

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 these specific cases](#), 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 [Also suggesting an effect of movement-related processes on metre perception](#), the
178 active sensing framework states that the motor system modulates the cortical

179 processing of auditory information by refining attention surrounding relevant sensory
180 information (Morillon et al., 2014, 2015). Specifically, motor delta oscillations (0.5–4
181 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). [The action simulation for auditory prediction \(ASAP\)](#)
184 [hypothesis proposes that](#) the simulation of periodic movement shapes metre perception
185 (Patel & Iversen, 2014; Proksch et al., 2020). According to this hypothesis, cortical
186 motor planning regions would thus be entrained by an implicit and automatic process of
187 movement simulation triggered by rhythmic sounds, and this oscillatory pattern would
188 propagate to auditory areas, influencing the metric interpretation of rhythm (Iversen
189 et al., 2009). Although these theoretical models of musical rhythm perception diverge in
190 a number of ways (e.g., anatomical substrates, directionality of relationship between
191 movement and meter perception), they can be viewed as mutually reinforcing (e.g., by
192 describing mechanisms at the brain level or at the cognitive level; see Large et al., 2023;
193 Zalta et al., 2024); and importantly, each of them presupposes a strong role of motor
194 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, [both active and passive body movement coordinated with a rhythmic pattern](#)
198 according to a specific metre was found to bias the way individuals subsequently
199 perceive a rhythm, possibly through vestibular-mediated processes (Phillips-Silver &
200 Trainor, 2008; Trainor et al., 2009). Specifically, both adults and infants have been
201 shown to develop increased expectancy of salient sounds at those positions within a
202 rhythmic pattern that were aligned with the metre the individual had previously moved
203 to (Phillips-Silver & Trainor, 2005, 2007; Su & Pöppel, 2012). Nonetheless, the
204 behavioural measures used in these studies only constitute an indirect way to capture
205 the internal representation of metre elicited by a rhythm (Lenc et al., 2021). [Convergent](#)
206 [evidence across various forms of measurements](#) (e.g., measurements of both the neural
207 and behavioural responses as recorded in separate sessions in response to rhythmic

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

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

232 The objective of this study is to capture direct neuroscientific evidence for the
233 shaping of auditory information by the pace of previous movement. If significant, this
234 effect would thus likely be intrinsically supported by a number of distinct processes,
235 including motor planning, visual, auditory, somatosensory and vestibular cues combined
236 together (Phillips-Silver & Trainor, 2008; Trainor et al., 2009). Movement-related

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

246 **Stage 1 #2 Introduction**

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

262 The particular metre elicited by an external rhythmic stimulus seems to be
263 determined by various factors operating on a short timescale, for example body
264 movement performed concurrently with the stimulus and following a specific metre
265 (Phillips-Silver & Trainor, 2007). Specifically, over the past decades, a number of

266 theoretical models have proposed that prior and concurrent motor production plays an
267 important role in metre perception (e.g., predictive-coding theory of music, neural
268 resonance theory, active sensing, action simulation for auditory perception; Large et al.,
269 2015; Morillon et al., 2019; Patel & Iversen, 2014; Proksch et al., 2020; Vuust et al.,
270 2018).

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

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

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

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

314 **Research Hypotheses**

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

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

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

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

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

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

381 necessarily be able to use the internal representation of the metre induced by the
382 movement session to guide overt movement beyond the movement session itself.

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

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

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

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

428

Methods

429 Ethical Clearance

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

434 Participants

435 Adult volunteers considered eligible to participate in the study will be aged
436 between 18 and 45 years, non-musicians and non-dancers, free of sensory (i.e., no
437 auditory impairment or uncorrected visual impairment) and motor dysfunctions (i.e., no

438 upper- and/or lower-limb disorders), and not self-identify as having psychiatric or
439 neurological disorders. In the present research project, non-musicians or non-dancers are
440 defined as those meeting at least two out of the three following criteria: (a) not
441 considering themselves as such, (b) not having more than four years of practice, and (c)
442 not having played an instrument/danced in a concert or performance on stage in front
443 of an audience.

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

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

467 session ($f = 0.89$; $\alpha = .02$; $1-\beta = .90$). In addition, 20 participants per group would be
468 needed for the interaction effects of H_5-H_7 ($f = 0.89$; $\alpha = .02$; $1-\beta = .90$). Therefore, a
469 total sample of 40 participants (i.e., 20 per movement condition) will be recruited for
470 each of the two proposed studies, which means a total of 80 participants for the whole
471 research project (see see Table 1).

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

480 **Experimental Procedure and Tasks**

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

484 ***Experimental Procedure***

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

496 movement during the pre- and post-movement sessions, the accelerometer will be placed
497 on the participant's head.

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

505 *Auditory Stimulus*

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

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

525 Lenc et al., 2021; Nozaradan et al., 2016). This holds for beat pulses that are used in
526 both the three- or four-beat metre condition. Moreover, an overlap between the internal
527 beat and the arrangement of tones in the rhythm cannot be achieved by simply shifting
528 the phase (or alignment) of the beat with respect to the stimulus.

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

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

554 to the shortest intervals between single events (i.e., $1/0.2 \text{ s} = 5 \text{ Hz}$; Lenc et al., 2021).
555 To match analysis of the EEG signals (see below ‘EEG Data’ subsection), the first and
556 last frequency of the spectrum were discarded from further computation.

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

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

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

570 *Tasks Description*

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

582 of the underlying time grid by 7.5%, lengthening the duration of that repetition from 2.4
583 s to 2.58 s. There will be a total of two trials per session containing this deviant period
584 (with those trials being randomly positioned across participants), and these trials will
585 be discarded from further analyses. In the hand-clapping task (i.e., which will directly
586 follow the listening task in both the pre- and post-movement sessions; see Figure 1), the
587 participant will be instructed to clap along with the beat they perceive in the auditory
588 stimulus ('Clap your hands as you would clap in sync with the music at a concert').

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

597 *Experimental Design*

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

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

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

611 collection and analysis will not be performed blind to the conditions of the study. To
612 avoid a confounding effect of the experimenter, the first and second authors of this
613 Stage 1 manuscript (who will each lead one of the two Stage 2 manuscripts) will each
614 collect data from half of the two groups. Pilot tests were run ($n = 1$ in the three- and
615 four-beat movement condition) to confirm that the proposed experimental protocol and
616 data collection are logistically feasible and that planned analyses will allow us to test
617 the research hypotheses (see Supplementary File 2).

618 *EEG Data*

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

626 The EEG data will be pre-processed using Letswave6 built-in functions
627 (<https://github.com/NOCIONS/letswave6>) and custom MATLAB scripts. The raw
628 data will be band-pass filtered using a 0.1–64 Hz Butterworth filter (4th order) in order
629 to eliminate very slow drifts and high frequencies irrelevant to the proposed study
630 (while also allowing further down sampling of the data if necessary). The filtered signals
631 will be segmented from -5 s to +45.8 s (i.e., 5-s buffer at the beginning and end) with
632 respect to the onset to each trial. Based on visual inspection, channels containing
633 excessive artefacts or noise will be linearly interpolated using the three closest channels
634 (based on Cartesian coordinates). Note that a channel that will be interpolated in one
635 EEG session will also be interpolated in the other EEG session of the same participant
636 to prevent confounds. In addition, trials showing excessive artefacts will be rejected.
637 The full data set of a participant will be removed prior to further analyses if $> 15\%$ of
638 the channels are interpolated and/or > 3 trials per session are rejected (see Figure 3).
639 Any excluded participants will be replaced to ensure that $n = 20$ per group.

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

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

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

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

674 From this set, the purpose of the study is to assess the relative prominence of
675 frequencies considered as related to the metre periodicity vs. the other, metre-unrelated
676 frequencies (Lenc et al., 2018). To this aim, the amplitude at each of these 10
677 frequencies of interest will be converted into z scores (see Equation 1). Finally, the
678 obtained z scores will be averaged across metre frequencies (i.e., 1.25 and 3.75 Hz in the
679 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
680 condition [i.e., $\bar{z}_{\text{EEG},4\text{-beat}}$]). Along the lines of the sound analysis, the sixth frequency
681 (i.e., 2.5 Hz) will be dismissed as it is found in both metrical interpretations. In each
682 condition, Δ_{EEG} will also be computed as the difference between $\bar{z}_{\text{EEG},3\text{-beat}}$ and
683 $\bar{z}_{\text{EEG},4\text{-beat}}$ (i.e., a positive value indicates more activity at three-beat frequencies when
684 compared to four-beat frequencies).

685 *Behavioural Data*

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

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

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

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

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

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

725 *Control Measures*

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

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

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

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

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

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

754 **Statistical Analyses**

755 *Data Eligible for Analysis*

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

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

761 **Positive Control.** A participant's data set will be excluded from the analyses if
762 $z_{\text{SNR,EEG}} < 1.96$ (i.e., $\alpha > .02$), which would indicate an absence of neural responses
763 elicited by the rhythmic stimulus.

764 *Planned Analyses*

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

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

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

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

792 **Open Practices**

793 ***Data Availability***

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

798 ***Code Availability***

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

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809 S. M. R. G.: Conceptualisation; Methodology; Formal analysis; Investigation;
810 Data curation; Software; Visualisation; Project Administration; Writing – original draft;
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816

Competing Interests

817 The authors have no competing financial interests to declare.

818

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1107 <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}_{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>	
<p>Stage 1 #2 (Western-enculturated individuals and cross-cultural comparisons)</p>					
<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)

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}_{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}).	Mixed-model ANOVA (Group \times Metre Frequency) 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 ($d_{\text{SESOI}} = 0.47$).	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 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}).	Mixed-model ANOVA (Group \times Metre Frequency) 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 ($d_{\text{SESOI}} = 0.47$).	

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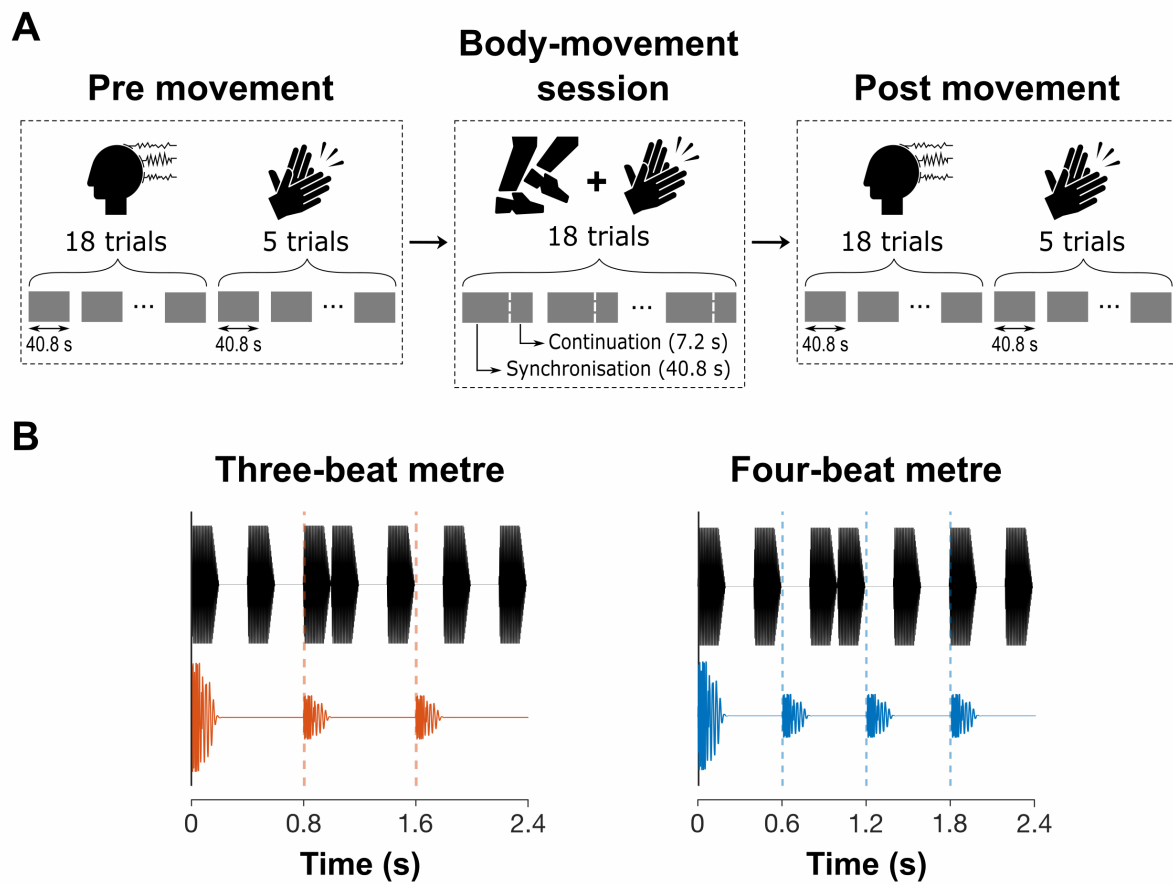
The pre-movement bias toward a specific metrical interpretation will be more important among African-enculturated individuals.	During the pre-movement session, \bar{z}_{EEG} of four-beat frequencies in the African-enculturated group will be more important than \bar{z}_{EEG} of three-beat frequencies 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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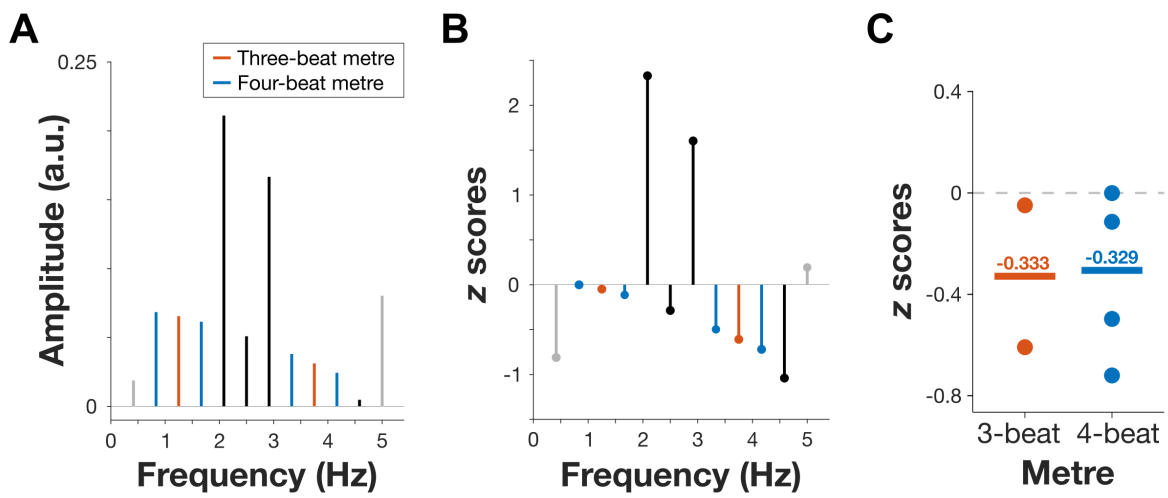
African-enculturated individuals will display larger learning effect for metrical interpretation that is less predominant in their traditional, cultural background.	During the post-movement session, Δ_{EEG} of the African-enculturated group in the three-beat metre condition will be more important than 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

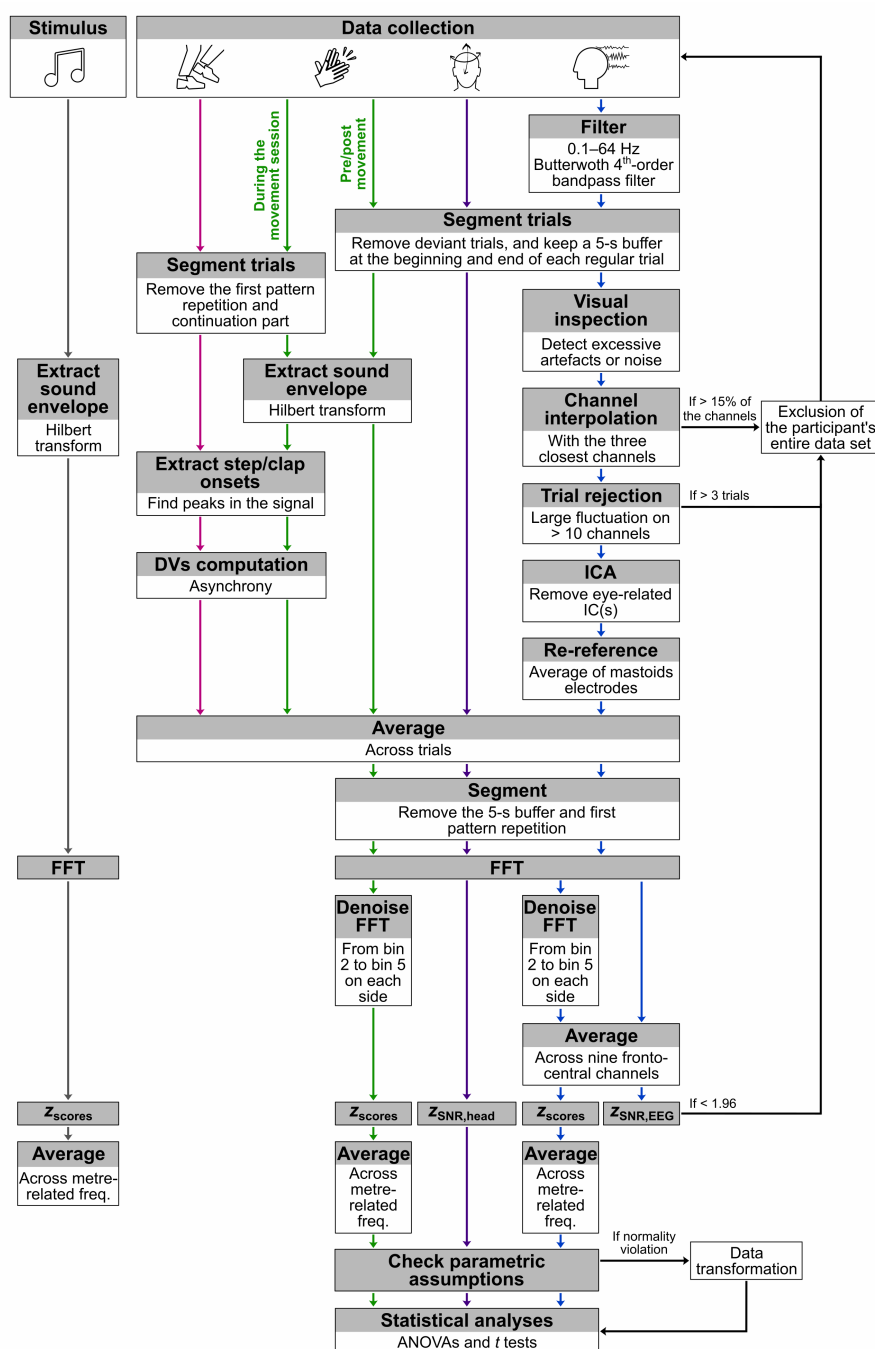
Note. Panel A: Diagrammatic representation of the experimental design. Panel B: Rhythmic pattern with the overlaid drum sound that will be used during the body-movement session in the three-beat (left) and four-beat (right) metre condition. Icon sources: ‘EEG’ by Aenne Briemann, ‘Clap hand’ by Ainul 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 Briemann (modified) from the Noun Project under CC BY 3.0 license.