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Individual Tempo Asymmetries and Coupling Dynamics in Dyadic Musical Synchronization

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Abstract

Interpersonal synchronization supports social interaction by enabling coordinated behavior and shared emotional experience, yet how emotions influence the mechanisms underlying synchronization remains poorly understood. We investigated how emotional feedback influences auditory–motor synchronization between dyadic partners with faster and slower Spontaneous Production Rates (SPR). Nonmusicians completed a joint tapping task with pre-feedback, feedback (matched or mismatched positive or negative), and post-feedback phases. Temporal asynchronies were modeled using a delay-coupled oscillator model to estimate participant-specific coupling parameters. Model comparisons between delay-coupled and zero-delay models showed that allowing for a delay significantly improved model fit. Slower-SPR partners coupled more strongly than faster partners, while feedback valence did not affect coupling strength. Coupling strength was positively associated with arousal in pre-feedback trials and with perceived synchronization success under mismatched feedback trials. These findings demonstrate the role of intrinsic frequency differences and shared feedback structure in organizing interpersonal synchronization and its subjective correlates.

Keywords: emotion induction; dyadic synchronization; musical synchrony; computational models; delay-coupling

Introduction

As social beings, humans thrive through interaction, with shared emotions playing a central role in social functioning. A fundamental biological mechanism supporting such interaction is interpersonal synchronization - the temporal alignment of actions between individuals - which facilitates coordinated behavior and emotional attunement (Burgoon, Stern, & Dillman, 1995). Through synchronized interaction, individual emotional states can converge, blurring the boundaries between self and others, and can support the emergence of social bonds (Launay, Tarr, & Dunbar, 2016). In turn, the development of social bonds can influence emotional experience and synchronization, highlighting the bidirectional relationship between synchrony and emotion. In this context, music production, through its inherent motor component, may offer an affiliative framework that fosters the sharing of emotional and mental states between individuals, thereby reinforcing both social bonding and interpersonal synchronization (Miu & Vuoskoski, 2017; Tzanaki, 2022).

Although a substantial body of research has examined the social and emotional consequences of synchronized interaction (Rennung, & Göritz, 2016), considerably less is known about how emotions themselves influence interpersonal synchronization, particularly during joint action (Bieńkiewicz et al., 2021). This gap is especially relevant in musical contexts, where multi-person performance often requires precise temporal coordination and elicits emotional responses. At the same time, individuals differ markedly in their timing abilities, including synchronization abilities and their Spontaneous Production Rates (SPR), both of which can influence how partners coordinate in time (Scheurich, Zamm, & Palmer, 2018; Zamm, Wellman, & Palmer, 2016). Despite extensive research on temporal synchronization between individuals, less is known about how emotional states interact with individual differences in intrinsic timing to influence synchronization dynamics and social interaction.

The present study examined whether emotionally valenced performance feedback affects auditory–motor synchronization in dyads by modulating interpersonal coupling. To capture the temporal dynamics underlying dyadic synchronization, we adopt a delay-coupled oscillator model grounded in dynamical systems theory. In this framework, coupling refers to the exchange of information between interacting systems that enable mutual adaptation and coordinated behavior (Pikovsky et al., 2001). Musical synchronization requires individuals to anticipate upcoming events based on previously perceived auditory information, often leading to anticipatory behavior (Stephen et al., 2008; Stepp, 2009). Such anticipation can be modeled using nonlinear oscillators with time-delayed feedback, in which a system's current behavior is influenced by its past states which include both the self and interactions with others (Demos et al., 2019). Delay-coupled systems provide a principled way to formalize how individuals adjust their timing in response to perceived asynchronies, allowing coupling strength to be interpreted as an index of mutual temporal adaptation. By combining this modeling approach with experimentally induced emotional feedback, the present study aims to clarify how emotional feedback influences the mechanisms that support interpersonal synchronization.

Building on prior work demonstrating that predetermined success–failure feedback affects emotional responses during synchronization tasks (Smykovskyi et al., 2022, 2024), this study advances the paradigm in several critical ways. Unlike

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prior triadic designs, we adopt a dyadic framework to isolate bidirectional coupling without the additional interaction dynamics introduced in triadic settings. We further manipulated whether partners received matched or mismatched feedback to examine whether a shared emotional experience is required to influence synchronization and the perception of social interaction such as pleasantness, arousal, social bonding, and perceived success in the synchronization task.

We hypothesized that coupling strength would decrease following negative emotional feedback and increase following positive feedback. Additionally, we explored whether differences in partners' intrinsic tempo, which are reflected in SPR, would be associated with greater susceptibility to changes in coupling and their corresponding perceptual correlates.

Methods

Participants

Seventy healthy adults (18–45 years old), with less than two years of formal musical training on an instrument (mean = 0.45 years) and no reported hearing impairments or neurological conditions, participated in the study. One participant failed the auditory perceptual screening and was excluded from further analysis (see Procedure). The participants (mean age = 20.5 years, SD = 1.36; 12 males, 58 females) were randomly assigned to 35 dyads. Participants were recruited at McGill University and received course credit for their participation. The study was approved by the McGill University Research Ethics Board (REB #24-11-051).

Equipment and Stimulus Materials

Participants generated musical tones by tapping on force-sensitive resistors connected to a Bela ultra-low-latency audio platform. Tap onsets were detected and time-stamped using a custom Pure Data (v 0.55.2) patch running on the Bela hardware. The Bela platform delivered tones to participants via Sennheiser HD 280 Pro headphones. The experimental protocol was controlled by an external Linux-based computer running a separate Pure Data patch, which communicated with the Bela platform over a USB connection to initiate and manage experimental trials.

The musical stimuli included a 32-beat melody that participants confirmed was familiar (e.g., Mary had a little lamb) and an unfamiliar melody created for the experiment (8 notes long, consisting of 4 rising and 4 falling scale tones), designed to be repeated. The unfamiliar melody began on G4 for Partner1 and an octave lower, on G3 for Partner 2, to be easily distinguishable.

Procedure

Phase 1: Solo Production. Participants were instructed to tap a familiar melody at a comfortable and consistent tempo on a force sensor with auditory feedback (see Equipment and Stimulus Materials) via headphones to estimate SPR. Each tap generated the next tone in the familiar melody; thus, participants controlled the production rate.

Phase 2: Auditory Perception Screening. Participants completed an auditory task assessing their sensitivity to temporal asynchronies between simultaneously presented tones. Eight of 12 trials presented the 8-tone unfamiliar melody (same as used in the experiment) containing a single 75-ms asynchrony; only participants who achieved ≥75% accuracy completed the study.

Phase 3: Dyadic Synchronization and Emotion Induction Task. Dyads performed a synchronization–continuation task with the unfamiliar melody. Each trial began with an 8-beat auditory metronome cue sounded every 450 ms and participants were instructed to tap the melodies with their partner once the cues stopped while attempting to synchronize at the cued metronome rate. Each trial lasted for 72 tones, with each participant producing 36 taps. As part of the cover story, participants were instructed to outperform the average score of previous participants and were informed that they would receive feedback based on their synchronization performance after selected trials. They were further informed that the average score could vary across trials to support the credibility of emotion induction. Participants were unaware that the feedback was experimentally manipulated.

Each dyad completed 18 trials across four blocks of trials in which they synchronized with a partner: A pre-feedback condition (hereafter "Pre") where no feedback was delivered; two feedback conditions designed to elicit emotional states, termed "Matched" and "Mismatched" emotional feedback; and a post-feedback condition (hereafter "Post") where no feedback was delivered. Emotional states were induced via predetermined verbal feedback ("Well done! You and your partner succeeded at the trial." / "That's too bad! You and your partner failed at the trial.") delivered individually over headphones three times per induced emotional state within each block of trials. The feedback was generated using a text-to-speech system implemented via the ElevenLabs platform. In Matched trials, both partners heard the same feedback. In Mismatched trials, one partner heard positive feedback and one heard negative feedback. Two other (baseline) conditions contained no feedback and were measured at the beginning ("Pre") and end ("Post") of the study.

As a manipulation check, participants completed ratings after each block to assess the effectiveness of emotion induction. They evaluated arousal, pleasantness, social bonding, and perceived synchronization success using 7-point Likert scales, with lower scores indicating lower arousal, reduced pleasantness and social bonding, and decreased perceived synchronization success, and higher scores indicating higher arousal, greater pleasantness and social bonding, and increased perceived synchronization success. Only the arousal measures (most sensitive to emotion induction) and synchronization success (most relevant to the task) are reported here.

Design

Each dyad completed the SPR task, followed by the Auditory Perception task, followed by the Dyadic Synchronization task in this within-subject design. The synchronization conditions of main interest manipulated the independent variables of Emotion Induction (Positive vs. Negative) and Matching feedback (Matched vs. Mismatched) and the synchronization task was identical across the four conditions. Trials were blocked by condition; order of Matched/Mismatched conditions was counterbalanced across dyads. All dyads performed in the Pre first and the Post last. Dependent measures from the SPR task were the mean inter-onset interval (IOI) for each participant. Dependent variables in the synchronization task included tone signed asynchronies (defined as Faster-SPR partner's onset minus Slower-SPR partner's onset) and the participants' subjective ratings of their perceived synchronization success and their arousal.

Model Implementations

The delay-coupled oscillator model was adopted from Demos et al. (2019) and includes a time-delay component. The time delay feeds back a time-shifted version of the system's dynamics, allowing past behavior to influence current phase values.

$$\dot{\theta}_i = \omega_i + \frac{1}{N}\sum_{j=1}^{N} k_{ij}\left(\theta_j - \theta_{i-\tau}\right)$$

Here, θ_i denotes oscillator phase, ω_i intrinsic frequency, k_{ij} coupling strength with which oscillator j influences oscillator i, and τ, a fixed time delay capturing the delayed influence of the previous system state on the participant's current state.

Each dyads' asynchronies (defined as Faster-SPR partner tone onset minus Slower-SPR partner tone onset, in ms) were computed for every eight melody repetitions, corresponding to the melodic structure.

A delay-coupled oscillator model was fitted to the asynchronies using a two-stage procedure (Plitchenko et al., 2024). In the first stage, parameters were estimated using a global genetic algorithm search. Intrinsic frequency difference (ω_1–ω_2 ; *omegadiff*) was set to between −300 and +300 ms, based on participants' SPR values; initial asynchronies were set to values between −200 and +200 ms; coupling strength (k) was allowed to vary between 0 and 50; and delay (τ) was allowed to vary between 0 and 50 ms. Ten fits were performed per trial, and the best fit was selected based on minimum RMSE. The median delay across trials was τ = 25.7 ms.

In the second stage, the delay-coupled model was fit again over 10 trials with τ fixed across participants to 25.7 ms. Coupling strength, intrinsic frequency difference, and initial asynchrony were allowed to vary within the same bounds. Parameters that reached boundary values ($k \geq 49$; $|\omega_1 - \omega_2| > 299$ ms) were excluded. The best-fitting model per trial, based on RMSE values, was retained for analysis.

Finally, a coupled oscillator model with tau set to 0 was fit to the same behavioral asynchronies, to confirm whether the time delay contributed to the model fits.

Data Analysis

All statistical analyses were conducted in R (version 4.5.2). For asynchronies, we used repeated-measures ANOVA with Synchronization condition (Pre, Matched, Mismatched, Post) as the within-subjects factor and with Dyad as the grouping variable. For questionnaire ratings (i.e., arousal and perceived synchronization success), we used nonparametric Friedman tests due to the ordinal nature of the data. Significant Friedman tests were followed by pairwise Wilcoxon signed-rank tests with Holm correction for multiple comparisons. For the delay-coupled model comparison, we used paired-samples t-tests to compare RMSE values between models with and without delay parameters. For coupling strength, we used a two-way mixed ANOVA with Participant SPR (Faster-SPR, Slower-SPR) as a within-dyad factor and Synchronization condition as a within-subjects factor. Associations between coupling strength and subjective ratings were assessed using Spearman's rank correlation coefficient (ρ).

Results

Spontaneous Production Rates (SPR). Each individual's mean IOI in the unpaced production of a familiar melody is ordered from fastest to slowest (Figure 1A). The slowest participant was more than twice as fast as the fastest participant. Each dyad's mean SPR difference is ordered in Figure 1B from smallest to largest difference. The standard error bars indicate that participants were consistent in their tempo productions, despite large individual differences.

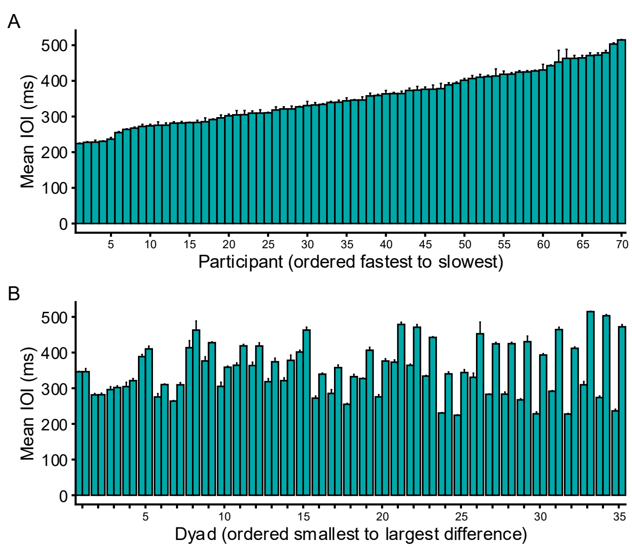

Figure 1: (A) Participants' mean SPR values sorted in ascending order. (B) Dyads' SPR values, sorted from smallest to largest pairwise difference. Error bars indicate the standard error of the mean.

Synchronization asynchronies. Signed mean asynchronies (FasterSPR – SlowerSPR partner) were negative across all Synchronization conditions, indicating earlier responses by the faster SPR partner. Each mean differed significantly from 0 (one-tailed, $p < .05$) indicating the Faster-SPR partner was reliably faster than the Slower-SPR partner in the synchronization tasks. Mean (± SE) asynchrony was −14.4 (1.50) ms in the Pre, −13.5 (1.42) ms in the Matched condition, −12.6 (1.17) ms in the Mismatched condition, and −15.2 (3.58) ms in the Post. A repeated-measures ANOVA revealed no significant differences in mean asynchronies across Synchronization conditions (Pre, Matched, Mismatched, Post), $F(3, 102) = 0.28$, $p = .84$, generalized $\eta^2 = .001$.

Social interaction ratings. Mean (with SE) arousal ratings (Figure 2A) differed across conditions, with highest values in the Pre, 4.11 (0.15), followed by the Matched, 3.89 (0.14) and Mismatched conditions, 3.91 (0.14), and lowest values in the Post, 3.71 (0.15). Friedman's test revealed significant effects of Synchronization condition on arousal ratings, $\chi^2(3) = 10.30$, $p = .016$, W =0.049. Post-hoc Wilcoxon signed-rank tests indicated that arousal was significantly lower in the Post compared to the Pre ($p = .029$). No other pairwise comparisons reached significance ($p \geq .36$).

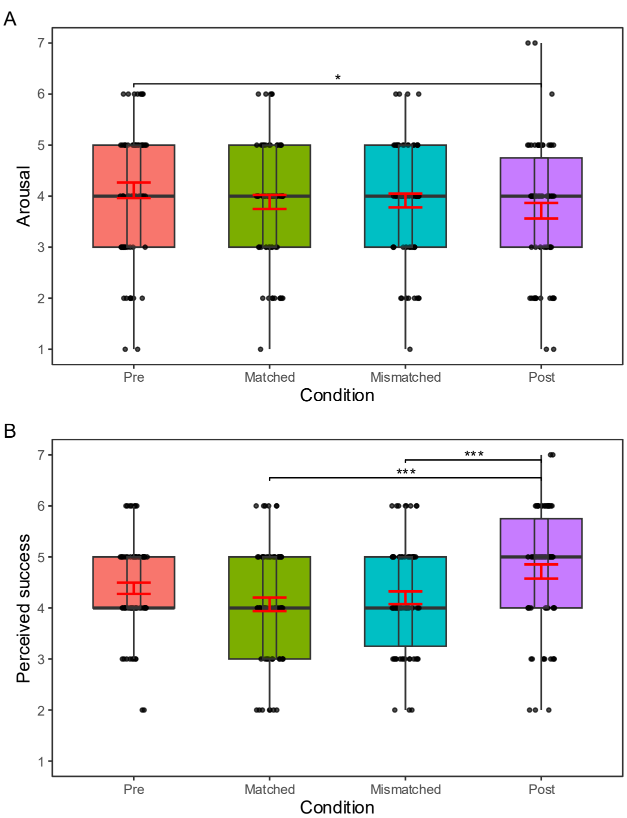

Figure 2: Mean arousal (A) and perceived success of synchronization (B) ratings by Synchronization condition. The red error bars are calculated using the standard error of the mean.

Perceived synchronization success ratings (Figure 2B) also differed across Synchronization conditions, Friedman test $\chi^2(3) = 22.30$, $p < .001$. Mean (± SE) success ratings were 4.39 (0.11) for the Pre, 4.07 (0.13) for the Matched condition, 4.20 (0.13) for the Mismatched condition, and were highest in the Post, 4.71 (0.14). The effect size was small (Kendall's $W = 0.106$), indicating modest but reliable differences across conditions. Post-hoc Wilcoxon signed-rank tests showed that perceived success was significantly higher in the Post compared to both the Matched ($p < .001$) and Mismatched ($p < .001$) conditions. No other pairwise comparisons were significant ($p \geq .07$).

Delay-coupled model. The fit of the delay-coupled model to the asynchronies yielded a mean (± SE) RMSE of 13.93 (0.11), whereas the no-delay model ($\tau = 0$) yielded a higher mean RMSE of 15.73 (0.14), indicating a worse fit (paired-samples t-test, $t(6239) = -16.48$, $p < .001$), with a mean RMSE reduction of 1.80 ms (95% CI [1.59, 2.02]). These results indicate that incorporating a non-zero delay substantially improved the model's ability to capture the dyadic synchronization measures. Therefore, the remaining analyses were conducted only on the delay-coupled model fits. Figure 3 illustrates a representative trial, in which the observed mean asynchronies are shown together with the estimates produced by the delay-coupled model.

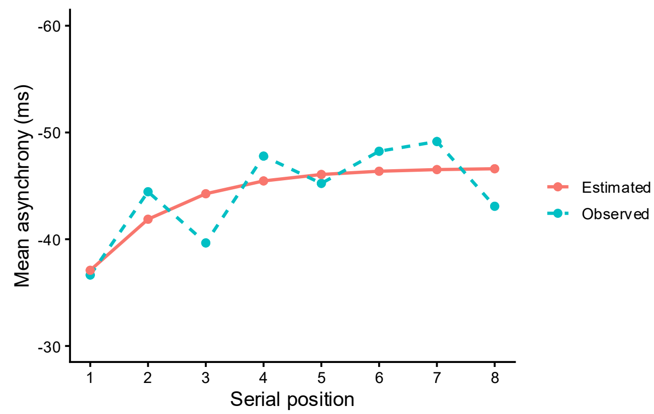

Figure 3: Observed asynchronies and model fit for a representative trial. The dashed line denotes the observed mean asynchronies, whereas the solid line represents the model-predicted asynchronies.

Tests of the model-derived coupling parameter for each participant showed the largest mean values in the Pre (M = 18.8, SE = 1.37), followed by the Matched (M = 18.4, SE = 0.90) and Mismatched conditions (M = 18.3, SE = 0.91), and the smallest values in the Post (M = 16.5, SE = 1.26). A two-way mixed ANOVA by Participant SPR (Faster-SPR, Slower-SPR) and Synchronization condition (Pre, Matched, Mismatched, and Post) revealed a significant main effect of Participants' SPR, $F(1, 34) = 8.42$, $p = .006$, $\eta^2\_G = .016$, indicating stronger coupling for the Slower-SPR partner than the Faster-SPR partner. No main effect of synchronization conditions or Participant SPR × Condition interaction was observed ($p \geq .21$). Together, these findings indicate a stable directional difference in coupling strength across experimental conditions, with the Slower-SPR partner consistently showing stronger adaptation to the Faster-SPR partner than vice versa.

Comparison of delay-coupled model results with social interaction ratings. Of most interest is the delay-coupled model's coupling parameters from the asynchronies and whether they align with social interaction ratings following the synchronization tasks. In the Pre condition (Figure 4), individuals' larger coupling values were associated with higher arousal ratings (Spearman's $\rho = 0.27$, $p = .02$), suggesting that increased arousal at the beginning of the dyadic interaction was accompanied by a heightened state of effort to synchronize with a novel (unknown) partner.

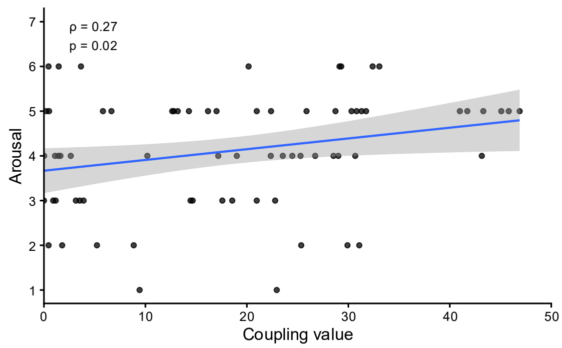

Figure 4: Individual mean coupling values by mean arousal ratings in the Pre condition.

In the Mismatched (Emotional induction) condition (Figure 5), higher coupling strength was associated with greater synchronization success (Spearman's $\rho = 0.32$, $p = .01$). When participants exhibited lower coupling with their partner, they perceived lower synchronization success, suggesting that the mismatched emotion induction (one partner negative emotion, one partner positive) may have reduced perceived synchrony and overall coupling.

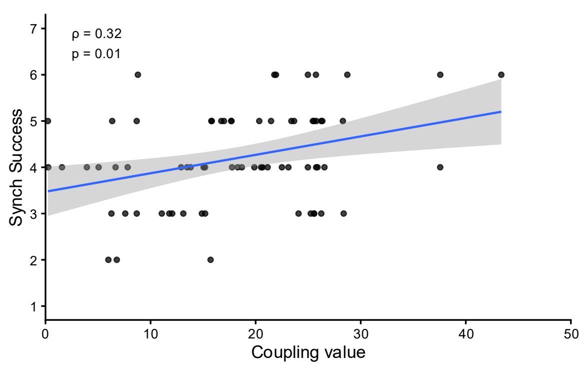

Figure 5: Individuals' mean coupling values by mean perceived synchronization success in the Mismatched Synchronization condition.

Discussion

The present study investigated the relationship between dyadic synchronization and participants' intrinsic tempo differences, emotional-inducing performance feedback, and resulting perceived synchronization success. Using a dyadic tapping paradigm, we modeled the dyads' temporal asynchronies using a delay-coupled oscillator model. We introduced a novel emotion-induction paradigm by providing positive or negative performance feedback to each participant and we examined their subsequent synchronization.

We hypothesized that the emotion induction method which gave positive or negative feedback on participants' synchronization abilities on each trial would directly modulate coupling strength, such that positive feedback would enhance coupling and negative feedback would weaken it. Contrary to this prediction, coupling strength was only reliably affected by partners' spontaneous rates (in which the slower partner was more coupled to the faster partner than vice versa).

One possible explanation is that emotional states do not influence synchronization. However, this interpretation is not consistent with previous findings showing that emotion manipulations can affect synchronization (e.g., Fujiwara & Daibo, 2018; Paxton & Dale, 2013; Smykovskyi et al., 2022, 2024). A more plausible explanation is that the brief performance feedback used in the present study was insufficient to induce stable emotional states that would have modulated sensorimotor coupling. The relatively small effect sizes observed in subjective ratings, together with the absence of effects on coupling strength, suggest that the trial-by-trial feedback manipulations did not generate emotional states that would have been sufficiently strong and sustained to impact synchronization mechanisms and may have interfered with one another across trials. An induction method that delivers emotional feedback interpersonally (instead of through headphones as used in the current study) may more successfully manipulate participants' emotional valence (Harmon-Jones, Amodio, & Zinner, 2007). Alternatively, the feedback manipulation may have primarily influenced participants' appraisal of the synchronization task rather than the synchronization process itself. Consistent with this interpretation, participants reported that the predetermined feedback they received did not always align with their own evaluation of their performance. Moreover, feedback that is more personally salient and sufficiently ego-involving, such as feedback that explicitly references the individual, is grounded in actual performance, or is embedded within tasks of personal relevance, may be necessary to influence synchronization dynamics (Nummenmaa & Niemi, 2004).

Fits of the delay-coupled model to dyadic synchronization resulted in a median delay parameter value ($\tau = 25.7$ ms) similar to (although slightly larger than) values reported in previous work with musically trained participants on the order of 10 to 25 ms (e.g., Bégel et al., 2022; Demos et al., 2019; van Kerrebroeck et al., 2025; Plitchenko et al., 2025). One plausible cause for the median delay is the inclusion of only nonmusicians in the present study. Simulations of neural pathways suggest that tau captures neural transmission speed, which plausibly is faster in musically trained than untrained individuals for a synchronization task (Machado & Matias, 2020). Some findings suggest that nonmusicians rely less on advance planning and more on auditory feedback when synchronizing, which can lead to larger delays, an interpretation consistent with evidence that musical expertise is associated with more stable internal timing and reduced reliance on external feedback (Finney & Palmer, 2003).

Delay-coupled models have demonstrated greater variability in the coupling estimates resulting from fits to dyadic synchronization tasks. Consistent with findings by Plitchenko et al. (2024), the present study yielded relatively large coupling values, whereas other investigations have reported smaller coupling estimates (e.g., Demos et al., 2019; Van Kerrebroeck et al., 2025). Because parameters in nonlinear models interact, larger intrinsic frequency differences (*omegadiff*) in this study and Plitchenko's, which reflect tempo change, may require stronger coupling for the model to compensate for greater tempo disparities. Our selection of initial parameter values, including *omegadiff*, was guided by the inclusion of only nonmusicians, who typically exhibit less flexibility in adapting to tempo changes than do musicians (Scheurich et al., 2018). Additionally, model fits based on smaller ranges of *omegadiff* values for these nonmusicians would likely increase the number of parameter values that reach boundary values included in parameter constraints placed on the modeling procedure. Interactions among coupling and other model parameters will require systematic comparisons across factors such as musical expertise, baseline tempo, and rhythmic complexity.

The nonlinear delay-coupling computational model applied here provides that emotional feedback may alter coupling strength and/or time delay parameters. Time delays were kept constant, similar to previous applications (Begel et al., 2024; Demos et al., 2019), in order to allow the evaluation of coupling strength changes across emotion conditions. Time delay parameters are thought to reflect neural transmission delays, which in many tasks are well-modeled as a constant value. There is evidence, however, that emotional states can alter the speed and efficiency of neural processing, with changes in emotional arousal reducing or increasing transmission speeds as well as coupling strength between neural networks (cf. Arias et al., 2020; Kim et al,. 2021). Future work may model different emotional states with distinct time delay parameters as well as coupling strength, particularly for conditions that induce heightened arousal or motivational engagement, attentional allocation, and/or response thresholds for initiating corrective adjustments.

Other frameworks from temporal coordination research suggest multiple ways through which emotions could modulate synchronization. Repp and Keller (2008) distinguish between two complementary linear timing control mechanisms: phase correction (rapid, automatic adjustments) and period correction (slower, more deliberate tempo adjustments). Following these findings, emotional feedback might influence the relative weighting or gain of phase versus period correction mechanisms

The current emotion induction paradigm and computational models have some limitations. First, social outcomes such as synchronization success were assessed via self-report only after each block of trials; long-term effects were not gauged. Second, auditory cues were designed to be perceptually distinct between partners to simplify the task for non-musicians. Future studies could address these limitations through several methodological improvements. First, examining whether changes in coupling dynamics predict sustained social bonding beyond an immediate interaction. Second, systematically manipulating perceptual similarity between self- and partner-generated outcomes could increase ambiguity between action sources, potentially amplifying self–other blending and its interaction with emotional and synchronization dynamics. Moreover, future studies should employ multimodal assessment of emotion induction effectiveness, incorporating behavioral and physiological indices alongside self-report measures. For instance, spontaneous eye blink rate has been shown to track attentional engagement and emotional valence during film viewing (Maffei & Angrilli, 2019) and pupil dilation indexes emotional arousal during picture viewing (Bradley et al., 2008). Such indices could verify whether feedback manipulations successfully modulate attention and arousal processes through which emotions may influence synchronization. Finally, nonlinear dynamics models offer insights into the dynamical development of emotional states at the cost of complexity. Future work may compare linear as well as nonlinear models in order to further isolate parameter values that capture the richness of human social interaction.

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