Universal and Cross-Cultural Variations in Audio-Motor Synchronization Between French and Indian Participants

Martin Le Guennec (1), Andon Tchechmedjiev (2), J. A. Scott Kelso (3,4,5), Julien Lagarde (6)

(1) Euromov Digital Health in Motion, Université de Montpellier, IMT Mines Alès, Montpellier, France
(2) SyCoIA – Systèmes Complexes et Intelligence Artificielle, IMT Mines Alès, Alès, France
(3) Center for Complex Systems, Florida Atlantic University, Boca Raton, USA
(4) Intelligent Systems Research Centre, Ulster University, Derry~Londonderry, N. Ireland
(5) Institute for the Augmented Human, University of Bath, UK
(6) Movement, Balance, Performance, and Health Laboratory (MEPS), Université de Pau et des Pays de l'Adour, Tarbes, France

Abstract

How does a person's cultural background and prior experience with diverse rhythms of music and life affect basic sensorimotor skill? The present research investigated invariance and variations in synchronization abilities among French and Indian non-musician and non-dancer students. Participants were instructed to tap along to a regular auditory sequence, whose rate was increased in a stepwise fashion. Relative phase variability and frequency mismatch did not show significant differences between the groups, indicating comparable levels of performance. Surprisingly, however, French participants exhibited a tendency to tap *before* the sound (considered as ubiquitous in previous studies), whereas Indian participants exhibited a mean asynchrony close to zero. When synchronization was lost at higher rates, the frequency mismatch between movement and metronome showed that only French participants overestimated the metronome rate. To our knowledge, using an empirical geographic proxy assuming a causal role of enculturation, this study is the first to provide evidence for such similarities and variations in the basic ability to synchronize movement with sound. The fact that enculturation could affect functions as elementary as simple synchronization suggests the need for a more systematic development of comparative studies in the classic paradigms typical of the human sciences.

Keywords: Sensorimotor Synchronization, Cross-Cultural, Enculturation, NMA, Coordination Dynamics, Universals

Graphical abstract

We suggest Figure 4 as the image to be included

This study explores enculturation effects on Indian and French synchronization abilities. We asked participants to tap along with a metronome, across a range of rates. We found invariance and diversity of synchronization performances: Stability measures and rate limit were similar while, surprisingly, mean timing error varied. Synchronization errors at higher rates suggest that frequency adaptation encapsulates the expression of rhythmic enculturation in this elementary synchronization.

Introduction

The fact that Western participants are overrepresented in behavioral and cognitive studies [1,2] places at risk an appreciation of the variation of adaptations common in all human beings. Here, we examined whether enculturation influences the synchronization of movement to a simple auditory sequence. The ability to coordinate perception and action is essential for a wide range of human activities. Such coordination is endowed with temporal dynamics [3–5], and may take the form of rhythmic patterns, common to basic behaviors like chewing or walking, but also intrinsic to speech, dance, sports and music—indeed, to all forms of human communication [6–11].

Although biomechanical, biophysical and neuronal mechanisms contribute greatly to such abilities, so also does learning the regularities in the physical and social environment and the actions they afford. Prolonged exposure to a social environment leads to perceptual learning [12], observed as an enhanced perception of the environment's regularities and an increased inhibition of unfamiliar information; the nervous system tunes itself from early childhood [13–15] to interact optimally with its environment (for a review, see [16]). For example, 12-month old infants are able to perceive both familiar and unfamiliar rhythms in the music of their social environment after short-term exposure while adults' accuracy of perception of the same unfamiliar rhythm does not exceed chance level [17,18]. As such, we conceive culture as communities of learning and practices as proposed by Polak and colleagues [19,20], rather than based on geographic or ethnic criteria. The modification of rhythm perception and production by long-term exposure to a specific culture is referred to as *enculturation*. It is characterized by a perceptual narrowing—exemplified by the work of Hannon and colleagues cited above—causing a decreased perception of unfamiliar rhythms, and an increased performance when perceiving or producing familiar rhythms. This latter point was demonstrated by cross-cultural studies showing that participants with prolonged exposure to certain non-isochronous rhythms, rare in Western music but pervasive in other cultures, perceive and produce them more proficiently compared to Western participants unfamiliar with them. For example, North Indian listeners show robust synchronization to *Jhaptal*-like meters composed of alternating units of 3 and 2 beats that impair American performance [21]; Balkan and Turkish listeners [15,17], as well as Bulgarian and Turkish traditional musicians [22], are proficient with meters involving 3:2 ratios and 2:2:3 rhythms that are difficult for Western listeners; Malian jembe musicians and dancers [19,22] tend to produce 4:3 and 7:2:3 rhythms; East African participants show culture-specific advantages for 12:8 compared to North Americans [23], and African musicians and dancers display pronounced 3:3:2 rhythm priors [22]; finally, Turkish classical and folk musicians are more sensitive to 5:8 meters compared to American listeners [24].

By studying variation between cultural groups, the foregoing studies also highlighted some commonalities that could reflect universals of rhythm perception and production [25]. Notably, a series of studies investigated the culture-specific rhythmic attractors with an iterative reproduction task of rhythmic ratios composed of three intervals sampled randomly. They recruited participants from more than 30 different countries and observed that after few iterations, the initially random ratios were attracted toward a small set of discrete prototypes, all of which were composed of small integer ratios specific to the music of our culture [14,22,26]. This shows that every perceived rhythm is assimilated toward a discrete prototype consisting of a ratio of simple integers [27]. While the presence of some prototypes vary with enculturation, others were found to be common to all cultures [14,22,26], and are even observed in other species [28], such as the isochronous rhythm, present in most of the cultures studied so far [29]. Even though isochronous rhythm can be considered a basic building block of the other rhythms in the Western musical theory [30], it is not necessarily the case for all cultures. Indeed, several studies found many occurrences of non-isochronous meters throughout the world (for a review, see [20]). North Indian classical music offers an example of such non-isochronous rhythms, with structures such as *jhaptal* and *rupak* employing non-isochronous beat groupings as structural features [31].

Simple sensorimotor synchronization (SMS) consists of synchronizing simple movements (e.g., flexion- extension of fingers, and tapping on a table) with an isochronous tone sequence (e.g., a ticking clock or a metronome) (for reviews, [5,32,33]). Brain imaging studies of SMS have unveiled the involvement of extended cortical and subcortical neuronal networks [34–37], in agreement with views that distributed brain areas subserve time processing [38,39]. Empirical cross-cultural studies of SMS remain scarce, as they used mostly non-isochronous stimuli as exemplars of culturally specific rhythmic patterns (see references below). When SMS has been studied in a cross-cultural context, it was restricted to a few rates, somewhat limiting our understanding of how cultural experience shapes synchronization dynamics. A wide variation of the metronome rate could reveal a wealth of interesting features. For example, how synchronization evolves with rate could tap into cultural variations in adaptation processes; measuring the rate limits of synchronization contributes to better quantifying synchronization performance; examining how synchronization is lost at higher rates could also enrich cross-cultural comparisons. Ullal-Gupta, Hannon and Snyder [21] compared Indian and US students tapping to very slow isochronous rhythm with and without subdivision and found no differences. Cameron, Bentley and Grahn [23] recruited Rwandans and Canadian adults to tap an isochronous beat along with composite rhythms derived from East African or Western music; asynchrony variability did not differ between groups, but Canadians showed smaller absolute mean asynchrony. Polak and colleagues [19] tested Malian percussionists, German and Bulgarian musicians: they found differences in synchronization variability but not in mean asynchrony, which was negative for all groups. Witek and colleagues [40] compared Ghanaians and US students on a synchronization task with an isochronous metronome but also some syncopated beats. They reported lower asynchrony variability in Ghanaians. Jakubowski and colleagues [41] compared musician and non-musician participants from UK, Uruguay and Mali who performed a synchronization task with an isochronous stimulus, finding larger asynchrony variability in non-musicians but relatively small differences between cultural groups. Danielsen and colleagues [42] recruited professional musicians in jazz, folk music or computer-based dance music to tap along on an isochronous rhythm and reported a difference between groups in both mean and variability of asynchrony. Finally, Jacoby and colleagues [22] recruited participants from 15 countries (musicians, non-musicians and students) who performed a tapping task with a metronome, reporting large variations in dispersion of asynchrony and mean value, though all groups displayed negative mean asynchrony.

These studies documented the influence of enculturation on basic SMS, but a more thorough investigation is required to delineate in further detail how SMS is shaped by enculturation. Simple SMS is known to display a significant degree of plasticity, as shown by the effect of musical expertise (e.g., [43–46]), and the potential mechanisms responsible for these learned effects have been addressed in modelling studies [47–52]. SMS has also fueled considerable modeling efforts, aiming at overarching theoretical questions, such as plasticity, dynamical self-organization, optimality, anticipation, and time keeping ([3,53–58], for a review see [59]). Few theoretical efforts however have addressed enculturation effects on rhythm [60], or rhythm plasticity in development [52] from a modelling perspective. None, so far, have tackled enculturation effects on SMS.

In the present study we examined whether plasticity resulting from rhythmic enculturation is exhibited in the ability to synchronize to a simple auditory metronome. We recruited French and Indian non-musician participants differing in their musical enculturation history and evaluated SMS performance across a wide range of auditory metronome rates. Our French sample was recruited in a Western European context [1] in which everyday exposure is typically dominated by musical styles with largely isochronous metrical organization. Our Indian sample was recruited in a context where listeners are commonly exposed to a wider variety of metrical structures, including both isochronous and non-isochronous patterns [21,31,61]. We do not treat these samples as representative of "Western" and "Indian" populations; rather, we use this geographic criterion as a proxy for differences in rhythmic enculturation. We conceive culture as the product of learning and practice [19,20,22] rather than as being defined solely by geography, however our sampling strategy does not link participants to a specific community. Nevertheless, among different potential sources of diversity, exposure to different musical rhythmic structure would be the most probable to explain variations observed on a synchronization task. Additionally, multilingualism may constitute another explanation, but we emphasize the musical experience consistent with previous evidence that language has limited influence on rhythm enculturation [22]. Therefore, the present study constitutes a step toward a comprehensive study of enculturation. We predicted that the culture-specific rhythmic structures acquired through everyday listening experience would influence basic SMS performance [16]. Specifically, Indian participants' broader exposure to rhythmic diversity may yield a less dominant isochronous "prior" or dynamical attractor, thereby reducing synchronization stability in SMS, compared to French participants. Considering the latter, enculturation to predominantly isochronous musical structure should increase their synchronization stability.

We firstly examined the dispersion of relative phase and its evolution with the systematic increase of metronome rate, a well-grounded measure of synchronization stability in coordination dynamics [3,62] and on the basis of forced oscillator models [59]. To further quantify synchronization performance, we counted the number of plateaus corresponding to well-defined synchronization across the full range of rates tested. Secondly, expecting a loss of synchronization at higher rates [5,63], we examined the frequency mismatch, that is, the difference between the movement frequency and the stimulus rate. Even a small frequency mismatch is indicative of a loss of synchronization [5,64] and, we hypothesized, may characterize the way French and Indian participants behave when they reach their limit of synchronization capability, namely at the highest metronome rates. Finally, we investigated the mean asynchrony between movements and stimuli. Classically, the mean asynchrony is found to be negative, indicating that the movement occurs before the sound (typically around 40 ms, for reviews see [32,33,65]). Such Negative Mean Asynchrony (NMA) is often interpreted as the anticipation of the movement with respect to the metronome—and is known to be influenced by characteristics such as musical expertise [44–46,53,66] and brain pathology [67,68]. In principle, if enculturation effects on SMS are minimal, we did not expect to see any differences between the populations studied. But as we shall show, subtle and interesting effects on SMS are, in fact, a distinguishing feature of our results.

Material and methods

Participants

13 French (2 F, 11 M; age = 29.5 ± 4.4 years) and 15 Indian (3 F, 12 M; age = 29.3 ± 4.1 years) participants were recruited in Université de Montpellier (France). All were right-handed. The Indian participants had left India for France less than 2 years prior to the experiment. They spoke between 1 and 6 Indian languages (including Gujarati, Hindi, Kannada, Kumauni, Ladakhi, Marathi, Punjabi, Sindhi, Tamil, Telugu, Urdu) and they were fluent in English but not in French. All participants were self-reported non-musicians and non-singers, with no formal training or regular practice in music or singing. All participants provided written informed consent prior to the experiment. The protocol was approved by the Université de Montpellier ethics committee (IRB local committee number 1904A).

Task

The task consisted of synchronizing sequences of finger tapping on a hard table surface with an auditory metronome. The finger movements, measured with a goniometer, consisted of flexion-extension of the metacarpophalangeal joint of the index finger of participants' preferred hand (right) to tap on the table, with the forearm resting on the table to avoid any movement of the wrist. Thumb and other fingers were flexed and rested on the table too. The movement was constrained to ensure that the goniometer was recording the finger movement correctly. The experimenter demonstrated the execution of one tap on the table to illustrate the required movement, involving full flexion-extension at the metacarpophalangeal joint. Each plateau presented 15 beeps except for the 1st plateau, in which the metronome emitted 5 extra beeps to ease establishing synchronization. The rate increased by increments (referred to as plateaus) of 0.3 Hz every 15 stimuli. The plateaus were presented in a continuous sequence to limit the duration of the experiment and to reduce the adaptation time at high rates. The instruction was to "synchronize every finger tap with every metronome beat as best you can". Participants were informed that the rate of the metronome increased gradually, and that the task was to keep trying to synchronize as accurately as possible, even if they found it very challenging at higher rates. The instructions to synchronize were repeated several times between trials of the experiment. Rests were allowed between each trial to reduce any possibility of fatigue.

The experiment started with a familiarization trial: participants were asked whether they needed clarification about the task to be performed. All performed 3 trials of synchronization with a pacing metronome scaled up from 1.0 Hz to 6.1 Hz (18 plateaus; termed the long form), affording measures of successful synchronization, evolution of synchronization with rate, as well as the rate limit above which loss of synchronization may occur. Finally, participants performed 4 trials of the synchronization task with a pacing metronome scaled up from 1.0 to 4.0 Hz (11 plateaus; termed the short form). By choosing a more restricted range of frequencies for which synchronization was presumably stable, our aim was to improve the estimation of the mean asynchrony and the dispersion of relative phase on synchronized plateaus while completely avoiding fatigue.

Stimuli and data acquisition

The stimuli on each trial consisted of sound beats 40 ms long with a carrier frequency of 440 Hz. The stimuli were displayed through loudspeakers located in front of the participant, using custom programs, and using the sound card of a computer controlled by the Data Acquisition Toolbox from Matlab. Finger movement was captured using a second computer, by means of a goniometer (Biometrics Ltd) affixed to the metacarpophalangeal joint and connected to an A/D card (National Instruments, USB-6002), and the Data Acquisition Toolbox from Matlab. The voltage sent to the speakers was simultaneously collected by the same A/D card using a splitter. This setup was previously used in synchronization experiments with millisecond precision (e.g., [69,70]). The data were sampled at 5 kHz to ensure good accuracy when detecting the onset of stimuli.

Data preprocessing

Data preprocessing was performed using Matlab (Mathworks, 2021b). Raw movement signals were downsampled to 500 Hz and low-pass filtered with a dual-pass Butterworth filter (order 5, 5 Hz cutoff frequency).

Estimation of relative phase between movement taps and metronome

The taps were identified using the *findpeaks* function; correct identification of the peaks was verified by visual inspection of all trials. Stimulus onsets were identified using a threshold. To do so, we first applied a moving average with a 3-sample window, then downsampled the time series to 500 Hz. Next, onsets were defined as data points exceeding 500 μV that were separated by at least 100 samples (20 ms) from the preceding suprathreshold sample.

The relative phase was calculated as $(t_{\text{tap}} - t_{\text{stim}})/T \times 2\pi$, where t_{tap} is the time of the tap, t_{stim} is the time of the closest stimulus, and T is the period between the two stimuli surrounding the current peak. This calculation was performed by the *relphase* function from the *RelPhase* toolbox [71]. The relative phase is an angle corresponding to the (period-normalized) time gap between the taps and the stimuli. A relative phase of 0 radians means that the tap was performed at the same time as the onset of the stimulus, whereas a relative phase of $\pm\pi$ means that the tap was performed at half the period between two stimuli. Following convention, a negative relative phase indicated that the movement occurred before the beep. The first three values of relative phase of a plateau were excluded from the subsequent analysis to eliminate transient effects.

Synchronized plateaus

A given plateau was retained for subsequent analysis on the basis of the stationarity of the relative phase measure. To do so, we used the slope of the relative phase time series [63]. This slope is equal to the frequency mismatch, i.e., the difference between the tapping frequency and the metronome rate. Synchronization is achieved when these two frequencies are equal on average, corresponding to a slope—and hence a frequency mismatch—that fluctuates around zero. To reduce the effect of noise, the derivative of the relative phase time series was smoothed using a 3rd order median filter, followed by a 4-point moving average. The proportion of points for which the derivative was smaller than 0.2 was calculated for each plateau; this threshold was set after data inspection, quantifying the time spent with a stationary relative phase (see Figure 1 and [72,73]). Finally, the plateau was considered synchronized and thus kept for the analysis of relative phase if this proportion was at least 50%. The proportion of plateaus considered synchronized is shown in Figure 3A.

Variables and Statistical Analyses

Statistical analyses were performed using R [74], with the libraries *lmerTest* [75] for fitting linear mixed models, *emmeans* [76] for pairwise comparisons and *effectsize* to compute effect sizes. For each model, assumptions of linearity, homoscedasticity and normality of the residuals and random effects were verified through examination of diagnostic plots (see supplementary materials). When outliers were observed in the residuals, the robustness of the inferential results obtained from the linear mixed models were verified using non-parametric permutations with the *permuco* library [77]. The Satterthwaite approximation was used to estimate degrees of freedom [78]. The effect of group, metronome rate and their interaction was evaluated using type III F-tests on the linear mixed models, and reported in Tables S1, S3 and S5. Between-group comparisons were performed at each metronome rate using t-tests, p-values were Bonferroni corrected and Cohen's d was computed to report effect size.

The model-based mean, standard errors, and confidence intervals reported in the results, and all figures were estimated from the linear mixed models fit using a restricted maximum likelihood method. For comparison with more classical estimations and to quantify dispersion of data not provided by the linear mixed model outputs, the arithmetic means and standard deviations were also included (see Tables S2, S4 and S6).

Frequency mismatch ($\Delta\omega$)

Frequency mismatch refers to the difference between finger and metronome frequency; it is a discriminating index of synchronization stability since even a small frequency mismatch indicates loss of synchronization [5]. For each plateau, the movement and metronome frequencies were calculated respectively as the inverse of the average period between two taps and two beeps. The frequency mismatch was the difference between these average frequencies. A positive frequency mismatch indicated that tapping was faster than the metronome, and vice-versa. A linear mixed model was fitted on all plateaus to determine the effect of group, metronome rate and their interaction, with a random intercept per frequency for each participant.

Maximum frequency mismatch

The maximum of the frequency mismatch was obtained from long synchronization trials. Frequency mismatch was calculated as defined above. However, we considered that if participants reached the highest frequency of movement they were able to produce, irrespective of the intent to synchronize, then the frequency mismatch was not considered as informative about synchronization per se. Indeed, by construction in such a case an increase of the metronome frequency leads to an increase of the frequency mismatch. Visual inspection indicated that at higher rates the actual frequency of tap movements could eventually reach a maximum before the last plateau of the trial. Accordingly, on a trial-by-trial analysis, we kept only the plateaus for which the average frequency was smaller than a threshold, while reducing the impact of extreme values. To do so, we computed the average frequency of all the plateaus of the trial and selected the plateau with the maximum average frequency. From the series of frequencies obtained in this plateau we took the 95% confidence interval (CI) of the average frequency and SD. Next, for the same trial, we discarded plateaus having an average frequency falling within this 95% CI. Moreover, if the CI upper bound exceeded the highest metronome rate of 6.1 Hz, all plateaus were retained since the participant was able to synchronize up to the fastest metronome rate. Finally, from the plateaus selected, the maximum frequency mismatch, calculated as defined above, was identified as the 20th or 80th percentile value having the largest absolute magnitude, thereby preserving the direction, or sign, of the mismatch.

Rate limits quantified by the number of synchronized plateaus

We observed that some participants were initially synchronized with the metronome, then lost the synchronization before synchronizing once again in following plateaus. Accordingly, to quantify the rate limits of synchronization we counted the number of synchronized plateaus for each trial, as defined above in the Preprocessing section. A linear mixed model was fitted to determine the effect of group on the number of synchronized plateaus, with a random intercept per participant.

Dispersion of relative phase of synchronized plateaus (SD ϕ)

The dispersion of the relative phase (SD ϕ) was calculated for each plateau separately using circular statistics [79], including short and long synchronization trials. This dispersion is a well-grounded measure of the stability of synchronization [3,62]. A large increase of SD ϕ—considering all plateaus, synchronized or not—with the increase of the metronome rate is indicative of loss of synchronization [5,63]. A linear mixed model was fitted on the SD ϕ values from the synchronized plateaus only (see subsection Synchronized Plateaus and Figure 3A) between 1.0 to 3.7 Hz (a range of rates where most participants were able to synchronize; see Figure 2B) to determine the effect of group, metronome rate and their interaction, with a random intercept for each participant.

Mean asynchrony

The mean relative phase was calculated using circular statistics [79] for each synchronized plateau (see Data preprocessing and Figure 3A) of both long and short synchronization trials between 1.0 and 3.7 Hz. These values were converted from angles to duration as follows: $\text{mean async} = T \times \text{mean}\,\phi\ /2\pi$, where mean async is the mean asynchrony, $\text{mean}\,\phi$ is the circular mean relative phase and T is the duration between two consecutive stimuli (in ms). A linear mixed model was fitted on the mean asynchrony values from the synchronized plateaus only (see subsection Synchronized Plateaus and Figure 3A) to determine the effect of group, metronome rate and their interaction, with a random intercept per frequency for each participant.

Relationship between mean asynchrony and frequency mismatch

A linear mixed model was fitted to explore the effect of the maximum frequency mismatch and metronome rate on the mean asynchrony separately for each group.

1

Results

Participants from both groups synchronized successfully across low metronome rates and gradually lost synchronization as pacing increased. Figure 1 illustrates finger movement time series and metronome onsets for these two regimes: stable synchronization at low rates, characterized by the relative phase fluctuating around a central value, and loss of synchronization at higher rates, where the relative phase drifts in time. Four analyses confirmed that French and Indian participants showed equally stable synchronization. First, the median dispersion of relative phase (SD ϕ; see Figure 2B) was small over this low-rate range, from 1.0 Hz to 3.7 Hz, for both French and Indian participants. The associated interquartile range (IQR) of SD ϕ was also small but increased before the median (at 3.1 Hz for French and 3.4 Hz for Indian; Figure 2B), suggesting that inter-individual variability increased before the synchronization degraded at the group level. Even though median and IQRs were comparable between groups, more outliers were observed in Indian participants at those low rates. Second, both groups exhibited frequency mismatch close to 0 Hz at metronome rates from 1.0 Hz up to 3.7 Hz for French participants and up to 4.0 Hz for Indian participants, as indicated by the medians in Figure 2A. Third, the linear mixed model fitted only on the synchronized plateaus revealed that while frequency had an influence on SD ϕ ($p < 0.001$, η_p^2 [95% CI] $= 0.05\ [0.03, 1.00]$), neither group ($p = 0.31$, η_p^2 [95% CI] $= 0.04\ [0.00, 1.00]$) nor the interaction between group and frequency ($p = 1.00$, η_p^2 [95% CI] $= 0.00\ [0.00, 1.00]$) had a detectable impact on SD ϕ, implying no clear between-group differences in stability (Figure 3B; Table S3). Pairwise comparisons of SD ϕ between French and Indian participants were likewise compatible with negligible between-group differences across all metronome rates (Table S4). Fourth, the number of synchronized plateaus did not differ ($t(26) = 0.08$, $p = 0.939$, d [95% CI] $= 0.18\ [-4.56, 4.91]$) between French (10.13 ± 1.00) and Indian participants (10.02 ± 0.93). To summarize: at low metronome rates, the relative phase was successfully attracted toward a central value with small fluctuations in both groups; and French and Indian participants achieved similarly stable synchronization over an equivalent range of rates. Around 4 Hz, frequency mismatches began to depart from 0 and SD increased sharply in both groups, marking a loss of synchronization.

Figure 2A shows that French and Indian participants lost synchronization differently. For Indian participants, frequency mismatch stayed centered around 0 until 4.9 Hz with growing variability between participants. Then it became increasingly negative from 5.2 Hz onward, indicating that finger movements were slower than the metronome. In contrast, French participants progressively moved faster than the metronome from 3.7 Hz onward, resulting in positive frequency mismatch values. It was only at highest frequencies, above 5.2 Hz, that they exhibited a negative frequency mismatch—though still closer to 0 Hz than their Indian counterparts. This difference was confirmed statistically with the substantial influence of group ($p < 0.001$, η_p^2 [95% CI] $= 0.06\ [0.03, 1.00]$) and of the interaction group × frequency on the frequency mismatch ($p < 0.001$, η_p^2 [95% CI] $= 0.10\ [0.03, 1.00]$): the frequency mismatch differed between groups and this difference evolved with metronome rate (for more details, see Table S1). Pairwise comparisons by metronome rate show that while both groups had an initially comparable frequency mismatch up to about 3.4 Hz ($p \geq 0.726$, $d \leq 0.22$), French participants then exhibited a progressively more positive frequency mismatch producing a substantial effect from 4.6 Hz onward ($p \leq 0.019$, $d \geq 1.55$; see Table S2). To summarize, Indian participants synchronized with the auditory metronome until they couldn't move as fast as the rate of the metronome anymore, whereas French participants lost synchronization firstly by moving faster than the metronome, and then at higher rates—similar to Indian participants—moved slower than the metronome. As we argue in the following, such differences in the loss of synchronization at higher rates can fuel the interpretation of variations found in stable SMS at lower rates.

A further cross-cultural variation was demonstrated by the mean asynchrony shown in Figure 4. French participants exhibited negative mean asynchrony (classical NMA) centered near -50 ms at low metronome frequencies, ranging between 1.0 and 2.2 Hz, rates classically investigated in the SMS literature. Differently, Indian participants' mean asynchronies were consistently closer to 0 ms. This is illustrated by the histograms of the mean asynchrony values for every trial in Figure 4A. The mean asynchronies of Indian participants were shifted toward more positive values compared to French participants. This is confirmed by the substantial effect of group ($p < 0.001$, η_p^2 [95% CI] $= 0.22$ $[0.14, 1.00]$) reported in Table S5, and the significant differences ($p < 0.05$) for all plateaus between 1Hz and 2.8Hz (see Table S6). We illustrated this difference by the histograms of the asynchrony values for both groups in Figure 4C. At plateaus corresponding to 1.0 Hz and 2.2 Hz pacing, French participants displayed the classical NMA while Indians' mean asynchrony was closer to 0 ms. The difference displayed by the two histograms is confirmed by Kolmogorov Smirnov tests ($p < 0.05$; insert Figure 4C).

However, despite this shift in central value, both groups shared a comparable evolution of mean asynchrony as a function of the metronome's rate, as illustrated by the absence of interaction between group and metronome rate ($p = 0.70, \eta_p^2$ [95% CI] $= 0.03$ $[0.00, 1.00]$; Table S5) and in Figure 4B. Between 1.0 and 2.2 Hz, the mean asynchrony was kept close to a constant around a value, -50 ms for French participants, 0 ms for Indian participants, after which it increased almost linearly with metronome rate.

To summarize, commonalities and variations between French and Indian participants were observed across several dimensions. Firstly, stability of the relative phase and rate limits indicated comparable performance in synchronization. Secondly when synchronization was well established French participants' movements preceded the metronome, exhibiting the NMA, while Indian participants displayed a marked smaller asynchrony. Finally, when loosing synchronization, French participants tapped faster than the metronome while Indian participants in the same situation tended to tap slower.

Given that French and Indian participants only differed in their mean asynchrony and frequency mismatch, we explored whether these two variables were related. We computed the linear relationship between mean asynchrony and the maximum frequency mismatch in the trial. For French participants, we identified a negative relationship between these variables, indicating that mean asynchrony was even more negative if the participant tapped too fast at higher rates (slope of -47.13 ± 17.61 ms/Hz, $p = 0.009$). By contrast, the negative linear trend for Indian participants was not statistically reliable (-8.87 ± 9.07 ms/Hz, $p = 0.329$).

Discussion

Our findings indicate that while important synchronization features were common to French and Indian participants, interesting differences were also observed on several dimensions. In the following, we first discuss the commonalities observed between French and Indian coordination and then the variations revealed by our results.

Enculturation does not change synchronization stability

We obtained converging results showing that French and Indian participants exhibited comparable levels of stable synchronization. This claim is supported by several experimental observations. Firstly, at a coarse scale, the synchronization dynamics were comparable between the two groups with stable synchronization at low metronome rates then a sudden loss of stability around 4 Hz, as shown by the marked increase of the standard deviation of relative phase (SD ϕ; Figure 2B), a well-grounded observable for the coupling strength between perception and action [5,80,81]. Secondly, the frequency mismatch was close to 0 Hz in the same low-rate range, then increased and inter-individual variability grew from 4 Hz onward, indicating again a sudden loss of synchronization around the same rate for both French and Indian participants. Thirdly, the coupling strength between the metronome and the sensorimotor processes observed during stable synchronization did not vary between groups. This is supported by the absence of group difference in the SD ϕ of synchronized plateaus at any rate (Figure 3B). Fourth, successful matching of the rate did not vary between groups: No differences were found in the number of synchronized plateaus between French and Indian participants.

These observations are consistent with predictions from the coordination dynamics approach [3,62,80]. This approach considers that SMS can be modelled as a nonlinear oscillator forced by a periodic stimulus, thereby capturing how much the stimulus influences the oscillator (for a review, see [59]). This relation could represent a neuronal audio-motor coupling, as suggested for speech processing [47], and could also account for the magnitude of the sensory pacing, or the attention level devoted to the task. To a first approximation, the oscillator models the periodic movement characteristic of the SMS task and possesses an intrinsic frequency. If the frequency of the stimulus is close enough, then, because of the coupling, the effective frequency of the oscillator is attracted toward the frequency of the stimulus, giving rise to synchronization. The gap between the intrinsic frequency and the stimulus frequency is often called *detuning*. The range of frequency for which there is synchronization defines the width of the so-called *Arnold' tongue* (see Chapter 4 in ref. [3]) The limits of the Arnol'd tongue depend on the *coupling strength*. Note that this framework can account for both isochronous and polyrhythmic synchronization, oscillatory processes being locked-in when their frequencies are related by integer ratios (e.g., 1:2, 2:3, [54]).

We argue that the theory of Arnol'd tongues can account for a significant part of the results from our study. Both French and Indian participants demonstrated stable synchronization at low rates with a frequency mismatch close to 0 Hz. At those rates, the detuning is small enough so that the coupling strength can compensate for it. After 4 Hz, the detuning overcomes the coupling strength: the movement frequency does not match the stimulus frequency anymore and synchronization is lost. Our results suggest that French and Indian participants have equivalent coupling strength since they exhibit stable synchronization in the same range of metronome rates. The observed equivalent synchronization capabilities may originate from an equivalent enculturation to isochronous patterns, known to pervade a wide range of cultures [29]. Within the limits of our methodology used to sample the two populations, a unique temporal coupling may be instantiated by brain networks subserving both SMS and music cognition [35].

Previous studies have reported contradictory results, with some identifying cross-cultural differences in synchronization stability with isochronous rhythms and others finding none. Absence of difference was reported when comparing Indian and US students [21], Rwandans and Canadian adults [23], or musician and non-musician participants from the UK, Uruguay and Mali [41]. However, other studies found the opposite, showing cross-cultural differences: German musicians had lower variability than Bulgarian and Malian musicians [19]; Ghanaian students had lower dispersion than American students [40]; Differences in synchronization stability were found comparing musical training, jazz musicians, folk musicians and dance-music producers, [42]. Finally, a study including participants from 15 countries reported cross-cultural variations of tapping variability, but we notice that the variability of Indian non-musician participants was comparable to that of US non-musician participants, and the variability of Indian musician participants was comparable to that of US, UK and Swedish musician participants (being considered as representative of Western populations; see [22]). To date, these studies show an effect of enculturation on synchronization stability with important variations between cultural basins. However, when including samples for Indian and Western populations [21,22], variability does not differ. In line with the foregoing findings, the present study, albeit using different methodology and data processing, confirms that synchronization variability is comparable between Indian and Western samples.

Cross-Cultural Variation of Mean Asynchrony and frequency mismatch

To our surprise, whereas most French participants exhibited the classical negative mean asynchrony (NMA), mean asynchrony for Indian participants was closer to 0 ms or even slightly positive. We also found a diversity among participants within each group, and some overlap between the two groups. Indeed, some French and Indian participants displayed comparable mean asynchrony (Figure 4A). On a broader scale, however, both groups displayed a similar curve of evolution of mean asynchrony as a function of rate (Figure 4B). Mean asynchrony was essentially flat at lower rates evolving, after 2.2 Hz, with a positive slope for both. This brought the French participants' asynchrony close to zero, while the curve already crossed zero for Indian participants, their taps lagging the metronome. Such common evolution with rate, simply shifted between the two groups, is consistent with previous results [45,46,53,68,82–87].

There is an apparent tension between the observation of previous cross-cultural studies and the robustness of our results, with a large number of trials for each participant—presented in Figure 4A—on a wide range of metronome rates. In fact, Jacoby and colleagues [22] recruited participants from 15 different countries and reported important variation in mean asynchrony across cultures. In contrast to our results, recruiting Indian non-musician participants, they reported a mean asynchrony around -45 ms with a metronome at 1.25 Hz (ISI = 800 ms) and 1.67 Hz (ISI = 600 ms). One cannot rule out the possibility that this discrepancy with our results may originate from distinct data analysis procedures performed between the two studies. However, it seems more likely that the differences originate from the sampling of participants. Firstly, in the Jacoby et al. study, 6 out of 15 participants were students, whereas in the present study all our Indian participants were students. Secondly, the basins of recruitment of the two samples could have influenced synchronization ability. Previous studies [31,61] suggest significant differences in musical practices among the different regions of India. In Jacoby et al. [22] the non-musician participants were recruited at I.I.I.T in Mumbay, whereas we did not attempt to control the geographic origin of our participants. A more systematic study, covering larger parts of India, and informed by the analysis of the specific rhythmic enculturation, could clarify this discrepancy.

Given that stability and range of adaptation to pacing rate are similar between French and Indian participants, it seems unlikely that the differences in NMA originate from different levels of expertise. This is a surprising and serendipitous result since NMA is assumed to be ubiquitous among human beings (for reviews see [32,33,65])—although there is also some evidence of positive mean asynchrony [82,88,89]. Classically, NMA was reported in studies where the task consisted of synchronizing only at a few different rates, typically in the range of 1 Hz to 2 Hz.

It has often been proposed that NMA is caused by neural delays ([90,91], see [92] for a model that includes delays) or processing time [65]. Assuming auditory input propagates faster than tactile information, a reliable solution may be to advance the phase of movement so as to re-synchronize centrally the two sub-processes [65]. This explanation seems very unlikely in the light of our results since this would imply that French and Indian participants possess different neural propagation delays and/or ability to integrate afferent sensory inputs. Nevertheless, future brain imaging and electrophysiology measurements over a broad range of pacing rates could investigate this possibility.

Another hypothesis focuses on the impact of the proficiency in a certain musical repertoire on the perceived temporal location of a stimulus, otherwise known as the *P-center*. Across a series of studies [42,93–95], musicians from different musical genres performed finger tapping tasks to estimate P-center location and its variability for sounds varying in duration, attack, and genre specificity. Such studies show that enculturation affects both P-center location and variability, particularly for genre-specific stimuli. In contrast, stimuli that are non-genre specific— brief with rapid rise time like our stimuli —exhibited only marginal cultural differences. Therefore, it seems unlikely that the perception of the P-center accounts for the marked differences observed in our results between French and Indian participants.

Alternatively, our results suggest that NMA may be a consequence of an overestimation of the metronome rate [96]. We found that French participants had a higher frequency mismatch than Indian participants (Figure 2A). It is noteworthy that such variations in frequency mismatch were obtained only when synchronization was lost, i.e., at higher metronome rates; whereas negative mean asynchrony was estimated on synchronized plateaus at lower rates. Actually, several studies reported a tendency to overestimate the frequency between two stimuli [86,97] and a reduced magnitude of NMA when subdividing the interval between two stimuli with contact-free movements or additional beats between the stimuli [85,96].

Our interpretation assumes that synchronization for French participants included a tendency for overestimation, independently of rate. At lower rates, this could have been compensated by auditory-motor coupling, giving rise to stable synchronization. It is noteworthy that assuming an estimation of the rate of the metronome per se is taken with a grain of salt, and an alternative is to ascribe dynamics to the eigenfrequency of the oscillator, following the models of adaptative frequency oscillator (see [98–102]). Moreover, in the present work, the maximum frequency mismatch was linearly related to mean asynchrony only for French participants. A larger overestimation of the metronome rate was reliably associated with a more negative mean asynchrony. For Indian participants, no such reliable relationship was observed. This suggests that synchronization performance is not supported by fully equivalent processes in both groups. We believe that this difference may be explained by enculturation to musical rhythm; in Indian classical music for example, Hindustani and Carnatic, the rhythmic musical structure evolves through the performance with an important role of improvisation and mixing various rhythms [31,61]. Although India encompasses many diverse rhythmic cultures, and no singular Indian rhythmic musical structure has been clearly documented so far, exposure to changing rhythms could enhance performers' and listeners' rhythmic adaptation mechanisms, notably those related to frequency estimation [98–101]. To avoid overgeneralization, this line of interpretation indeed warrants additional research. Additionally, to further examine how adaptation at multiple scales, involving phase and frequency changes, can be shaped by enculturation, future studies may include the study of phase response curves and the response to phase and period changes of the stimuli [103].

We hypothesize that the mean asynchrony findings observed here can be accounted for by adding a frequency adaptation mechanism to the oscillator model. This theoretical proposal has already been incorporated in recent versions [98–101]. Instead of having a fixed intrinsic oscillation frequency, participants would be able to adapt this frequency to match the metronome. In doing so, French participants would slightly overestimate the metronome frequency, causing a phase advance [64] corresponding to NMA. For Indian participants, the intrinsic oscillation frequency would adapt without such an overestimation, resulting in a smaller NMA. However, our results showed that the NMA varies with rate (Figure 4C). This suggests that frequency adaptation between 1.0 Hz and 2.2 Hz causes mean asynchrony to be essentially flat. For higher rates adaptation could be somewhat limited, reaching a saturation threshold, which may explain the slope found in the curves; mean asynchrony crosses the zero line and becomes positive. Movement lags the sound. Therefore, the variation observed between French and Indian participants may be quantitative rather than qualitative, in the sense that they share a common mechanism. However, some parameters of this proposed mechanism may differ due to enculturation.

To summarize, French participants demonstrated a tendency to overestimate the metronome frequency and this was linked to the mean asynchrony, while Indian participants demonstrated neither the overestimation nor the relationship with mean asynchrony. The frequency overestimation was previously documented in western participants [85,86,96,97], though its cross-cultural invariance has not been addressed. The variation observed in our article, based on geographical criterion, could show that exposure to musical performances with changing structure might improve the frequency adaptation mechanism [31,61]. However, other causes of enculturation effects on elementary rhythmic capabilities couldn't be neglected that may motivate additional investigation. In that respect, a rather broad spectrum of factors could be addressed, including the case for speech, or culturally prominent sport practices involving timing and rhythmic capabilities.

Limitations and perspectives for future work

One limitation of the present study concerns sample size and demographic origins of the participants. Future studies should employ a sampling methodology which targets specific cultural specificities as recommended by Polak and colleagues [20]. We tested only 15 Indian and 13 French participants, limiting the interpretation of the statistical results. Furthermore, our participants were students, a population known to underrepresent cultural variations from WEIRD populations (for western, educated, industrialized, rich and democratic; see [1]) because of their exposure to Western culture [22]. However, it is noteworthy that the evidence gathered in the present study is quite robust considering the number of repetitions of the tasks, the number of rates tested, and the number of asynchronies analyzed (i.e., a total of more than 17,000). Here we extensively tested the synchronization capabilities of a modest sample, which might explain several inconsistencies relative to previous studies, and also place constraints regarding generalization. To address this in part, we performed a retrospective power analysis to determine the sample size necessary to replicate our main result, namely, the group difference in mean asynchrony. We calculated the necessary sample size for a power of 0.80 with the smallest effect size from the 95% CI of the group effect from the F-test ($\eta_p^2 = 0.14$; see Table S5) for 2 groups and 10 plateaus (from 1.0 Hz to 3.7 Hz). We obtained an estimated total sample size of 6, providing good support for the sample size employed in the present study. In future work, authors should envision recruiting participants beyond university students, and consider also where the participants grew up, as musical culture and languages, particularly in India, vary widely among regions [31,104].

The concept of culture encompasses manifold meanings beyond a mere geographic point of view. It is widely debated, and covers an extended range of complex social constructs [23,105,106].We are mindful of limitations also in comparing French participants as a proxy for Western societies, and Indians as a proxy for non-Western society for which rhythmic pattern variation is documented. Western culture is heterogeneous (*e.g.*, French-English speech rhythms, see [107,108]), as is Indian culture [31,104].

Conclusion

Our results extend previous cross-cultural studies by providing compelling evidence that enculturation influences are not limited to perception, (re)production, or synchronization with socially significant, complex and ecological rhythms, but are also visible in the most basic form of sensorimotor synchronization. This transfer from rather rich and complex domains of practice to an elementary task performance gives credence to the hypothesis of a common temporal mechanism responsible for relative timing. This common building block may be shaped by exposure to the rhythmic patterns of the individuals' environment and would operate across a wide range of rhythmic abilities. Seeking invariance and changes, comparative studies can offer a more complete understanding of elementary mechanisms of synchronization. In the long run, such a perspective embraces both shared lawful and idiosyncratic behaviors within and between different cultures. The step taken here is to tighten the linkage between behavioral sciences and the humanities, aiming at basic research and clinical purposes.

Acknowledgements: The Modpuls French ANR, and the EU FET PROACTIVE 4-year project EnTimeMent participated in the funding. JASK is supported by the FAU Foundation (Eminent Scholar in Science) and the Bath Global Chair Program. The authors wish to thank Anthony Laurens for his help in collecting the data. A preliminary version of the analysis was previously communicated in a preprint [109].

Author contribution: M.L.G and J.L. conceptualized the study, conceptualized the data processing, contributed to formal analysis and writing the manuscript. J.L. was responsible for data collection and secured funding. A.T. and J.A.S.K. contributed to formal analysis and writing the manuscript.

Conflicts of Interest: The authors declare that they have no competing interests

Data Availability Statement: The data and codes that support the findings of this study are openly available at https://github.com/martinleguennec/Cross-Cultural-Synchronization

References

1. Henrich, J., Heine, S. J., & Norenzayan, A. (2010). Most people are not WEIRD. *Nature*, *466*(7302), 29–29. https://doi.org/10.1038/466029a
2. Jakubowski, K., Ahmad, N., Armitage, J., Barrett, L., Edwards, A., Galbo, E., Gómez-Cañón, J. S., Graves, T. A., Jadzgevičiūtė, A., Kirts, C., Lahdelma, I., Lennie, T. M., Ramatally, A., Schlichting, J. L., Steliou, C., Vishwanath, K., & Eerola, T. (2025). Participant and Musical Diversity in Music Psychology Research. *Music & Science*, *8*, 20592043251317180. https://doi.org/10.1177/20592043251317180
3. Kelso, J. A. S. (1995). *Dynamic Patterns: The Self-organization of Brain and Behavior*. MIT Press.
4. Lee, D. N. (1976). A Theory of Visual Control of Braking Based on Information about Time-to-Collision. *Perception*, *5*(4), 437–459. https://doi.org/10.1068/p050437
5. Kelso, J. A. S., DelColle, J. D., & Schöner, G. (1990). Action-Perception as a Pattern-Formation Process. In M. Jeannerod (Ed.), *Attention and Performance XVIII. Motor Representation and Control: XVIII* (pp. 139–169).
6. Clayton, M., Sager, R., & Will, U. (2005). In time with the music: The concept of entrainment and its significance for ethnomusicology. *European Meetings in Ethnomusicology*, *11,* 3–142.
7. Fiveash, A., Bedoin, N., Gordon, R. L., & Tillmann, B. (2021). Processing rhythm in speech and music: Shared mechanisms and implications for developmental speech and language disorders. *Neuropsychology*, *35*(8), 771–791. https://doi.org/10.1037/neu0000766

8. Gratier, M. (1999). Expressions of belonging: The effect of acculturation on the rhythm and harmony of mother-infant vocal interaction. *Musicae Scientiae*, *3*(1_suppl), 93–122. https://doi.org/10.1177/10298649000030S107

9. Gratier, M. (2003). Expressive timing and interactional synchrony between mothers and infants: Cultural similarities, cultural differences, and the immigration experience. *Cognitive Development, The Sociocultural Construction of Implicit Knowledge*, *18*(4), 533–554. https://doi.org/10.1016/j.cogdev.2003.09.009

10. Harding, E. E., Kim, J. C., Demos, A. P., Roman, I. R., Tichko, P., Palmer, C., & Large, E. W. (2025). Musical neurodynamics. *Nature Reviews Neuroscience*, 1–15. https://doi.org/10.1038/s41583-025-00915-4

11. McNeill, W. H. (1995). *Keeping Together in Time: Dance and Drill in Human History*. Harvard University Press.

12. Gibson, E. J. (1963). Perceptual Learning. *Annual Review of Psychology*, *14*(1), 29–56. https://doi.org/10.1146/annurev.ps.14.020163.000333

13. Hannon, E. E., Vanden Bosch der Nederlanden, C. M., & Tichko, P. (2012). Effects of perceptual experience on children’s and adults’ perception of unfamiliar rhythms. *Annals of the New York Academy of Sciences*, *1252*(1), 92–99. https://doi.org/10.1111/j.1749-6632.2012.06466.x

14. Nave, K., Carrillo, C., Jacoby, N., Trainor, L., & Hannon, E. (2024). The development of rhythmic categories as revealed through an iterative production task. *Cognition*, *242*, 105634. https://doi.org/10.1016/j.cognition.2023.105634

15. Soley, G., & Hannon, E. E. (2010). Infants prefer the musical meter of their own culture: A cross-cultural comparison. *Developmental Psychology*, *46*(1), 286–292. https://doi.org/10.1037/a0017555

16. Hannon, E. E. (2010). Musical Enculturation: How Young Listeners Construct Musical Knowledge through Perceptual Experience. In S. Johnson (Ed.), *Neoconstructivism: The New Science of Cognitive Development* (pp. 142–156). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195331059.003.0007

17. Hannon, E. E., & Trehub, S. E. (2005). Metrical Categories in Infancy and Adulthood. *Psychological Science*, *16*(1), 48–55. https://doi.org/10.1111/j.0956-7976.2005.00779.x

18. Hannon, E. E., & Trehub, S. E. (2005). Tuning in to musical rhythms: Infants learn more readily than adults. *Proceedings of the National Academy of Sciences*, *102*(35), 12639–12643. https://doi.org/10.1073/pnas.0504254102

19. Polak, R., Jacoby, N., Fischinger, T., Goldberg, D., Holzapfel, A., & London, J. (2018). Rhythmic Prototypes Across Cultures: A Comparative Study of Tapping Synchronization. *Music Perception*, *36*(1), 1–23. https://doi.org/10.1525/mp.2018.36.1.1

20. Polak, R., Danielsen, A., Jacoby, N., Pearson, L., Horlor, S., Aubinet, S., London, J., & Nozaradan, S. (2026). *Culture in psychology and neuroscience: Concepts, relevance, and empirical evidence in rhythm perception* (Sqbzn_v1). PsyArXiv. https://osf.io/preprints/psyarxiv/sqbzn_v1/

21. Ullal-Gupta, S., Hannon, E. E., & Snyder, J. S. (2014). Tapping to a Slow Tempo in the Presence of Simple and Complex Meters Reveals Experience-Specific Biases for Processing Music. *PLoS ONE*, *9*(7), e102962. https://doi.org/10.1371/journal.pone.0102962

22. Jacoby, N., Polak, R., Grahn, J. A., Cameron, D. J., Lee, K. M., Godoy, R., Undurraga, E. A., Huanca, T., Thalwitzer, T., Doumbia, N., Goldberg, D., Margulis, E. H., Wong, P. C. M., Jure, L., Rocamora, M., Fujii, S., Savage, P. E., Ajimi, J., Konno, R., … McDermott, J. H. (2024). Commonality and variation in mental representations of music revealed by a cross-cultural comparison of rhythm priors in 15 countries. *Nature Human Behaviour*, *8*(5), 846–877. https://doi.org/10.1038/s41562-023-01800-9

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

24. Yates, C. M., Justus, T., Atalay, N. B., Mert, N., & Trehub, S. E. (2017). Effects of musical training and culture on meter perception. *Psychology of Music*, *45*(2), 231–245. https://doi.org/10.1177/0305735616657407

25. Rad, M. S., Martingano, A. J., & Ginges, J. (2018). Toward a psychology of Homo sapiens: Making psychological science more representative of the human population. *Proceedings of the National Academy of Sciences*, *115*(45), 11401–11405. https://doi.org/10.1073/pnas.1721165115

26. Jacoby, N., & McDermott, J. H. (2017). Integer Ratio Priors on Musical Rhythm Revealed Cross-culturally by Iterated Reproduction. *Current Biology*, *27*(3), 359–370. https://doi.org/10.1016/j.cub.2016.12.031

27. Barbero, F. M., Lenc, T., Jacoby, N., Polak, R., Varlet, M., & Nozaradan, S. (2025). Revealing rhythm categorization in human brain activity. *Science Advances*, *11*(31), eadu9838. https://doi.org/10.1126/sciadv.adu9838

28. Roeske, T. C., Tchernichovski, O., Poeppel, D., & Jacoby, N. (2020). Categorical Rhythms Are Shared between Songbirds and Humans. *Current Biology*, *30*(18), 3544-+. https://doi.org/10.1016/j.cub.2020.06.072

29. Savage, P. E., Brown, S., Sakai, E., & Currie, T. E. (2015). Statistical universals reveal the structures and functions of human music. *Proceedings of the National Academy of Sciences*, *112*(29), 8987–8992. https://doi.org/10.1073/pnas.1414495112

30. London, J. (2012). *Hearing in Time: Psychological Aspects of Musical Meter*. Oxford University Press.

31. Clayton, M. (2000). *Time in Indian Music: Rhythm, Metre, and Form in North Indian Rag Performance*. Oxford University Press.

32. Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review*, *12*(6), Article 6. https://doi.org/10.3758/BF03206433

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

34. Grahn, J. A., & Brett, M. (2007). Rhythm and Beat Perception in Motor Areas of the Brain. *Journal of Cognitive Neuroscience*, *19*(5), 893–906. https://doi.org/10.1162/jocn.2007.19.5.893

35. Jantzen, K. J., Steinberg, F. L., & Kelso, J. A. S. (2009). Coordination Dynamics of Large-scale Neural Circuitry Underlying Rhythmic Sensorimotor Behavior. *Journal of Cognitive Neuroscience*, *21*(12), 2420–2433. https://doi.org/10.1162/jocn.2008.21182

36. Nozaradan, S., Peretz, I., & Keller, P. E. (2016). Individual Differences in Rhythmic Cortical Entrainment Correlate with Predictive Behavior in Sensorimotor Synchronization. *Scientific Reports*, *6*(1), Article 1. https://doi.org/10.1038/srep20612

37. Schwartze, M., Keller, P. E., & Kotz, S. A. (2016). Spontaneous, synchronized, and corrective timing behavior in cerebellar lesion patients. *Behavioural Brain Research*, *312*, 285–293. https://doi.org/10.1016/j.bbr.2016.06.040

38. Buonomano, D. V., & Karmarkar, U. R. (2002). Book Review: How Do We Tell Time? *The Neuroscientist*, *8*(1), 42–51. https://doi.org/10.1177/107385840200800109

39. Chen, Y., Ding, M., & Kelso, S. J. (2003). Task-related power and coherence changes in neuromagnetic activity during visuomotor coordination. *Experimental Brain Research*, *148*(1), 105–116. https://doi.org/10.1007/s00221-002-1244-0

40. Witek, M. A. G., Liu, J., Kuubertzie, J., Yankyera, A. P., Adzei, S., & Vuust, P. (2020). A Critical Cross-cultural Study of Sensorimotor and Groove Responses to Syncopation Among Ghanaian and American University Students and Staff. *Music Perception*, *37*(4), 278–297. https://doi.org/10.1525/mp.2020.37.4.278

41. Jakubowski, K., Polak, R., Rocamora, M., Jure, L., & Jacoby, N. (2022). Aesthetics of musical timing: Culture and expertise affect preferences for isochrony but not synchrony. *Cognition*, *227*, 105205. https://doi.org/10.1016/j.cognition.2022.105205

42. Danielsen, A., Nymoen, K., Langerød, M. T., Jacobsen, E., Johansson, M., & London, J. (2022). Sounds familiar(?): Expertise with specific musical genres modulates timing perception and micro-level synchronization to auditory stimuli. *Attention, Perception, & Psychophysics*, *84*(2), 599–615. https://doi.org/10.3758/s13414-021-02393-z

43. Jantzen, K. J., Fuchs, A., Mayville, J. M., Deecke, L., & Kelso, J. A. S. (2001). Neuromagnetic activity in alpha and beta bands reflect learning-induced increases in coordinative stability. *Clinical Neurophysiology*, *112*(9), 1685–1697. https://doi.org/10.1016/S1388-2457(01)00626-5

44. Krause, V., Pollok, B., & Schnitzler, A. (2010). Perception in action: The impact of sensory information on sensorimotor synchronization in musicians and non-musicians. *Acta Psychologica*, *133*(1), Article 1. https://doi.org/10.1016/j.actpsy.2009.08.003

45. Ono, K., Hashimoto, J., & Sasaoka, T. (2022). Intertap interval dependence of the subdivision effect in auditory-synchronised tapping. *European Journal of Neuroscience*, *55*(11–12), 3391–3401. https://doi.org/10.1111/ejn.15529

46. Repp, B. H., & Doggett, R. (2007). Tapping to a Very Slow Beat: A Comparison of Musicians and Nonmusicians. *Music Perception*, *24*(4), 367–376. https://doi.org/10.1525/mp.2007.24.4.367

47. Assaneo, M. F., & Poeppel, D. (2018). The coupling between auditory and motor cortices is rate-restricted: Evidence for an intrinsic speech-motor rhythm. *Science Advances*, *4*(2), eaao3842. https://doi.org/10.1126/sciadv.aao3842

48. Bose, A., Byrne, Á., & Rinzel, J. (2019). A neuromechanistic model for rhythmic beat generation. *PLOS Computational Biology*, *15*(5), Article 5. https://doi.org/10.1371/journal.pcbi.1006450

49. Cannon, J., & Kaplan, T. (2024). Inferred representations behave like oscillators in dynamic Bayesian models of beat perception. *Journal of Mathematical Psychology*, *122*, 102869. https://doi.org/10.1016/j.jmp.2024.102869

50. Doelling, K. B., Assaneo, M. F., Bevilacqua, D., Pesaran, B., & Poeppel, D. (2019). An oscillator model better predicts cortical entrainment to music. *Proceedings of the National Academy of Sciences*, *116*(20), Article 20. https://doi.org/10.1073/pnas.1816414116

51. Large, E. W. (2000). On synchronizing movements to music. *Human Movement Science, Debates in Dynamics*, *19*(4), 527–566. https://doi.org/10.1016/S0167-9457(00)00026-9

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

53. Cos, I., Girard, B., & Guigon, E. (2015). Balancing out dwelling and moving: Optimal sensorimotor synchronization. *Journal of Neurophysiology*, *114*(1), 146–158. https://doi.org/10.1152/jn.00175.2015

54. de Guzman, G. C., & Kelso, J. A. S. (1991). Multifrequency behavioral patterns and the phase attractive circle map. *Biological Cybernetics*, *64*(6), 485–495. https://doi.org/10.1007/BF00202613

55. Elliott, M. T., Wing, A. M., & Welchman, A. E. (2014). Moving in time: Bayesian causal inference explains movement coordination to auditory beats. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1786), 20140751. https://doi.org/10.1098/rspb.2014.0751

56. Schöner, G. (2002). Timing, Clocks, and Dynamical Systems. *Brain and Cognition*, *48*(1), 31–51. https://doi.org/10.1006/brcg.2001.1302

57. Van Der Steen, M., & Keller, P. (2013). The ADaptation and Anticipation Model (ADAM) of sensorimotor synchronization. *Frontiers in Human Neuroscience*, *7*. https://www.frontiersin.org/articles/10.3389/fnhum.2013.00253

58. Vorberg, D., & Schulze, H.-H. (2002). Linear Phase-Correction in Synchronization: Predictions, Parameter Estimation, and Simulations. *Journal of Mathematical Psychology*, *46*(1), 56–87. https://doi.org/10.1006/jmps.2001.1375

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

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

61. Clayton, M., Jakubowski, K., & Eerola, T. (2019). Interpersonal entrainment in Indian instrumental music performance: Synchronization and movement coordination relate to tempo, dynamics, metrical and cadential structure. *Musicae Scientiae*, *23*(3), 304–331. https://doi.org/10.1177/1029864919844809

62. Schöner, G., Haken, H., & Kelso, J. A. S. (1986). A stochastic theory of phase transitions in human hand movement. *Biological Cybernetics*, *53*(4), 247–257. https://doi.org/10.1007/BF00336995

63. Lagarde, J., & Kelso, J. A. S. (2006). Binding of movement, sound and touch: Multimodal coordination dynamics. *Experimental Brain Research*, *173*(4), Article 4. https://doi.org/10.1007/s00221-006-0410-1

64. Pikovsky, A., Rosenblum, M., & Kurths, J. (2001). *Synchronization: A Universal Concept in Nonlinear Sciences* (1st edition). Cambridge University Press.

65. Aschersleben, G. (2002). Temporal Control of Movements in Sensorimotor Synchronization. *Brain and Cognition*, *48*, 66–79. https://doi.org/10.1006/brcg.2001.1304

66. Scheurich, R., Zamm, A., & Palmer, C. (2018). Tapping Into Rate Flexibility: Musical Training Facilitates Synchronization Around Spontaneous Production Rates. *Frontiers in Psychology*, *9*, 458. https://doi.org/10.3389/fpsyg.2018.00458

67. Slis, A., Savariaux, C., Perrier, P., & Garnier, M. (2023). Rhythmic tapping difficulties in adults who stutter: A deficit in beat perception, motor execution, or sensorimotor integration? *PLoS One*, *18*(2), Article 2. https://doi.org/10.1371/journal.pone.0276691

68. Tokushige, S., Matsuda, S., Tada, M., Yabe, I., Takeda, A., Tanaka, H., Hatakenaka, M., Enomoto, H., Kobayashi, S., Shimizu, K., Shimizu, T., Kotsuki, N., Inomata-Terada, S., Furubayashi, T., Ichikawa, Y., Hanajima, R., Tsuji, S., Ugawa, Y., & Terao, Y. (2024). Roles of the cerebellum and basal ganglia in temporal integration: Insights from a synchronized tapping task. *Clinical Neurophysiology*, *158*, 1–15. https://doi.org/10.1016/j.clinph.2023.11.018

69. Roy, C., Dalla Bella, S., & Lagarde, J. (2017). To bridge or not to bridge the multisensory time gap: Bimanual coordination to sound and touch with temporal lags. *Experimental Brain Research*, *235*(1), 135–151. https://doi.org/10.1007/s00221-016-4776-4

70. Tognoli, E., Lagarde, J., DeGuzman, G. C., & Kelso, J. A. S. (2007). The phi complex as a neuromarker of human social coordination. *Proceedings of the National Academy of Sciences*, *104*(19), 8190–8195. https://doi.org/10.1073/pnas.0611453104

71. Dijkstra, T. M., Giese, M. A., & Schöner, G. (1997). *RelPhase.box* [Matlab]. https://www.cs.ru.nl/~tjeerdd/teaching/RelPhaseManual.pdf

72. Kelso, J. A. S., de Guzman, G. C., Reveley, C., & Tognoli, E. (2009). Virtual Partner Interaction (VPI): Exploring Novel Behaviors via Coordination Dynamics. *PLoS One*, *4*(6), e5749. https://doi.org/10.1371/journal.pone.0005749

73. Zelic, G., Mottet, D., & Lagarde, J. (2012). Behavioral Impact of Unisensory and Multisensory Audio-Tactile Events: Pros and Cons for Interlimb Coordination in Juggling. *PLoS One*, *7*(2), e32308. https://doi.org/10.1371/journal.pone.0032308

74. R Core Team. (2023). *R: A Language and Environment for Statistical Computing* (Version 4.3.2) [R; Aarch64]. R Foundation for Statistical Computing. https://www.R-project.org/

75. Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, *82*, 1–26. https://doi.org/10.18637/jss.v082.i13

76. Lenth, R. V. (2023). *emmeans: Estimated Marginal Means, aka Least-Squares Means* (Version 1.9.0) [Computer software]. https://cran.r-project.org/package=emmeans

77. Frossard, J., & Renaud, O. (2021). Permutation Tests for Regression, ANOVA, and Comparison of Signals: The permuco Package. *Journal of Statistical Software*, *99*, 1–32. https://doi.org/10.18637/jss.v099.i15

78. Satterthwaite, F. E. (1946). An Approximate Distribution of Estimates of Variance Components. *Biometrics Bulletin*, *2*(6), 110–114. https://doi.org/10.2307/3002019

79. Mardia, K. V. (1972). *Statistics of Directional Data*. Academic Press, London.

80. Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, *51*(5), Article 5. https://doi.org/10.1007/BF00336922

81. Schöner, G., & Kelso, J. A. S. (1988). Dynamic Pattern Generation in Behavioral and Neural Systems. *Science*, *239*(4847), 1513–1520. https://doi.org/10.1126/science.3281253

82. Fujii, S., Hirashima, M., Kudo, K., Ohtsuki, T., Nakamura, Y., & Oda, S. (2011). Synchronization Error of Drum Kit Playing with a Metronome at Different Tempi by Professional Drummers. *Music Perception*, *28*(5), 491–503. https://doi.org/10.1525/mp.2011.28.5.491

83. Mates, J., Müller, U., Radil, T., & Pöppel, E. (1994). Temporal Integration in Sensorimotor Synchronization. *Journal of Cognitive Neuroscience*, *6*(4), 332–340. https://doi.org/10.1162/jocn.1994.6.4.332

84. Miyake, Y., Onishi, Y., & Pöppel, E. (2004). Two types of anticipation in synchronization tapping. *Acta Neurobiologiae Experimentalis*, *64*(3), Article 3. https://doi.org/10.55782/ane-2004-1524

85. Repp, B. H. (2003). Rate limits in sensorimotor synchronization with auditory and visual sequences: The synchronization threshold and the benefits and costs of interval subdivision. *Journal of Motor Behavior*, *35*(4), Article 4. https://doi.org/10.1080/00222890309603156

86. Repp, B. H. (2008). Metrical Subdivision Results in Subjective Slowing of the Beat. *Music Perception*, *26*(1), 19–39. https://doi.org/10.1525/mp.2008.26.1.19

87. Zendel, B. R., Ross, B., & Fujioka, T. (2011). The Effects of Stimulus Rate and Tapping Rate on Tapping Performance. *Music Perception*, *29*(1), 65–78. https://doi.org/10.1525/mp.2011.29.1.65

88. Madison, G. (2014). Sensori-motor synchronisation variability decreases as the number of metrical levels in the stimulus signal increases. *Acta Psychologica, Temporal Processing Within and Across Senses - Part-1*, *147*, 10–16. https://doi.org/10.1016/j.actpsy.2013.10.002

89. Woodrow, H. (1932). The effect of rate of sequence upon the accuracy of synchronization. *Journal of Experimental Psychology*, *15*(4), 357–379. https://doi.org/10.1037/h0071256

90. Fraisse, P. (1980). Les synchronisations sensori-motrices aux rythmes. In *Anticipation et comportement* (pp. 233–257).

91. Paillard, J. (1946). Quelques données psychophysiologiques relatives au déclenchement de la commande motrice. *L'Année psychologique*, *47*(1), Article 1. https://doi.org/10.3406/psy.1946.8279

92. Roman, I. R., Washburn, A., Large, E. W., Chafe, C., & Fujioka, T. (2019). Delayed feedback embedded in perception-action coordination cycles results in anticipation behavior during synchronized rhythmic action: A dynamical systems approach. *PLOS Computational Biology*, *15*(10), Article 10. https://doi.org/10.1371/journal.pcbi.1007371

93. Danielsen, A., Brøvig, R., Bøhler, K. K., Câmara, G. S., Haugen, M. R., Jacobsen, E., Johansson, M. S., Lartillot, O., Nymoen, K., Oddekalv, K. A., Sandvik, B., Sioros, G., & London, J. (2024). There's More to Timing than Time: Investigating Musical Microrhythm Across Disciplines and Cultures. *Music Perception*, *41*(3), 176–198. https://doi.org/10.1525/mp.2024.41.3.176

94. Danielsen, A., Nymoen, K., Anderson, E., Câmara, G. S., Langerød, M. T., Thompson, M. R., & London, J. (2019). Where is the beat in that note? Effects of attack, duration, and frequency on the perceived timing of musical and quasi-musical sounds. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(3), 402–418. https://doi.org/10.1037/xhp0000611

95. London, J., Paulsrud, T. S., & Danielsen, A. (2025). The influence of vocal expertise on the perception of microrhythm in song and speech. *Attention, Perception, & Psychophysics*, *87*(5), 1750–1770. https://doi.org/10.3758/s13414-025-03057-y

96. Wohlschläger, A., & Koch, R. (2000). Synchronization error: An error in time perception. In P. Dessain & L. Windsor (Eds.), *Rhythm perception and production* (pp. 115–127). Swets. https://pure.mpg.de/pubman/faces/ViewItemOverviewPage.jsp?itemId=item_726717

97. Repp, B. H., & Bruttomesso, M. (2010). A filled duration illusion in music: Effects of metrical subdivision on the perception and production of beat tempo. *Advances in Cognitive Psychology*, *5*, 114–134. https://doi.org/10.2478/v10053-008-0071-7

98. Nordham, C. A., Tognoli, E., Fuchs, A., & Kelso, J. A. S. (2018). How Interpersonal Coordination Affects Individual Behavior (and Vice Versa): Experimental Analysis and Adaptive HKB Model of Social Memory. *Ecological Psychology*, *30*(3), Article 3. https://doi.org/10.1080/10407413.2018.1438196

99. Righetti, L., Buchli, J., & Ijspeert, A. J. (2006). Dynamic Hebbian learning in adaptive frequency oscillators. *Physica D: Nonlinear Phenomena*, *216*(2), 269–281. https://doi.org/10.1016/j.physd.2006.02.009

100. Roman, I. R., Roman, A. S., Kim, J. C., & Large, E. W. (2023). Hebbian learning with elasticity explains how the spontaneous motor tempo affects music performance

synchronization. *PLOS Computational Biology*, *19*(6), e1011154. https://doi.org/10.1371/journal.pcbi.1011154

101. Ermentrout, B. (1991). An adaptive model for synchrony in the firefly Pteroptyx malaccae. *Journal of Mathematical Biology*, *29*, 571–585. https://doi.org/10.1007/BF00164052

102. Dumas, G., de Guzman, G. C., Tognoli, E., & Kelso, J. A. S. (2014). The human dynamic clamp as a paradigm for social interaction. *Proceedings of the National Academy of Sciences*, *111*(35), E3726–E3734. https://doi.org/10.1073/pnas.1407486111

103. Repp, B. H. (2011). Tapping in Synchrony With a Perturbed Metronome: The Phase Correction Response to Small and Large Phase Shifts as a Function of Tempo. *Journal of Motor Behavior*, *43*(3), 213–227. https://doi.org/10.1080/00222895.2011.561377

104. Castellano, M. A., Bharucha, J. J., & Krumhansl, C. L. (1984). Tonal hierarchies in the music of North India. *Journal of Experimental Psychology: General*, *113*(3), 394–412. https://doi.org/10.1037/0096-3445.113.3.394

105. Astuti, R., & Bloch, M. (2010). Why a theory of human nature cannot be based on the distinction between universality and variability: Lessons from anthropology. *Behavioral and Brain Sciences*, *33*(2–3), Article 2–3. https://doi.org/10.1017/S0140525X10000026

106. Baumard, N., & Sperber, D. (2010). Weird people, yes, but also weird experiments. *Behavioral and Brain Sciences*, *33*(2–3), 84–85. https://doi.org/10.1017/S0140525X10000038

107. Patel, A. D., Iversen, J. R., & Rosenberg, J. C. (2006). Comparing the rhythm and melody of speech and music: The case of British English and French. *The Journal of the Acoustical Society of America*, *119*(5), 3034–3047. https://doi.org/10.1121/1.2179657

108. Vatikiotis-Bateson, E., & Kelso, J. A. S. (1993). Rhythm type and articulatory dynamics in English, French and Japanese. *Journal of Phonetics*, *21*(3), 231–265. https://doi.org/10.1016/S0095-4470(19)31338-5

109. Lagarde, J. (2021). *The classical mean negative asynchrony in sensorimotor synchronization is not universal in humans. A cross-cultural study.* PsyArXiv. https://doi.org/10.31234/osf.io/rf7ku

Figures and tables

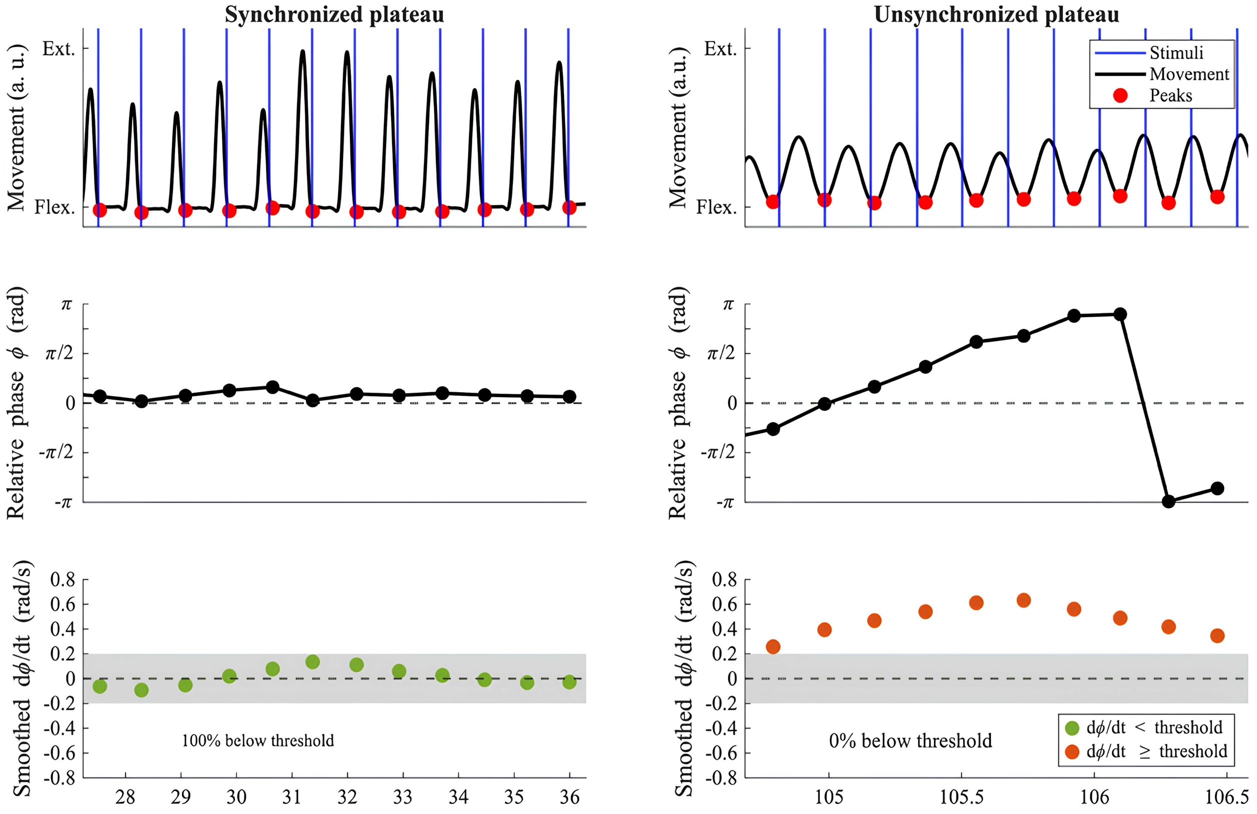

Figure 1. *Example of the index finger flexion-extension movement and metronome onsets (arb. units), and relative phase for an Indian participant. The left panels show an example of stable synchronization at 1.3 Hz; the right panels show an example of loss of synchronization at 5.8 Hz.* ***(Upper panels)*** *Time series of the index finger position with peaks identified with a red dot and stimuli represented by blue vertical lines. At 1.3Hz one can see discrete tapping behavior: The index finger stays on the table, then goes up (extension) and goes down (flexion) to tap on the table.* ***(Middle panels)*** *The corresponding relative phase time series. A relative phase of 0 rad. corresponds to a peak flexion perfectly coincident with the stimulus, while a value of ±π corresponds to a peak flexion at mid-period between two stimuli.* ***(Lower panels)*** *A schematic of the criterion based on the derivative of the relative phase, used to determine if a plateau was synchronized. The plateau was considered synchronized if 50% of the absolute values of the derivative were smaller than a threshold, thus bounded within the grey area. The dotted line represents a derivative equal to zero. The derivative is simply the slope of the relative phase time series in the Middle panels, and is the difference between the frequencies of the movement and the stimuli (in rad/sec.).*

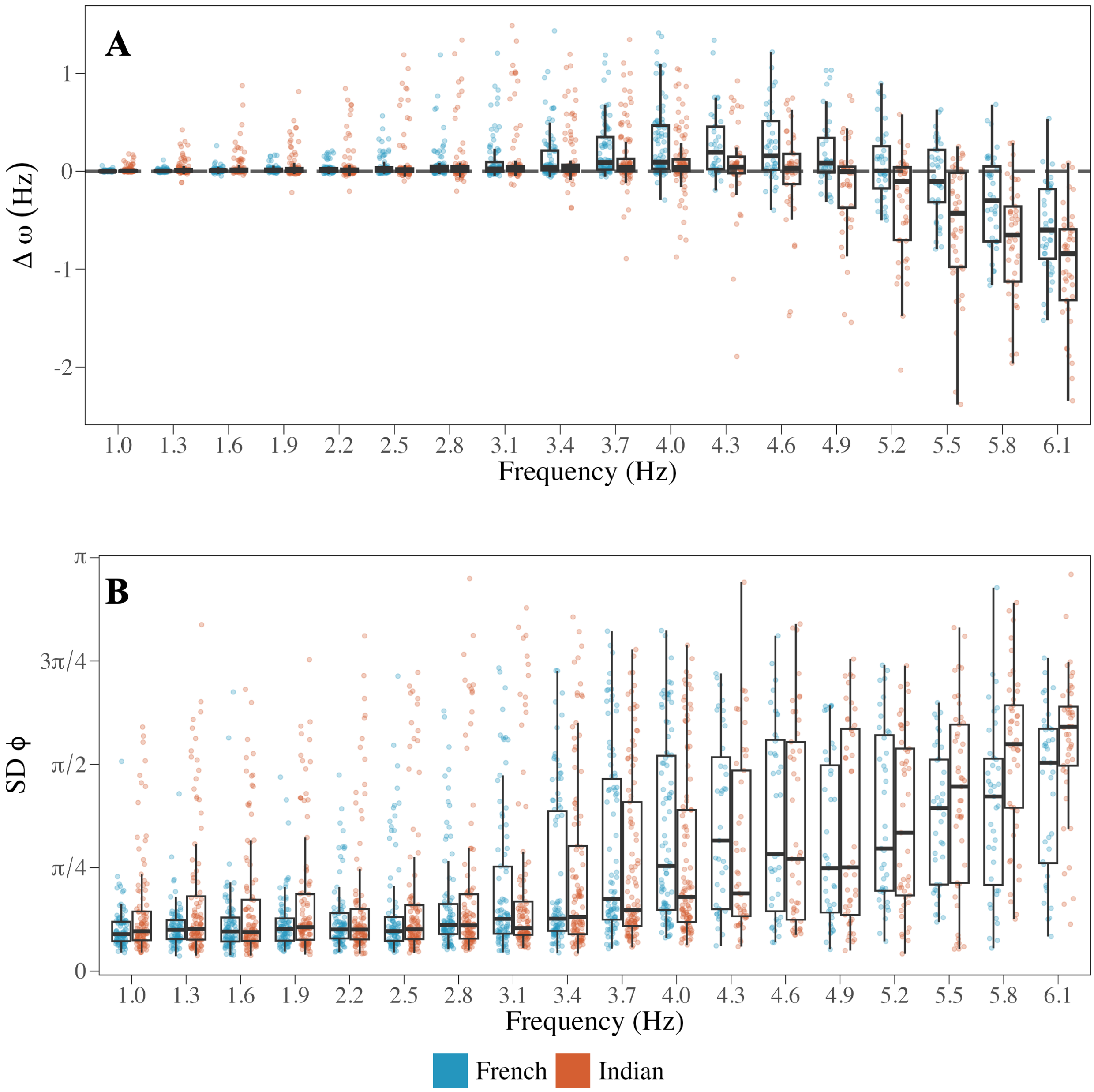

Figure 2. (A) *Evolution of the frequency mismatch as a function of metronome rate for French (FR) and Indian (IN) participants. The frequency mismatch is the difference between the tapping frequency and the metronome rate. Most of the frequency mismatch is positive until 4.9 Hz, with French participants having more positive frequency mismatch values than Indian participants. One point represents one trial (between 1.0 Hz and 4.0 Hz, 90 FR and 105 IN; between 4.3 Hz and 6.1 Hz, 39 FR and 45 IN).* ***(B)*** *Evolution of the dispersion of relative phase values for all trials as a function of the metronome rate for French and Indian participants. Initially, the dispersion is low and constant until around 3.4 Hz where there is a sudden increase, marking a loss of synchronization. One point represents one trial (between 1.0 Hz and 4.0 Hz, 90 FR and 105 IN; between 4.3 Hz and 6.1 Hz, 39 FR and 45 IN). For both panels, boxplots show the median, 1st (Q1)*

and 3rd quartile (Q2) with whiskers extending to the minimum and maximum value (within 1.5×IQR of the Q1 and Q3, respectively).

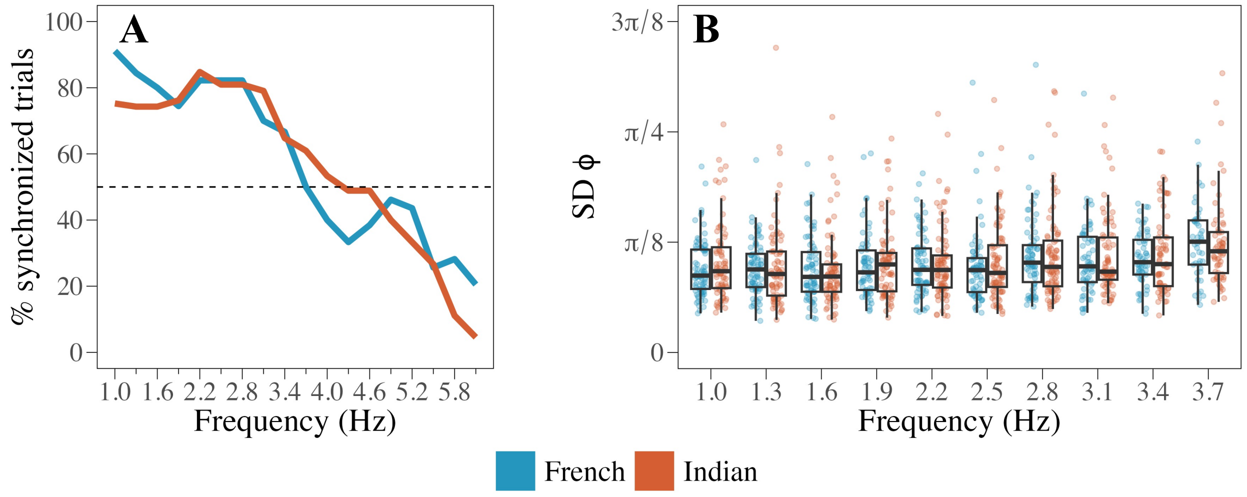

Figure 3. (A) *Percentage of synchronized trials for each metronome rate. A plateau was considered synchronized if the relative phase time series stayed constant, as described in the Data preprocessing section. Less than 50% of the trials we considered synchronized from 3.7 Hz onwards for French participants and from 4.0 Hz onwards for Indian participants.* ***(B)*** *Evolution of the dispersion of relative phase values for synchronized trials only as a function of the metronome rate for French and Indian participants. The SD ϕ values are equivalent across groups and increase with frequency. The boxplots show the median, 1st (Q1) and 3rd quartile (Q2) with whiskers extending to the minimum and maximum value (within 1.5×IQR of the Q1 and Q3, respectively).*

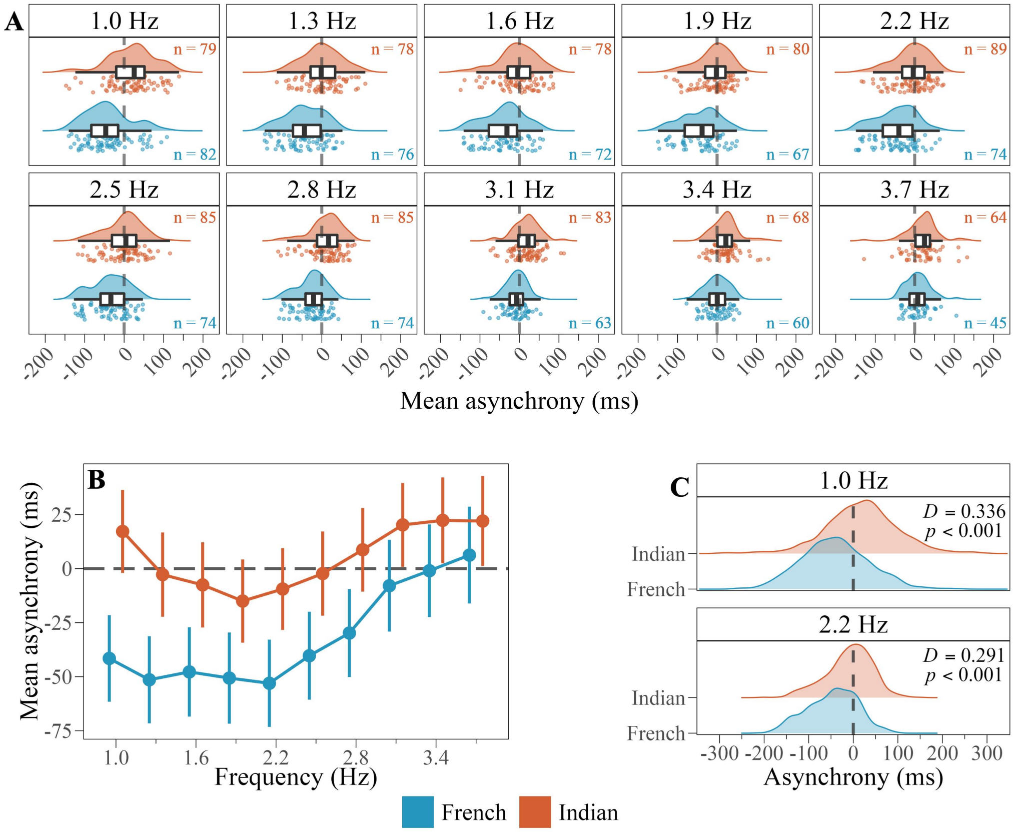

Figure 4. ***(A)*** *Comparison of the mean asynchrony values of synchronized plateaus between French (lower distributions, in blue) and Indian participants (upper distributions, in red). Indian participants exhibited mean asynchronies closer to 0 compared to French participants. Each point represents the average of one trial. The number of trials kept after the stationarity check (See Methods) is indicated is the upper right corner for Indian participants and in the lower right corner for French participants. Considering that 12 asynchronies were used for each plateau, the number of asynchronies for each group and plateau ranged from 540 to 1068, with a total of 17 712 asynchrony values. Boxplots show the median, 1st (Q1) and 3rd quartile (Q2), with whiskers extending to the minimum and maximum value (within 1.5×IQR of the Q1 and Q3, respectively). Kernel density estimates were used to represent the underlying distributions.* ***(B)*** *Evolution of the average mean asynchrony with the metronome rate for French and Indian participants. The points represent the average of the trials' mean asynchrony values estimated from the linear mixed model and the error bar represents the corresponding standard error. After the 1st plateau at 1Hz, the mean asynchrony was centered between 0 and 10 ms for Indian participants and close to -50 ms for French participants. The mean asynchrony increased from 2.2 Hz onward for both groups. For the Indian group after the 2.8Hz plateau it crossed 0 ms and became positive, while it was centered on 0 ms for French participants.* ***(C)*** *Example of distribution of asynchrony values at two rates (1Hz and 2.2Hz) using a kernel density to represent the underlying distributions. The statistics displayed are the results of the Kolmogorov-Smirnov nonparametric test between French and*

Indian distributions calculated under the null hypothesis that both groups have the same distribution.