\beta = .90$). In addition, 20 participants per group would be
466 needed for the interaction effects of H_5-H_7 ($f = 0.89$; $\alpha = .02$; $1-\beta = .90$). Therefore, a
467 total sample of 40 participants (i.e., 20 per movement condition) will be recruited for

468 each of the two proposed studies, which means a total of 80 participants for the whole
469 research project (see see Table 1).

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

478 **Experimental Procedure and Tasks**

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

482 ***Experimental Procedure***

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

496 In the pre- and post-movement sessions, the participant will be seated in a
497 comfortable chair, with their head resting against the back of the chair. In these
498 sessions, the participant will be instructed to relax, avoid any unnecessary movement,
499 and keep their eyes fixated on a marker displayed on the wall ~1 m in front of them (to
500 minimise large eye movements). During the movement session, the EEG electrode cables
501 will be unplugged from the amplifier and attached on the participant's shoulders to free
502 their movements.

503 *Auditory Stimulus*

504 **Description.** The rhythmic pattern used throughout the experiment originates
505 from West and Central Africa and is often referred to as Bembé, bell/clave pattern, or
506 standard timeline. In this experiment, this pattern will have a duration of 2.4 s and will
507 be seamlessly repeated 17 times to form a long sequence, with a total duration of 40.8 s
508 (see Figure 2, Panel A). Its 'x.x.xx.x.x.x' structure is based on a 12-intervals grid (200
509 ms \times 12 = 2.4 s), following a specific arrangement of seven 200-ms sound events
510 (depicted by the 'x', and made of a 200-Hz pure tones with 10-ms rise and 50-ms fall
511 linear ramps) and five 200-ms silent intervals (depicted by the '?').

512 This rhythmic stimulus is particularly relevant to the proposed study for several
513 reasons. Firstly, the rhythmic pattern is culturally valid due to its wide use across
514 musical traditions in Central and West Africa (Locke, 1982; Temperley, 2000). Yet, the
515 pattern can be presented in a decontextualized fashion for the purposes of the current
516 study (e.g., by using pure tones instead of a clave sound that typically delivers the
517 pattern in stylistically valid contexts), thus minimising the interference caused by
518 non-rhythmic contextual cues in participants familiar with musical repertoires
519 containing this pattern. Unlike stimuli used in the majority of prior studies (e.g.,
520 Chemin et al., 2014; Phillips-Silver & Trainor, 2005, 2007), the groups of tones making
521 up the pattern are arranged in a way that a tone does not systematically coincide with
522 each beat, thus reducing the likelihood of acoustic or low-level sensory confounds (see
523 Lenc et al., 2021; Nozaradan et al., 2016). This holds for beat pulses that are used in
524 both the three- or four-beat metre condition. Moreover, an overlap between the internal

525 beat and the arrangement of tones in the rhythm cannot be achieved by simply shifting
526 the phase (or alignment) of the beat with respect to the stimulus.

527 In the movement session, a metronome-like acoustic pulse will be added to the
528 auditory stimulus and will serve as a cue to the beat from the targeted metre. This
529 pulse consists of a low-pitched drum sound presented isochronously with an inter-onset
530 interval of 800 ms in the three-beat metre condition and 600 ms in the four-beat metre
531 condition, thus yielding three or four drum cues per repetition of the 2.4-s rhythmic
532 pattern, respectively. In the three-beat metre condition, the pulses are aligned with the
533 first, fifth, and ninth time point on the grid used to generate the rhythmic pattern. In
534 the four-beat metre condition, the pulses occur at the first, fourth, seventh, and tenth
535 grid point (see Figure 1, Panel B). The drum sound coinciding with the first grid point
536 is accented (sound intensity increased by 2.5 dB) to emphasise the onset of each
537 repetition of the pattern. Three additional repetitions of the rhythmic pattern without
538 the overlaid pulse will be appended at the end of the auditory stimulus (40.8 s of
539 auditory stimulation with the overlaid pulse and 7.2 without, for a total trial duration
540 of 48 s; see Figure 1, Panel A). The three auditory stimuli will be generated using
541 MATLAB (version R2022a; MathWorks, Portola Valley, CA).

542 **Sound Analysis.** To control for acoustic or low-level sensory confounds that
543 may bias the results, it is critical to first measure how prominent the periodicities
544 corresponding to the three- and four-beat metrical interpretations are in the rhythmic
545 stimulus (Lenc et al., 2021). To measure this, the amplitude envelope of the 40.8-s
546 auditory sequence was extracted using a Hilbert transform and converted into the
547 frequency domain using a fast Fourier transform (Lenc et al., 2021; Nozaradan et al.,
548 2017), allowing to estimate the prominence of periodicities in the continuous
549 modulation of the stimulus acoustic features. The obtained envelope spectrum contains
550 12 distinct amplitude peaks (see Figure 2, Panel A), corresponding to the repetition
551 frequency of the whole rhythmic pattern (i.e., $1/2.4 \text{ s} = 0.42 \text{ Hz}$) and its harmonics up
552 to the shortest intervals between single events (i.e., $1/0.2 \text{ s} = 5 \text{ Hz}$; Lenc et al., 2021).

553 To match analysis of the EEG signals (see below ‘EEG Data’ subsection), the first and
554 last frequency of the spectrum were discarded from further computation.

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

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

559 where i is a given frequency of interest, A is the amplitude, and s is the standard
560 deviation. Finally, the obtained z scores were averaged across metre frequencies (i.e.,
561 the frequency corresponding to the metre periodicity and harmonics: 1.25 and 3.75 Hz
562 in the three-beat condition, and 0.83, 1.67, 3.33 and 4.17 Hz in the four-beat condition).
563 Note that the sixth frequency (i.e., 2.5 Hz) was dismissed as it is found in both metrical
564 interpretations. As displayed in Figure 2 (right part), the stimulus contains a virtually
565 equivalent low acoustic energy (z scores < 0) at either of the two metre periodicities
566 considered here, when compared to the remaining frequencies constituting the envelope
567 spectrum of the rhythm.

568 *Tasks Description*

569 The auditory stimuli will be presented [binaurally via](#) insert earphones (ER-2,
570 Etymotic Research; [air-conducted sound from the level of the participant’s clavicle to](#)
571 [decrease magnetic interferences](#)), connected to a Fireface UC audio interface (RME
572 Audio, Haimhausen, Germany; sampling frequency = 44100 Hz; sound volume = 73 dB
573 [sound pressure level \[SPL\]](#)). In the listening task (i.e., [during which EEG signals will be](#)
574 [collected](#)), the auditory stimulus will be played to the participant while they will be
575 required to perform an orthogonal task to encourage attentive listening. More precisely,
576 the participant will be instructed to detect speed reduction in the temporal structure of
577 the auditory stimulus [and report their response at the end of each trial \(i.e., to avoid](#)
578 [speech-related artifacts during the EEG recording](#)). This tempo change will be applied
579 to the tenth repetition of the rhythmic pattern within the trial by increasing the spacing
580 of the underlying time grid by 7.5%, lengthening the duration of that repetition from 2.4

581 s to 2.58 s. There will be a total of two trials per session containing this deviant period
582 (with those trials being randomly positioned across participants), and these trials will
583 be discarded from further analyses. In the hand-clapping task (i.e., which will directly
584 follow the listening task in both the pre- and post-movement sessions; see Figure 1), the
585 participant will be instructed to clap along with the beat they perceive in the auditory
586 stimulus ('Clap your hands as you would clap in sync with the music at a concert').

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

595 *Experimental Design*

596 The experiment will use a fixed block-design procedure (see Figure 1), with each
597 trial lasting 40.8 s in the pre- and post-movement sessions and 48 s in the movement
598 session. The pre- and post-movement sessions will be composed of 18 trials for the
599 listening task (including two randomly placed trials containing the deviant period to be
600 detected for the orthogonal task), followed by five trials for the hand-clapping task. The
601 movement session will consist of 18 trials. To assess the participant's familiarity with
602 the stimulus, they will be asked during the debriefing session at the end of the
603 experiment whether they recognised the rhythmic pattern. The total duration of the
604 experimental procedure will be ~1 hr.

605 **Data Acquisition and Pre-Processing Analyses**

606 Data acquisition will be performed using an ActiveTwo system (BioSemi,
607 Amsterdam, Netherlands) and facilitated by the ActiView software (version 8.13). All
608 the pre-processing analyses will be performed using MATLAB (version R2022a). Data
609 collection and analysis will not be performed blind to the conditions of the study. To

610 avoid a confounding effect of the experimenter, the first and second authors of this
611 Stage 1 manuscript (who will each lead one of the two Stage 2 manuscripts) will each
612 collect data from half of the two groups. Pilot tests were run ($n = 1$ in the three- and
613 four-beat movement condition) to confirm that the proposed experimental protocol and
614 data collection are logistically feasible and that planned analyses will allow us to test
615 the research hypotheses (see Supplementary File 2).

616 *EEG Data*

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

624 The EEG data will be pre-processed using Letswave6 built-in functions
625 (<https://github.com/NOCIONS/letswave6>) and custom MATLAB scripts. The raw
626 data will be band-pass filtered using a 0.1–64 Hz Butterworth filter (4th order) in order
627 to eliminate very slow drifts and high frequencies irrelevant to the proposed study
628 (while also allowing further down sampling of the data if necessary). The filtered signals
629 will be segmented from -5 s to +45.8 s (i.e., 5-s buffer at the beginning and end) with
630 respect to the onset to each trial. Based on visual inspection, channels containing
631 excessive artefacts or noise will be linearly interpolated using the three closest channels
632 (based on Cartesian coordinates). Note that a channel that will be interpolated in one
633 EEG session will also be interpolated in the other EEG session of the same participant
634 to prevent confounds. In addition, trials showing excessive artefacts will be rejected.
635 The full data set of a participant will be removed prior to further analyses if $> 5\%$ of
636 the channels are interpolated and/or > 2 trials per session are rejected (see Figure 3).
637 Any excluded participants will be replaced to ensure that $n = 20$ per group.

638 Independent component analysis will be applied to concatenated segments (from
639 0 to 40.8 s relative to the trial onset) of all trials and sessions, down-sampled to 256 Hz
640 with the purpose of reducing computation time. For each participant, the independent
641 component related to eye blinks will be identified through visual inspection of the first
642 10 independent components' waveform and topography, and removed from the EEG
643 signals. Data will then be re-referenced to the mean of the two mastoids electrodes,
644 averaged across trials, and epoched from 2.4 to 40.8 s with respect to trial onset (i.e.,
645 removal of the 5-s buffer and first pattern repetition), resulting in epochs of 38.4 s.

646 For each electrode, the averaged waveforms will be transformed into the
647 frequency domain using fast Fourier transform, yielding a spectrum of signal amplitudes
648 (in μV) ranging from 0 to 512 Hz, with a frequency resolution of 0.026 Hz (i.e., $1/38.4$
649 s). To obtain valid estimates of the EEG responses, the contribution of residual
650 background noise will be minimised by subtracting, at each frequency bin, the mean
651 amplitude of the four neighbouring bins (2nd to 5th on both sides; see Bouvet et al.,
652 2020; Lenc et al., 2022). The frequencies will then be averaged across a cluster of nine
653 fronto-central electrodes (i.e., F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2), which have been
654 found to exhibit strong frequency-tagged responses to rhythmic stimuli in previous
655 studies (see Nozaradan et al., 2012, 2016, 2017).

656 For each participant and session, the amplitude will be measured at frequencies
657 of interest that are defined based on the temporal structure of the rhythmic pattern.
658 Specifically, these frequencies of interest will correspond to the pattern repetition rate
659 and harmonics ($1/2.4 \text{ s} = 0.42 \text{ Hz}$), up to the frequency equivalent to the shortest
660 interval between the onset of individual sounds composing the rhythmic pattern ($1/0.2$
661 $\text{ s} = 5 \text{ Hz}$). This frequency range of interest is determined based on previous studies (see
662 e.g., Lenc et al., 2020, 2022), showing that surface EEG responses to rhythmic acoustic
663 patterns – similar to the one that will be used in the proposed study – mainly project
664 onto this frequency range. From the resulting set of 12 harmonic frequencies, the first
665 frequency (i.e., 0.42 Hz) will be discarded prior to further analyses, because located in a
666 frequency range that is typically strongly affected by the characteristic $1/f$ background

667 noise observed in EEG spectra (i.e., prone to unreliable measurement; Cirelli et al.,
668 2016; Lenc et al., 2022). The last harmonic frequency (i.e., 5 Hz) will also be dismissed,
669 as its amplitude is likely driven by the shape of the individual 200-ms sounds composing
670 the rhythmic pattern (see Figure 2, left part, for depiction of these frequencies as
671 identified in the modulation spectrum of the stimulus).

672 From this set, the purpose of the study is to assess the relative prominence of
673 frequencies considered as related to the metre periodicity vs. the other, metre-unrelated
674 frequencies (Lenc et al., 2018). To this aim, the amplitude at each of these 10
675 frequencies of interest will be converted into z scores (see Equation 1). Finally, the
676 obtained z scores will be averaged across metre frequencies (i.e., 1.25 and 3.75 Hz in the
677 three-beat condition [i.e., $\bar{z}_{\text{EEG},3\text{-beat}}$], and 0.83, 1.67, 3.33, and 4.17 Hz in the four-beat
678 condition [i.e., $\bar{z}_{\text{EEG},4\text{-beat}}$]). Along the lines of the sound analysis, the sixth frequency
679 (i.e., 2.5 Hz) will be dismissed as it is found in both metrical interpretations. In each
680 condition, Δ_{EEG} will also be computed as the difference between $\bar{z}_{\text{EEG},3\text{-beat}}$ and
681 $\bar{z}_{\text{EEG},4\text{-beat}}$ (i.e., a positive value indicates more activity at three-beat frequencies when
682 compared to four-beat frequencies).

683 *Behavioural Data*

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

687 ***Pre- and Post-Movement Sessions.*** The continuous sound signal recorded
688 during the pre- and post-movement sessions will be segmented into epochs lasting 38.4 s
689 (from 2.4 to 40.8 s with respect to trial onset). Note that the first pattern repetition of
690 each epoch will be removed to match epoching of the EEG data. Claps will be detected
691 in the sound signal using the ‘findpeaks’ function and IRIs will be computed for each
692 trial.

693 The recorded clapping signal will also be analysed in the frequency domain,
694 similarly to the EEG and sound signals. The continuous sound signal will be averaged
695 across trials. The amplitude envelope of this mean signal will be extracted using a

696 Hilbert transform and transformed in the frequency domain using a fast Fourier
697 transform (frequency resolution = 0.026 Hz; i.e., 1/38.4 s trial duration). To match with
698 the analysis procedure applied on EEG data, noise subtraction will also be applied to
699 the obtained spectra. Finally, $\bar{z}_{\text{clapping}}$ and Δ_{clapping} will be computed following the same
700 method described for the EEG data (see Equation 1), with the difference that the
701 frequency range of interest will be adjusted based on visual inspection – the shape of
702 clap events could project onto a larger frequency range than the one typically observed
703 for EEG responses (i.e., slightly beyond 5 Hz).

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

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

723 *Control Measures*

724 **Effectiveness of Auditory Stimulation.** A prerequisite to our hypotheses is
 725 the ability to capture the neural responses to an auditory rhythm with EEG. As a
 726 control measure for this assumption, the frequencies of interest as determined above
 727 (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
 728 stand out relatively to background noise in the EEG signal (see Lenc et al., 2018;
 729 Nozaradan, 2014; Nozaradan et al., 2018). Thus, as a positive control, an index of
 730 standardised signal-to-noise ratio ($z_{\text{SNR,EEG}}$) of the frequencies of interest will be
 731 computed from the raw, non-subtracted amplitude spectrum of EEG data averaged
 732 across the fronto-central channels (see Figure 3; Bottari et al., 2020; Vettori et al., 2020).

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

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

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

743 **Absence of Rhythmic Head Movements During EEG Recordings.** A
 744 possible confounding factor of the proposed study is that the selective enhancement of
 745 EEG responses at metre-related frequencies are not due to neural responses per se but
 746 to unintentional rhythmic movements of the participant’s head while they listened to
 747 the rhythmic stimulus. To control for this potential artefact, head movements will be
 748 recorded using the accelerometer during the listening trials of the pre- and post-training
 749 sessions. The $z_{\text{SNR,head}}$ of metre-related frequencies (i.e., 1.25, 2.50, and 3.75 Hz) will be

750 computed following the same method described for the EEG data (see Equation 2). This
751 index will serve as an indicator of head synchronisation with metre-related frequencies.

752 **Statistical Analyses**

753 *Data Eligible for Analysis*

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

756 **Outcome-Neutral Criteria.** As described in more details above, only data
757 coming from participants with $\leq 5\%$ of interpolated channels and ≤ 2 rejected trials
758 per session will be analysed (see Figure 3).

759 **Positive Control.** A participant's data set will be excluded from the analyses if
760 $z_{\text{SNR,EEG}} < 1.96$ (i.e., $\alpha > .02$), which would indicate an absence of neural responses
761 elicited by the rhythmic stimulus.

762 *Planned Analyses*

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

774 To examine H_1 – H_4 , a two-way mixed-model analysis of variance (ANOVA;
775 Session [pre vs. post movement] \times Movement Condition [three- vs. four-beat metre])
776 will be applied on the two dependent variables, \bar{z}_{EEG} and $\bar{z}_{\text{clapping}}$. To demonstrate that
777 periodic head movements do not contribute significantly to the effects found in the EEG
778 (if any), an identical ANOVA model will be applied on $z_{\text{SNR,head}}$. H_5 and H_6 will be

779 examined by means of a two-way mixed-model Group (African- vs.
780 Western-enculturated group) \times Metre Frequency (three- vs. four-beat metre)
781 mixed-model ANOVA. In addition, a two-way ANOVA (Group \times Movement Condition)
782 will be considered to examine H_7 (see Table 1).

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

790 **Open Practices**

791 *Data Availability*

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

796 *Code Availability*

797 The scripts used to conduct the power analysis are available on a public Zenodo
798 repository (<https://zenodo.org/doi/10.5281/zenodo.10221480>). All scripts supporting
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806

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807 S. M. R. G.: Conceptualisation; Methodology; Formal analysis; Investigation;
808 Data curation; Software; Visualisation; Project Administration; Writing – original draft;
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814

Competing Interests

815 The authors have no competing financial interests to declare.

816

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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}_{EEG} will be larger after when compared to before movement (H_{1a}).	Pairwise t test	$N = 8$ ($d = 1.53$; $\alpha = .020$; $1-\beta = .90$)	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 $d > d_{\text{SESOI}}$.
	\bar{z}_{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 \times 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)

<p>Movement will enhance the amplitude of metre frequencies in the clapping signal, and the four-beat metre condition will yield the most powerful effect.</p>	<p>$\bar{z}_{\text{clapping}}$ will be larger after when compared to before the movement (H_{2a}).</p>	<p>Pairwise t test</p>	<p>$N = 6$ ($d = 1.77$; $\alpha = .020$; $1-\beta = .90$)</p>	<p>Small telescopes approach ($d_{\text{SESOI}} = 0.47$).</p>	<p>The hypothesis will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\text{SESOI}}$.</p>
	<p>$\bar{z}_{\text{clapping}}$ post movement will be larger for the four-beat metre condition when compared to the three-beat metre condition (H_{2b}).</p>	<p>Mixed-model ANOVA (Movement Condition \times Session) followed by pairwise t test</p>	<p>$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .02$; $1-\beta = .90$) and $N = 6$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1-\beta = .90$)</p>	<p>Small telescopes approach ($d_{\text{SESOI}} = 0.47$).</p>	

Stage 1 #2 (Western-enculturated individuals and cross-cultural comparisons)

<p>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.</p>	<p>\bar{z}_{EEG} will be larger after when compared to before movement (H_{3a}).</p>	<p>Pairwise t test</p>	<p>$N = 8$ ($d = 1.53$; $\alpha = .020$; $1-\beta = .90$)</p>	<p>Small telescopes approach ($d_{\text{SESOI}} = 0.47$).</p>	<p>The hypotheses will be accepted if the statistical test is significant ($p < .020$) and the associated Cohen's $d > d_{\text{SESOI}}$.</p>
	<p>\bar{z}_{EEG} post movement will be larger for the three-beat metre condition when compared to the four-beat metre condition (H_{3b}).</p>	<p>Mixed-model ANOVA (Movement Condition \times Session) followed by pairwise t test</p>	<p>$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1-\beta = .90$) and $N = 6$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1-\beta = .90$)</p>	<p>Small telescopes approach ($d_{\text{SESOI}} = 0.47$).</p>	

(Continued)

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

(Continued)

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

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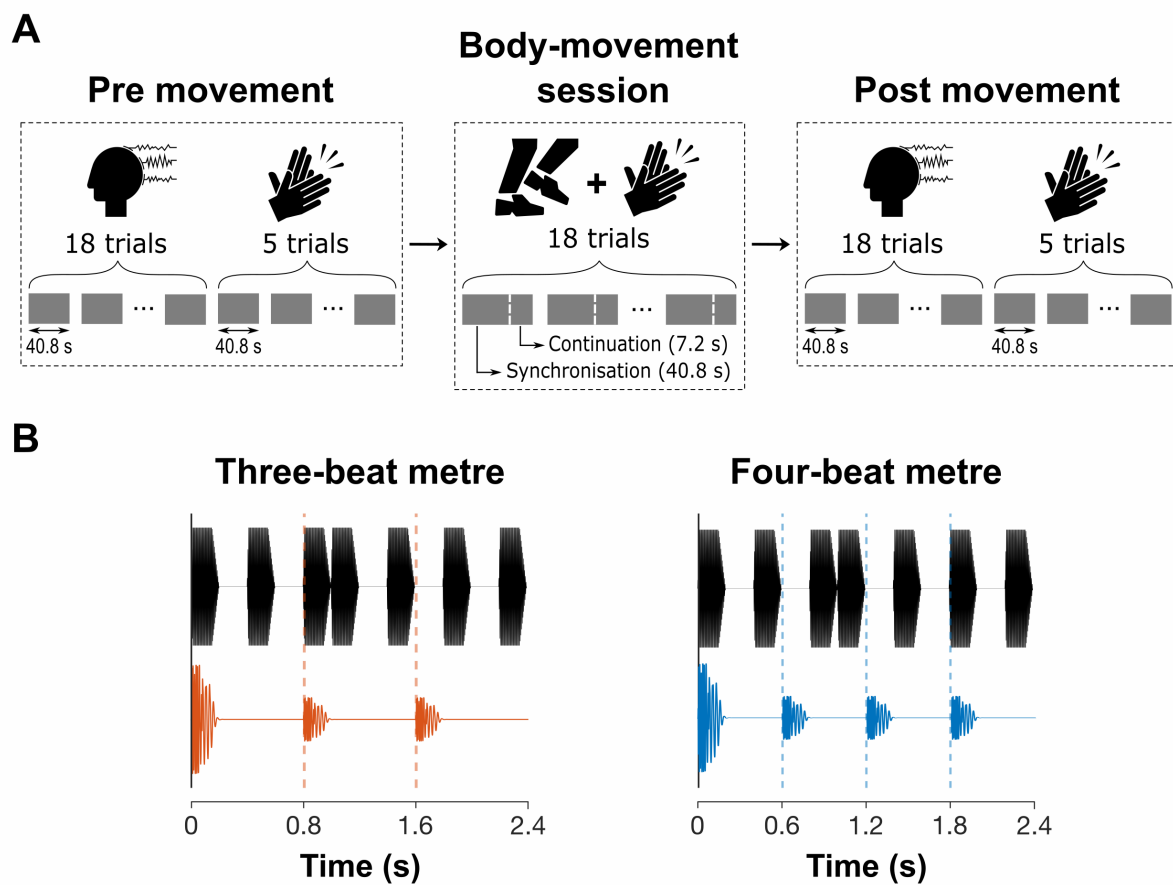
The pre-movement bias toward a specific metrical interpretation will be more important among African-enculturated individuals.	During the pre-movement session, \bar{z}_{EEG} of four-beat frequencies in the African-enculturated group will be more important than \bar{z}_{EEG} of three-beat frequencies in the Western-enculturated group (H_{6a}).	Mixed-model ANOVA (Group \times Metre Frequency) followed by independent t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1-\beta = .90$) and $N = 9$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1-\beta = .90$)	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 pre-movement session, $\bar{z}_{\text{clapping}}$ of four-beat frequencies in the African-enculturated group will be more important than $\bar{z}_{\text{clapping}}$ of three-beat frequencies in the Western-enculturated group (H_{6b}).	Mixed-model ANOVA (Group \times Metre Frequency) followed by independent 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 ($d_{\text{SESOI}} = 0.47$).	

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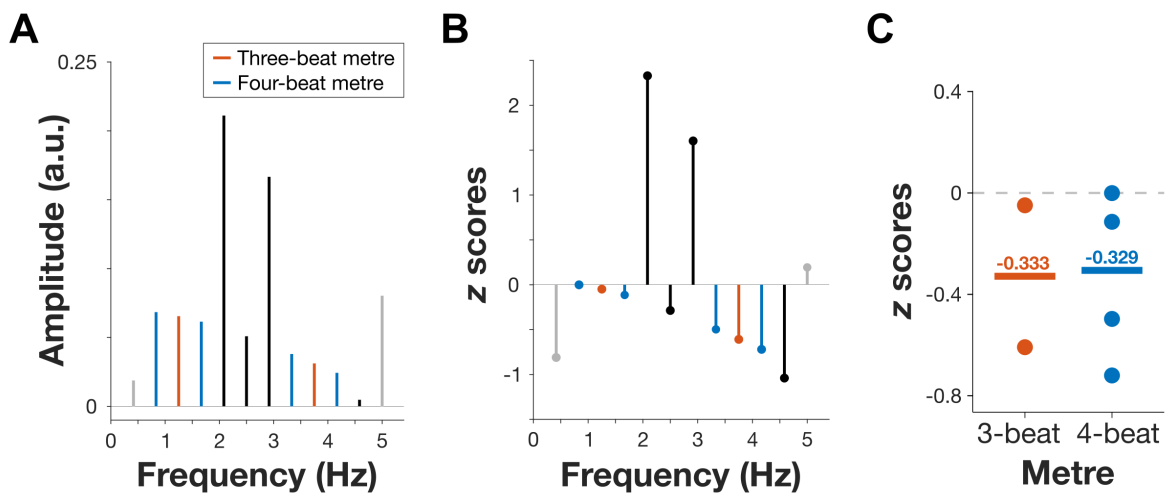
African-enculturated individuals will display larger learning effect for metrical interpretation that is less predominant in their traditional, cultural background.	During the post-movement session, Δ_{EEG} of the African-enculturated group in the three-beat metre condition will be more important than Δ_{EEG} in the Western-enculturated group in the four-beat metre condition (H_{7a}).	ANOVA (Group \times Movement Condition) followed by independent t test	$N = 20$ for the interaction effect ($f = 0.89$; $\alpha = .020$; $1-\beta = .90$) and $N = 9$ for the simple effect ($d = 1.77$; $\alpha = .020$; $1-\beta = .90$)	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 \times Movement Condition) followed by independent 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 ($d_{\text{SESOI}} = 0.47$).	

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

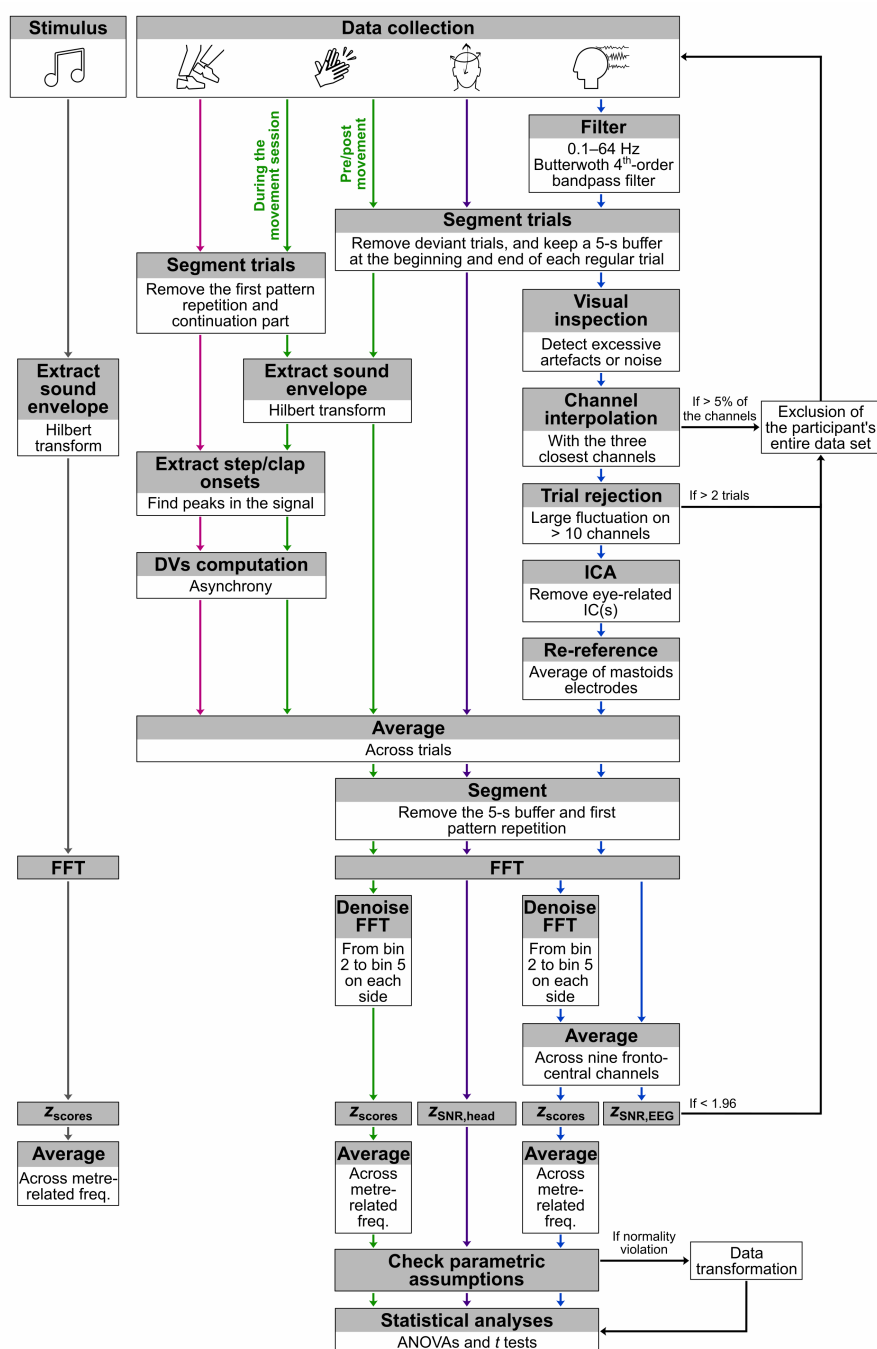
Note. Panel A: Diagrammatic representation of the experimental design. Panel B: Rhythmic pattern with the overlaid drum sound that will be used during the body-movement session in the three-beat (left) and four-beat (right) metre condition. Icon sources: ‘EEG’ by Aenne Briemann, ‘Clap hand’ by Ainul 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.