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Emotional states change the behavioral meaning of interbrain synchronization in dyadic bilingual language control

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ABSTRACT

Bilingual conversation requires coordination between a speaker who selects and produces the target language and a listener who monitors and responds to that output. The present study examined whether emotional state moderates the association between interbrain synchronization and behavioral performance during a controlled dyadic bilingual task. Sixty-two Chinese–English bilinguals formed 31 proficiency-matched dyads. One partner named pictures in Chinese or English, whereas the other made animacy judgments on the producer's spoken responses. Dyads completed mixed- and single-language blocks under experimentally induced negative, neutral, and positive emotional states while dual-EEG was recorded. Behaviorally, both negative and positive states were associated with faster overall responses than the neutral state in production and comprehension. Both states also reduced mixing costs in production, whereas the corresponding comprehension effects were more restricted. Critically, the association between interbrain phase-locking value (PLV) and reaction time differed across emotional states. Under neutral emotion, stronger PLV was often associated with slower responses. Several corresponding associations were more negative under the negative condition, with the clearest negative–neutral difference observed for producer alpha-band PLV. The positive condition produced a more heterogeneous pattern across interlocutor roles, frequency bands, and task contrasts. These findings indicate that PLV–behavior associations during bilingual interaction are not uniform across emotional states. These findings show that emotional context moderates how cross-brain phase consistency covaries with bilingual performance.

1. Introduction

Bilingual language control has been studied primarily as an individual-level process. Yet everyday bilingual conversation requires coordination between a speaker who selects and produces the target language and a listener who identifies and responds to that output (Zada et al., 2026). Language switching increases the regulatory demands placed on both partners, making bilingual control not only an intrapersonal challenge but also a dyadic coordination problem (Gambi & Hartsuiker, 2016; Green & Abutalebi, 2013). However, this coordination rarely occurs in an affect-neutral context. Everyday bilingual exchanges often occur in emotionally charged contexts. An important question is whether emotional state influences how bilingual partners coordinate during communication.

Evidence that emotional states affect bilingual control at the individual level is growing. Rather than simply disrupting cognitive processing, emotional states can modulate attention, monitoring, and the allocation of control resources (Dolcos & McCarthy, 2006; Eysenck et al., 2007; Pessoa, 2008, 2009). Recent bilingual studies have further shown that emotional states can influence switching costs, mixing costs, and control-related neural responses (Jiang et al., 2024; H. Liu et al., 2023; Wang et al., 2025). However, these single-participant studies do not address whether emotion alters dyadic coordination during bilingual communication.

EEG hyperscanning provides a means of examining this interpersonal level by recording neural activity from both interlocutors simultaneously (Carollo & Esposito, 2024; Schilbach & Redcay, 2025). One commonly used measure is the phase-locking value (PLV), which

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quantifies the consistency of oscillatory phase differences between two signals (Cassioli et al., 2025; Lachaux et al., 1999). In speaker–listener settings, interbrain synchronization has been associated with communicative success, shared attention, and interaction quality (Dikker et al., 2017; Pérez et al., 2019; Schoot et al., 2016; Stephens et al., 2010). In bilingual contexts, H. Liu et al. (2019) recorded simultaneous EEG from Chinese–English dyads during a cooperative picture-naming task and found stronger interbrain coupling when partners switched to the second language (L2) than the native language (L1), suggesting that language switching can increase cross-brain alignment. These findings were extended by further work showing that coupling strength varies with switching fluency and task demands (H. Liu et al., 2022). However, these bilingual hyperscanning studies were conducted under neutral affective conditions, leaving open whether emotional state alters interbrain synchronization or its association with behavioral performance.

A central issue is that stronger interbrain synchronization does not have a single behavioral interpretation. In some task contexts, higher synchronization has accompanied greater coordination demands or compensatory engagement and has co-occurred with slower performance (Cui et al., 2012; Xie et al., 2020). In other contexts, stronger synchronization has been associated with faster, more accurate, or more successful performance (Dikker et al., 2017; Stephens et al., 2010). The behavioral relevance of interbrain coupling may therefore depend on the context in which it occurs (Reinero et al., 2021). Emotional state is a plausible moderator because it can alter both the recruitment of control resources and the way those resources are deployed (Eysenck et al., 2007; Pessoa, 2009). The central question is therefore whether emotion moderates the association between interbrain synchronization and behavioral performance, rather than simply increasing or decreasing synchronization. Addressing this question requires simultaneous recording from both partners and an analysis linking dyad-level coupling to individual performance under different emotional conditions.

1.1. The present study

To address this question, we recorded dual-EEG from Chinese–English bilingual dyads performing a joint production–comprehension language-switching task. One participant served as the producer, naming pictures in Chinese or English according to a language cue, whereas the other served as the comprehender, making animacy judgments on the producer's spoken output. The task included mixed-language blocks, containing switch and nonswitch trials, and single-language blocks, allowing us to examine both switching and mixing contrasts. Dyad members were matched on L2 proficiency to minimize proficiency-driven asymmetries in coordination demands, and roles were fixed throughout the session to allow clear separation of production and comprehension processes. Dyads completed the task under experimentally induced negative, neutral, and positive emotional states, and production and comprehension performance were analyzed separately. The three emotion conditions were not designed as an orthogonal manipulation of valence and arousal.

Interbrain synchronization was quantified using PLV in the alpha (8–13 Hz) and gamma (30–50 Hz) bands. These bands were selected because previous hyperscanning and individual-level EEG studies have reported communication- and emotion-related modulations in both ranges (Codispoti et al., 2023; Ferrari et al., 2022; Garcia-Garcia et al., 2010; H. Liu et al., 2019). We treated alpha and gamma as frequency-specific windows for testing the same central hypothesis, rather than as direct indicators of distinct interpersonal control mechanisms.

Our primary prediction was that the relationship between PLV and reaction time would differ across the three emotional states. Drawing on evidence that negative affect can mobilize compensatory effort and support goal-directed processing under demanding conditions (Eysenck et al., 2007; Robert J. Hockey, 1997), we predicted that the PLV–RT slope would be more negative under the negative than the neutral condition. This difference was expected to be particularly evident under greater control demands, such as switch trials and mixed-language contexts. Such a pattern would indicate that stronger interbrain coupling was associated with more favorable behavioral performance under the negative than the neutral condition. We made no strong directional prediction for the positive condition because existing accounts suggest competing possibilities. Positive affect may broaden attentional scope and promote flexible processing, which could facilitate coordination (Fredrickson et al., 2003). However, broader processing may also reduce the selectivity of goal-directed control (Dreisbach & Goschke, 2004; van Steenbergen et al., 2010). The neutral condition therefore served as the reference for evaluating emotion-related differences in PLV–RT slopes. Because the three emotion conditions did not constitute an orthogonal manipulation of valence and arousal, any observed differences were interpreted as differences among the induced emotional states rather than as effects of a specific affective dimension.

2. Method

2.1. Participants

Seventy Mandarin Chinese–English bilinguals were recruited and randomly assigned into 35 dyads. To minimize potential gender-related variability in interactional settings, dyads were formed with same-gender partners. Participants were undergraduate or postgraduate students from higher education institutions. Eligibility criteria included right-handedness, normal or corrected-to-normal vision, no color blindness, no history of psychiatric disorders, and successful completion of the College English Test Band 4 (CET−4), a nationally administered English proficiency examination for Chinese non-English major undergraduates. All participants provided written informed consent prior to participation. The study protocol was approved by the Institutional Review Board of the Faculty of Psychology at Beijing Normal University (Protocol ID: BNU202503110080).

Because emotional states were induced via music, individuals with formal musical training or regular experience playing musical instruments were not enrolled. Prior to the experiment, participants completed the Quick Placement Test (QPT), a 60-item measure of L2 proficiency (maximum score = 60), with higher scores indicating greater proficiency. Participants received monetary compensation following the session. Four dyads were removed before analysis. Two dyads were excluded because participants reported that the music manipulation did not elicit the intended emotional states, and two additional dyads were excluded due to excessive electroencephalography (EEG) artifacts that resulted in unusable data across all experimental conditions. The final sample therefore comprised 31 dyads ($N = 62$ individuals; 26 males; M_age = 22 years, $SD = 3$). None of the included participants had lived or traveled outside their country of residence or birth for more than three months. In everyday life, Mandarin Chinese (L1) was the primary language of use, whereas English (L2) exposure was largely confined to formal academic environments (e.g., coursework, academic reading, and examinations). All participants reported classroom-based L2 learning, with a mean age of acquisition onset of 8 years ($SD = 2.00$).

Participants also provided self-ratings of L1 and L2 proficiency on a 6-point scale across listening, speaking, reading, and writing. For L1, mean ratings were 5.56 ($SD = 0.80$) for listening, 5.18 ($SD = 0.64$) for speaking, 4.79 ($SD = 0.85$) for reading, and 5.00 ($SD = 0.94$) for writing. For L2, corresponding means were 3.82 ($SD = 1.05$) for listening, 3.52 ($SD = 0.76$) for speaking, 3.34 ($SD = 1.02$) for reading, and 3.06 ($SD = 1.29$) for writing. Paired-samples t-tests confirmed robust L1–L2 differences across all four skills (listening: $t(61) = 14.47$, $p < .001$; speaking: $t(61) = 16.18$, $p < .001$; reading: $t(61) = 10.57$, $p < .001$; writing: $t(61) = 10.54$, $p < .001$). The mean QPT score for the final sample ($N = 62$) was 38.10 ($SD = 5.12$), corresponding to approximately B1

level on the Common European Framework of Reference for Languages (CEFR). Taken together with the self-rated proficiency measures and responses on a bilingual switching questionnaire, the sample was characterized as intermediate bilinguals with a dominant L1 and relatively limited day-to-day language switching experience (Jiang et al., 2024; Liu et al., Liu et al., 2022, 2023, 2025; Zhang et al., 2020).

2.2. Materials

2.2.1. Picture naming

To examine how emotional states modulate bilingual language control under tightly controlled task conditions, visual stimuli were presented as standardized pictures to both members of each dyad simultaneously. The stimulus set comprised 32 black-and-white line drawings (15 cm × 15 cm; 5.9 × 5.9 in), selected from the Snodgrass and Vanderwart (1980) norms and the Chinese-adapted version by Zhang and Yang (2003). All Chinese labels were disyllabic, whereas English labels were restricted to one or two syllables and 3–6 letters in length. To verify that the items were comparably familiar across languages, an independent group of 35 Chinese–English bilinguals (matched to the main sample in L2 proficiency, indexed by CET−4) rated the familiarity of each label in both languages on a 5-point Likert scale (1 = extremely unfamiliar; 5 = extremely familiar). These participants did not take part in the main experiment. Familiarity ratings did not differ between the L1 and L2 labels (L1: $M = 4.85$, $SD = 0.08$; L2: $M = 4.84$, $SD = 0.12$), $t(34) = 0.69$, $p = .759$).

2.2.2. Emotional induction and assessment

Emotional states were induced using musical excerpts drawn from the Chinese Affective Music System (CAMS; Li et al., 2012), a validated database containing 78 clips spanning symphonic, pop, and folk genres, with affective categories defined by normative ratings. All clips were digitized at a 22,050 Hz sampling rate (16-bit resolution) and lasted 50–70 s. Normative valence and arousal ratings were obtained during CAMS validation from 153 university students in Beijing using 9-point scales (higher scores indicate greater positivity/activation).

Following Jiang et al. (2024), we selected 9 positive, 9 negative, and 9 neutral instrumental clips. Using Adobe Audition CS6, all clips were RMS-normalized to 70 dB SPL to minimize potential confounds of intensity. A one-way ANOVA confirmed that clip duration did not differ across emotional categories, $F(2, 24) = 0.93$, $p = .41$, $\eta^2 = 0.07$. Emotion induction was implemented via a music-based affective priming procedure combined with guided affective imagery, a protocol shown to reliably elicit sustained affective states in psycholinguistic and neurocognitive research (Daly et al., 2015; Geethanjali et al., 2018). To assess subjective emotional experience, participants completed paper-and-pencil ratings on 9-point bipolar scales indexing pleasure (1 = extremely unpleasant; 9 = extremely pleasant) and arousal (1 = extremely sleepy; 9 = extremely aroused). The obtained ratings replicated the expected affective separation observed in prior work using this protocol (Jiang et al., 2024). Specifically, one-way ANOVAs on the normative ratings confirmed that negative clips were rated as less pleasant than neutral and positive clips, and positive clips were rated as more pleasant than neutral clips (all $ps < .001$). For arousal, positive clips were rated as more arousing than neutral and negative clips (all $ps < .001$), with negative clips rated as less arousing than neutral clips ($p < .01$).

2.3. Design and procedure

Eligible participants were randomly paired into same-gender dyads. To minimize proficiency-driven variability in bilingual control and coordination, dyad members were closely matched on L2 proficiency (QPT score difference ≤ 2 SD). Within each dyad, roles were assigned by computer randomization: one participant served as the producer (overt picture naming) and the other as the comprehender (responding to the producer's spoken output). Producers completed a cued language-switching picture-naming task. On each trial, a colored cue (green or blue square) instructed the target language, with cue–language mappings counterbalanced across individuals. Importantly, these mappings were not disclosed to comprehenders. To align the dyad members' processing streams while keeping their task requirements distinct, pictures were displayed to both partners at the same time, but comprehenders were instructed to perform an animacy judgment on the producer's vocal response (rather than on the picture itself) using a keypress (e.g., *F* = animate; *J* = inanimate; key mapping counterbalanced). To reduce strategic anticipation by comprehenders and ensure that their responses were driven by the producer's utterance, one third of trials in each block were designated as fillers. Fillers implemented two controls: (a) cross-modal incongruence, in which producer and comprehender viewed different pictures; and (b) category reversal, in which the comprehender's picture belonged to the opposite animacy category from the producer's. The 32 critical pictures were evenly split between animate and inanimate categories.

Dyad members sat at separate workstations with an opaque divider (0.8 m wide × 0.5 m high) that blocked direct view of each other's screens. The experiment was programmed and delivered in E-Prime 2.0 with millisecond timing precision. At the start of the session, participants completed baseline ratings of pleasure and arousal using 9-point paper scales, followed by a practice block with pictures not used in the main experiment. Emotion induction was administered to both partners concurrently. The order of emotion conditions (positive, negative, neutral) was counterbalanced across dyads using a Latin-square design. Each condition began with a 5-min induction phase, after which participants immediately re-rated pleasure and arousal. In addition, ratings were repeated whenever prompted on-screen during the session, allowing us to track the maintenance of induced states across blocks. To reinforce emotional engagement, a 2-min "booster" using affectively congruent music preceded each experimental block (Fig. 1a).

As shown in Fig. 1b, each trial started with a 250-ms colored cue presented to the producer, followed by a 500-ms blank interval. The cue indicated the language in which the picture should be named. For half of the producers, a green cue indicated Chinese (L1) and a blue cue indicated English (L2), whereas the cue–language mapping was reversed for the other half. Next, two pre-familiarized pictures were presented simultaneously to the producer and comprehender. The pictures were identical on critical trials but could differ on filler trials. Producers named their assigned picture in the cued language within 1500 ms; if no response occurred, the trial advanced automatically. Comprehenders then made an animacy judgment on the producer's spoken word within a 1000-ms response window, and the stimulus disappeared after a response or when the response window elapsed. Trials ended with a jittered inter-trial interval of 800–1500 ms. Producer vocal RTs were recorded using a PST SR-BOX voice key connected to a microphone, and all vocal responses were audio-recorded.

Within each emotion condition, participants completed four main task blocks: two mixed-language blocks, one single-L1 block, and one single-L2 block. Thus, the three emotion conditions comprised 12 main task blocks in total, in addition to one practice block completed at the beginning of the session. For behavioral analyses, critical trials were classified by whether the producer's target language repeated or switched relative to the immediately preceding target trial, yielding L1-switch, L1-non-switch, L2-switch, and L2-non-switch trials in mixed blocks, alongside non-switch trials in single-language blocks. Each block started with two practice (warm-up) trials that were not included in the analyses. The two mixed-language blocks comprised 88 experimental trials each (22 per condition) plus 10 filler trials, whereas each of the two single-language blocks included 44 experimental trials and 5 filler trials. Importantly, the block structure and trial composition were kept constant across the three emotion conditions (negative, neutral, positive). Warm-up trials (first two trials in each block), filler trials, and

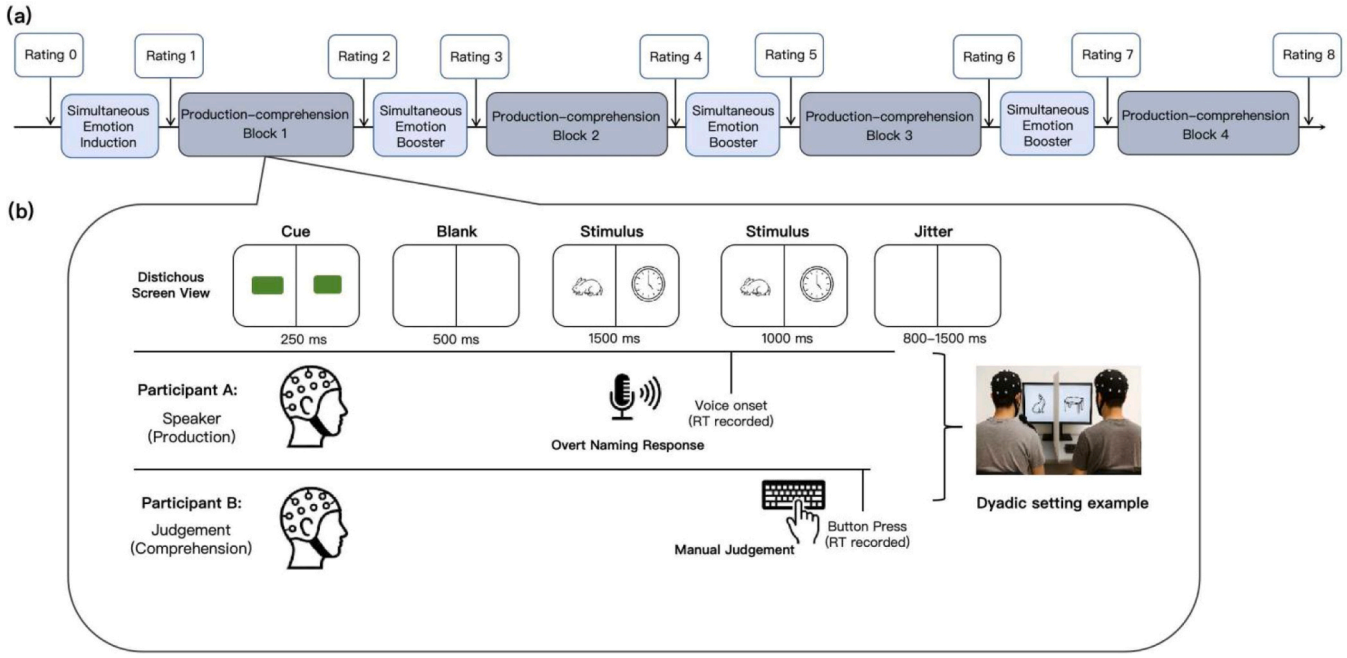


Fig. 1. (a) Schematic diagram of the experimental protocol. Ratings 0–8 denote the emotional state rating on the two-dimensional (valence/arousal) assessment procedure. (b) Temporal trial architecture and dyadic setting example.

trials immediately following fillers were excluded from inferential analyses.

2.4. Data recording and analyses

Electrophysiological data were recorded simultaneously from both partners using two identical 64-channel Neuroscan Quick-Caps (Ag/AgCl; extended 10–20 layout) at 1000 Hz, with impedances kept below 5 kΩ. Data were collected in Curry 9 using a dual-brain acquisition configuration. Preprocessing was conducted using standard pipelines: signals were band-pass filtered (0.1–50 Hz), downsampled to 500 Hz, and re-referenced to the average of the mastoids (M1/M2). Artifact Subspace Reconstruction (ASR; Plechawska-Wojcik et al., 2019) with a threshold of 10 was applied to attenuate transient high-amplitude artifacts and channel noise (Chang et al., 2020). Subsequently, Independent Component Analysis (ICA; Makeig et al., 1995) implemented in EEGLAB (Delorme & Makeig, 2004) was used to identify and remove artifactual components. Components related to ocular, muscle, or cardiac activity were detected via ICLabel and rejected if classified as noise with a probability exceeding 90% (D. Liu et al., 2025; Pion-Tonachini et al., 2019).

To evaluate whether the induction reliably differentiated affective states across the session, we analyzed ordinal pleasure and arousal ratings using cumulative link mixed-effects models. Fixed effects included emotion condition, rating time point (Ratings 0–8), and their interaction (Schad et al., 2020). Neutral served as the reference level for emotion contrasts, and Rating 0 was set as the initial reference for time-point contrasts. The baseline was iteratively shifted to test differences across the full rating sequence. Random effects followed a maximal structure when supported; if convergence failed, random slopes were reduced via backward pruning (Barr et al., 2013). All statistical analyses were conducted in R software (version 4.0.3) using mixed-effects models. Full results of the emotion manipulation check, together with the corresponding figure, are reported in the Supplementary Materials.

Behavioral analyses focused on response times (RTs) from both roles (producer vocal RTs; comprehender keypress RTs). Producer responses were audio-recorded and coded using an established taxonomy adapted from prior work (De Bruin et al., 2018; e.g., correct, lexical errors, hesitations/repairs, language errors in single-language blocks, etc.). Comprehender trials were coded as correct, no/delayed response, or incorrect due to the producer's error. RT analyses included only trials with valid responses. Because trial type was defined relative to the preceding trial, a trial was retained only when the immediately preceding trial had also been answered correctly; trials following an error were excluded to avoid ambiguity in trial classification. Overall accuracy was high (production: 95.30%; comprehension: 93.69%).

RTs were log-transformed, and extreme values beyond ±2.5 SD were removed. Linear mixed-effects models (lme4) were fitted to test emotion effects on RTs under (a) switching contrasts within mixed blocks and (b) mixing contrasts comparing mixed-block non-switch trials with single-language trials, alongside a global model estimating overall emotional influence. Predictors were coded using theoretically motivated contrasts (emotion: neutral as reference, with planned contrasts; language and trial-type/context using sum coding). Maximal random-effects structures for participants and items were specified initially; when singularity or non-convergence occurred, random slopes were reduced stepwise while retaining random intercepts. Key interactions were followed up using Tukey-corrected post hoc tests.

2.5. Interbrain synchronization analysis

Phase-locking value (PLV) was used to quantify the consistency of cross-brain phase differences between the producer's and comprehender's EEG signals (Aydore et al., 2013; Lachaux et al., 1999; Mormann et al., 2005). Unlike amplitude-based association measures, PLV is calculated from the instantaneous phases of two band-limited signals and is therefore insensitive to their absolute amplitudes. For a given time window w, PLV was calculated as:

$$\mathrm{PLV} = \left| \frac{1}{Nw} \sum_{t=1}^{N} e^{i[\phi A(t) - \phi B(t)]} \right|$$

where ϕ_A (t) and ϕ_B (t) represent the instantaneous phases of signals from participants A and B at time t, respectively, and N_w is the number of samples within the analysis window. PLV ranges from 0 to 1, with larger values indicating greater consistency in the phase difference between

the two signals. Importantly, PLV is a statistical measure of cross-brain phase consistency and does not, by itself, identify the functional mechanism underlying that association. In the present task, elevated PLV may reflect interpersonal interaction, but it may also be influenced by shared stimulus timing, common auditory input, attentional entrainment, or other forms of task-related co-activation. We therefore use PLV descriptively as an index of interbrain phase synchronization and do not assume that higher PLV necessarily reflects more efficient interpersonal coordination.

During EEG preprocessing, signals were low-pass filtered at 50 Hz. Based on previous evidence linking alpha-band activity to affect-related attentional regulation and inhibitory processing (Codispoti et al., 2023; Compton et al., 2013) and gamma-band activity to affective salience and integrative processing (Balconi & Lucchiari, 2008; Dejean et al., 2017), two frequency bands were defined a priori: alpha (8–13 Hz) and gamma (30–50 Hz). For each band, the producer's and comprehender's signals were band-pass filtered using a finite impulse response filter. The analytic signal was then obtained using the Hilbert transform, and instantaneous phase was extracted as the angle of the analytic signal. PLV was calculated between each of the 39 retained electrodes from the producer and each of the 39 retained electrodes from the comprehender, yielding 1521 possible cross-brain electrode pairs for each dyad. Within each 2,000-ms epoch, PLV was estimated using 600-ms sliding windows advanced in 300-ms steps, resulting in 50% overlap between adjacent windows. The window-level estimates were averaged to obtain one PLV value for each dyad, experimental condition, frequency band, and electrode pair.

To estimate the level of phase locking expected after disruption of the original temporal correspondence between the two participants' signals, we generated 1000 surrogate PLV values for each dyad, experimental condition, frequency band, and cross-brain electrode pair. In each permutation, the temporal order of the samples in the producer's and comprehender's signals was independently randomized without replacement before band-pass filtering, Hilbert-based phase extraction, and PLV calculation. This procedure preserved the marginal distribution of signal values within each participant but disrupted the original temporal structure and between-participant temporal alignment. Because the temporal ordering of the samples was permuted, the original spectral structure was not preserved. The 1000 surrogate PLV estimates were averaged to obtain one mean surrogate PLV value for each dyad, condition, frequency band, and electrode pair.

For each frequency band and electrode pair, observed and mean surrogate PLV values were first averaged across all experimental conditions within each dyad. The resulting pooled observed and surrogate PLV values were then compared across dyads using paired-samples *t*-tests. To control for multiple electrode-pair comparisons, the resulting *p* values were corrected using the Benjamini–Hochberg false discovery rate procedure separately within the alpha and gamma bands. Electrode pairs for which pooled observed PLV did not significantly exceed pooled surrogate PLV after correction were excluded from the subsequent emotion-related analyses. This screening step was condition-blind and based exclusively on the EEG signals; neither emotion-related PLV differences nor RT or any other behavioral measure was used to define the eligible electrode-pair set.

The PLV analyses addressed two related questions. First, we examined whether cross-brain phase synchronization differed between the negative and neutral emotional states and between the positive and neutral emotional states. For each frequency band and electrode pair, PLV was modeled as a function of emotion using treatment coding, with neutral emotion specified as the reference level and dyad included as a random effect. The model therefore yielded two planned coefficients for each electrode pair: the negative-versus-neutral contrast and the positive-versus-neutral contrast. Emotion-sensitive electrode pairs were defined as pairs showing a significant effect in either contrast after multiple-comparison correction. Within each frequency band, the *p* values from all negative-versus-neutral and positive-versus-neutral electrode-pair tests were jointly corrected using the Benjamini–Hochberg false discovery rate (FDR) procedure, with $q < .05$ as the significance criterion (Benjamini & Hochberg, 1995; Jones et al., 2024). PLV values were subsequently averaged across the electrode pairs identified as emotion-sensitive within each frequency band to construct the PLV predictor used in the PLV–RT analyses.

Second, we examined whether the association between PLV and RT differed across emotional states. Within each frequency band, PLV values were averaged across the electrode pairs identified as emotion-sensitive and then grand-mean centered before entering the trial-level mixed-effects models of log-transformed RT. Electrode-pair identification was based exclusively on emotion-related PLV differences and did not incorporate RT or any other behavioral outcome. Thus, behavioral performance was not used to define the neural predictor. Nevertheless, because the aggregated PLV predictor was constructed from electrode pairs selected partly on the basis of emotion-related PLV effects, we additionally examined whether the PLV–RT findings depended on this feature-selection procedure.

Two sets of mixed-effects models were fitted separately for producers and comprehenders and for the alpha and gamma bands. The switching model included emotion, language, trial type, centered PLV, and all interactions among these four predictors. The mixing model included emotion, language, context, centered PLV, and all interactions among these four predictors. Participant and item were included as random effects, consistent with the corresponding behavioral RT models.

The focal test in each model was a two-degree-of-freedom omnibus test of the emotion × PLV interaction. This test was based on the marginal PLV slopes for the three emotional states, averaged over the other experimental factors, and assessed whether the PLV–RT association differed across negative, neutral, and positive emotion. Emotion-specific PLV slopes and pairwise differences between slopes were estimated for each model, with inferential interpretation focused primarily on models showing a significant omnibus emotion × PLV interaction. Tests of the three emotion-specific slopes were Šidák-adjusted within each model (Müller & Lindenberger, 2026; Šidák, 1967; Van Drunen et al., 2024), whereas pairwise comparisons among the emotion-specific slopes were Tukey-adjusted (Chung-Fat-Yim et al., 2025; Tukey, 1949). These adjustments controlled the follow-up comparisons within an individual fitted model and were distinct from the electrode-level FDR correction used to identify emotion-sensitive electrode pairs.

The 8 omnibus emotion × PLV tests represented the prespecified combinations of role (producer vs. comprehender), frequency band (alpha vs. gamma), and behavioral analysis (switching vs. mixing). No additional correction was applied across these eight model-level tests. Results with $p \geq .05$ were treated as non-significant rather than as marginally significant.

To assess whether the PLV–RT findings depended on emotion-based electrode-pair selection, we conducted an additional emotion-blind all-pairs sensitivity analysis. For each frequency band—alpha (8–13 Hz) and gamma (30–50 Hz)—PLV was averaged across all 1521 cross-brain electrode pairs for every dyad and experimental condition. The same complete electrode-pair set was used for negative, neutral, and positive emotion, and neither behavioral performance nor emotion-related PLV effects contributed to construction of this predictor. The resulting all-pairs PLV measure was grand-mean centered and entered into the same switching and mixing models, with identical RT exclusions and fixed- and random-effects specifications. Full methods and results for this sensitivity analysis are reported in the Supplementary Materials.

3. Results

3.1. Behavioral results

3.1.1. Production RTs

Using neutral state as the baseline ($M = 763.88 \pm 176$ ms), both positive ($M = 757 \pm 177$ ms; $\beta = -.01$, $t = -2.65$, $p = .008$) and

negative emotional states ($M = 756 \pm 173$ ms; $\beta = .01$, $t = 2.44$, $p = .015$) yielded faster naming RTs, with no difference between the two emotional states ($\beta = 0.001$, $t = -0.22$, $p = .825$). However, no significant emotion-modulated RLDE or switch costs were detected (all interactions between Emotion and Language or Trial type ns).

For the mixing model, Negative × Context ($\beta = 0.02$, $t = 2.22$, $p = .027$) and Positive × Context ($\beta = -0.02$, $t = -2.09$, $p = .037$) interactions indicated reduced mixing costs under both negative and positive states relative to neutral state. Follow-up comparisons showed that the reduction in mixing costs under negative and positive states relative to neutral state was primarily attributed to nonswitch trials in mixed-language block. Specifically, in single-language blocked trials, no significant differences in RTs were observed across the three emotional states ($|t|$s < 0.52, $ps > .911$). However, within mixed-block nonswitch trials, both positive ($M = 758 \pm 178$ ms) and negative ($M = 753 \pm 170$ ms) emotional states elicited significantly faster RTs compared to the neutral state ($M = 766 \pm 172$ ms; Negative vs. Neutral: $\beta = -0.02$, $t = -3.02$, $p = .008$; Positive vs. Neutral: $\beta = 0.01$, $t = 2.42$, $p = .023$).

To investigate the potential language-specific differences in how positive and negative states modulate mixing cost reduction, additional comparisons were conducted. Results showed that this emotion-related mixing benefit was mainly L2-driven: only neutral showed an L2 mixing cost ($\beta = -0.04$, $t = -4.28$, $p < .001$), with slower responses for L2 nonswitch trials ($M = 753 \pm 166$ ms) compared to single-L2 trials ($M = 718 \pm 154$ ms). In contrast, positive and negative emotional states statistically abolished L2 mixing costs ($|t|$s < 1.00, $ps > .316$). L1 mixing costs remained robust across all emotional states ($|t|$s > 8.85, $ps < .001$), with slower L1 nonswitch RTs in mixed blocks (positive: $M = 772 \pm 187$ ms; neutral: $M = 781 \pm 177$ ms; negative: $M = 773 \pm 179$ ms) than in single-L1 blocks (positive: $M = 722 \pm 154$ ms; neutral: $M = 729 \pm 158$ ms; negative: $M = 726 \pm 159$ ms) Fig. 2a.

3.1.2. Comprehension RTs

In comprehension, statistical analyses revealed a significant omnibus effect of Emotion: relative to neutral state ($M = 537 \pm 249$ ms), responses were faster in both positive ($M = 528 \pm 259$ ms; $\beta = -0.02$, $t = -3.04$, $p = .002$) and negative ($M = 523 \pm 253$ ms; $\beta = 0.03$, $t = 4.39$, $p < .001$) emotional states. No significant difference in RTs emerged between positive and negative states ($\beta = -0.01$, $t = -1.33$, $p = .37$). The switching model yielded no reliable emotion-related interactions ($ps > .21$), indicating that emotion did not modulate switch costs or RLDE in comprehension.

The mixing model revealed a significant two-way Context × Language interaction ($\beta = -0.04$, $t = -2.77$, $p = .006$) and a three-way Context × Language × Positive interaction ($\beta = 0.09$, $t = 2.48$, $p = .013$), suggesting emotion-specific modulation of asymmetric mixing costs. Follow-up comparisons indicated that, in L1, the mixing cost was robust under neutral ($M = 65 \pm 77$ ms; $\beta = -0.09$, $t = -5.30$, $p < .001$) but was attenuated in the positive state ($M = 40 \pm 84$ ms; $\beta = -0.02$, $t = -1.03$, $p = .304$). No comparable positive benefit emerged for L2, as L2 mixing costs were non-significant under both neutral and positive states ($|t|$s < 1.54, $ps > .124$). Finally, negative emotion did not differ reliably from either neutral or positive in mixing-cost magnitude ($|t|$s < 1.52, $ps > .127$) Fig. 2b.

3.2. Emotional modulation of interbrain synchronization

As illustrated in Fig. 3a, using the neutral state as the baseline, we observed distinct emotion-driven alpha-band PLV modulations. Negative state exhibited enhanced synchronization in 39 electrode pairs but reduced synchronization in 55 pairs compared to neutral. Positive state showed increased synchronization in 43 pairs versus decreased synchronization in 22 pairs. Spatially, negative-enhanced synchronization was broadly distributed over the comprehender's posterior regions (central-parietal, parietal, and parietal-occipital areas), whereas

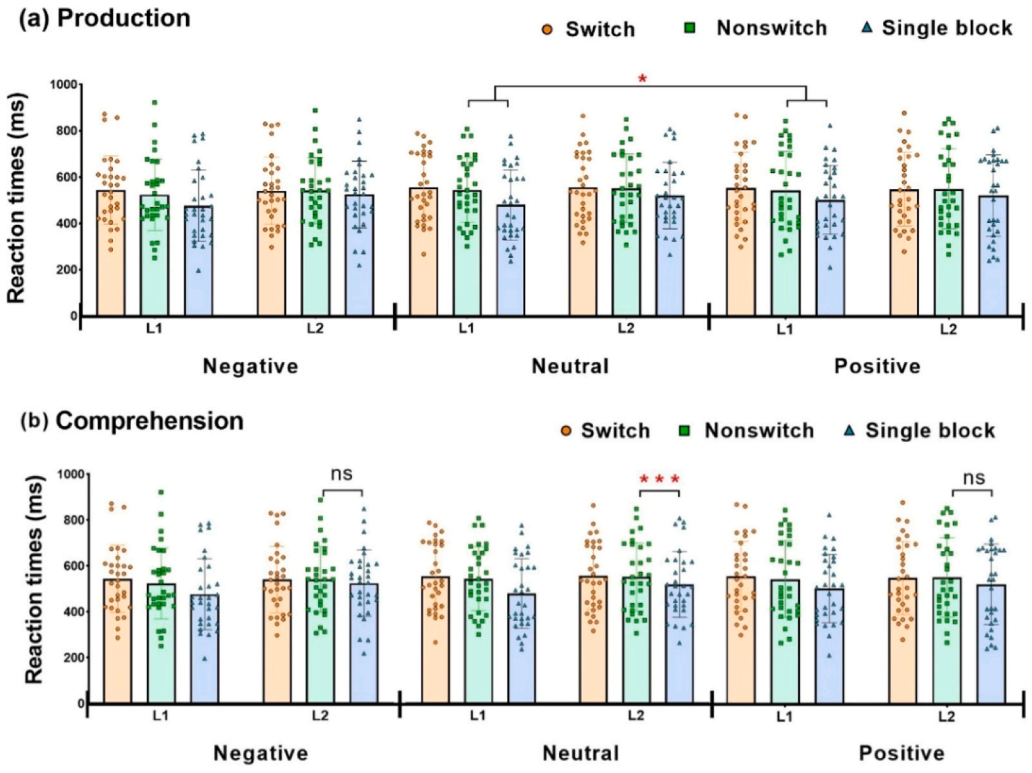


Fig. 2. Estimated reaction times per Language (L1, L2), emotional states (negative, neutral, positive), and Trial type for the mixed-language and single-language blocks in Production (a) and Comprehension (b). Dots represent individual participants, and vertical bars indicate the standard error of the mean (SEM). Orange circles represent switch trials in mixed-language blocks, green squares represent non-switch trials in mixed-language blocks, and blue triangles represent single-language trials (including both single-L1 and single-L2 conditions) in pure blocks.

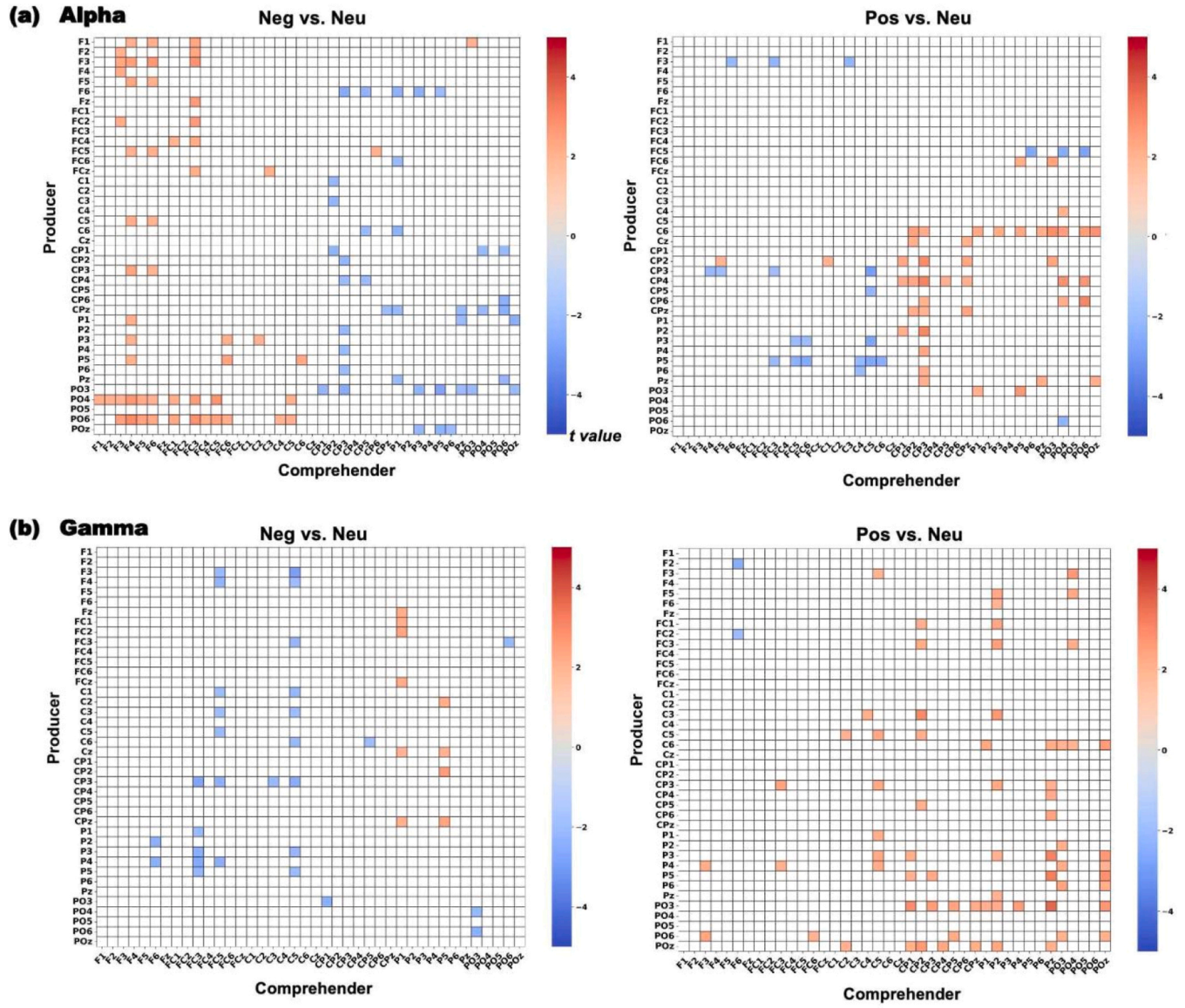


Fig. 3. Interbrain synchronization modulation by emotional states in alpha (a) and gamma (b) bands. Colored nodes represent significant electrode pairs ($p < 0.05$, FDR-corrected) under negative emotional state (left) and positive emotional state (right). Non-significant pairs are shown in white. Color gradients encode t-values from linear models. Blue nodes represent higher synchronization in negative state but smaller synchronization in the positive state (relative to neutral state), whereas the red nodes vice versa.

positive-enhanced synchronization selectively coupled the producer's and comprehender's posterior cortices.

The gamma-band analysis revealed asymmetric emotion effects: the negative state reduced interbrain synchronization in 10 electrode pairs relative to neutral but enhanced synchronization in 29 pairs, whereas positive emotion increased synchronization in 68 pairs with only 2 pairs showing decreased coupling. Spatially, negative-enhanced synchronization localized to parietal electrodes in comprehenders, while positive state broadly augmented dyadic synchronization across posterior cortices of both partners (see Fig. 3b).

3.3. Synchronization-behavior coupling

To examine whether PLV–behavior associations varied across emotional states, we separately aggregated PLV values across emotion-sensitive electrode pairs in the alpha and gamma bands. The resulting measures were mean-centered and entered as predictors into separate linear mixed-effects models of production and comprehension RTs. The analyses revealed emotion-dependent differences in the relationship between PLV and behavioral performance across the two roles.

3.3.1. Alpha synchronization (8–13 Hz): production

As illustrated in Fig. 4a, under the neutral state, higher PLV was significantly associated with longer RTs on nonswitch trials ($\beta = 0.36$, $z = 2.48$, $p = .013$), whereas the corresponding association on switch trials was non-significant ($\beta = 0.25$, $z = 1.77$, $p = .076$), indicating that stronger interbrain alpha synchronization predicted longer naming RTs. In contrast, negative state showed inverse trends (albeit nonsignificant for nonswitch trials, $\beta = -0.21$, $z = -1.34$, $p = .181$), where enhanced negative-driven synchronization accelerated switch trial RTs ($\beta = -0.48$, $z = -3.83$, $p < .001$). Specifically, each 1-unit increase in PLV during negative state significantly reduced log-transformed RTs by 0.48 units in switch trials. However, positive state induced a dual pattern: higher PLV prolonged RTs for switch trials but facilitated responses in nonswitch trials, suggesting emotion-dependent gating of synchronization effects by task demands. Furthermore, stronger synchronization

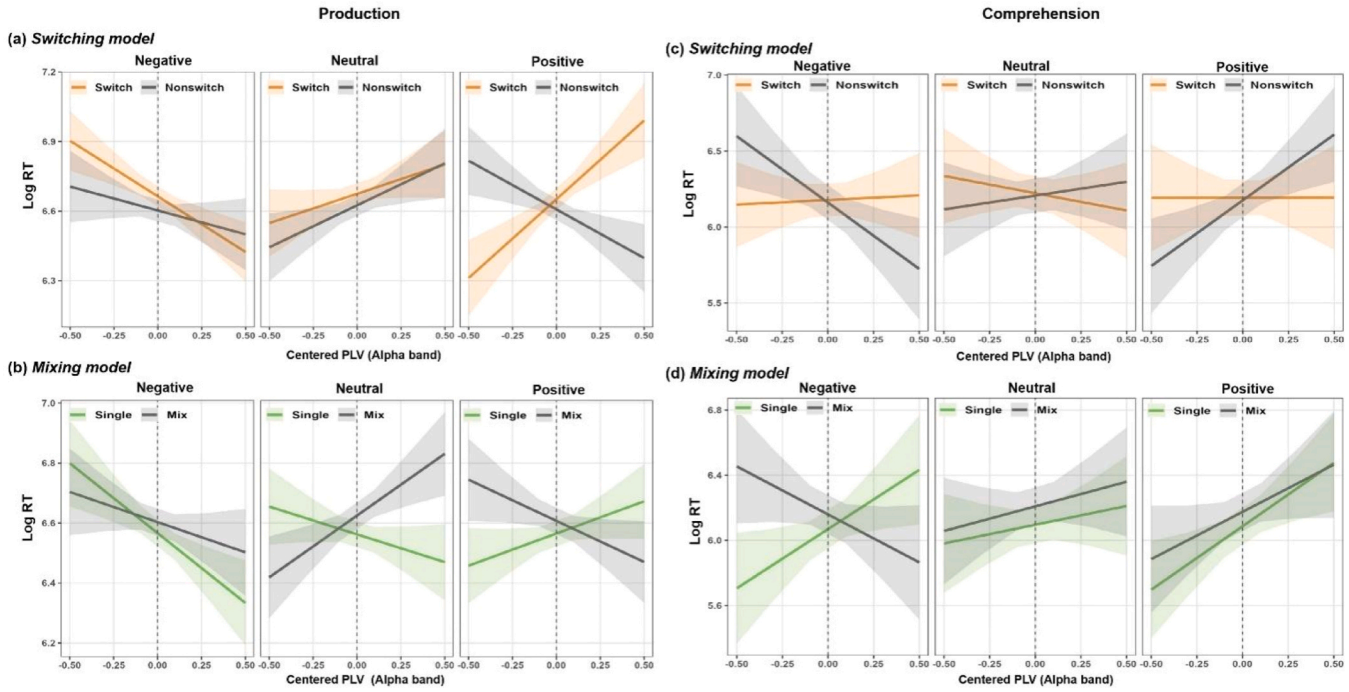


Fig. 4. The alpha interbrain synchronization effect on RTs (Log-transformed) across three emotional states. The interaction effect between centered PLV, emotional state and trial type in switching model for production (a) and comprehension (c). The interaction effect between centered PLV, emotional state and context in mixing model for production (b) and comprehension (d).

predicted larger L1 switch costs in the positive state ($\beta = 1.10$, $z = 5.24$, $p < .001$), while neutral and negative states showed no such association ($|z|$s < 1.41, $ps > .724$).

On the other hand, the mixing model also revealed divergent emotion-modulated PLV-RT relationships (Fig. 4b). Negative state maintained its characteristic inverse PLV-RT relationship, with enhanced synchronization accelerating responses in single-language trials ($\beta = -0.47$, $z = -3.32$, $p < .001$) despite nonsignificant mixed-context effects ($\beta = -0.20$, $z = -1.41$, $p = .159$). Interbrain synchronization in neutral state selectively prolonged RTs in mixed-context nonswitch trials ($\beta = 0.41$, $z = 3.03$, $p = .002$) while showing opposite (nonsignificant) trends in single-language contexts ($\beta = -0.19$, $z = -1.49$, $p = .137$). Critically, the higher alpha synchronization predicted larger mixing costs in neutral state ($\beta = -0.60$, $z = -3.36$, $p = .010$) (Fig. 5a). Notably, the synchronization-mixing cost linkage was absent under both positive and negative states ($|z|$s < 0.49, $ps > .059$), highlighting emotion-specific neurobehavioral coupling mechanisms. Positive state again exhibited dissociations, with higher synchronization reducing nonswitch trial RTs ($\beta = -0.28$, $z = -2.04$, $p = .041$) but showing no single-language effects ($\beta = 0.22$, $z = 1.76$, $p = .078$).

3.3.2. Alpha synchronization (8–13 Hz): comprehension

As shown in Fig. 4c, the switching model revealed no significant effects of alpha synchronization in neutral state on either trial type, nor did positive or negative states-modulated alpha synchronization predict switch trial RTs ($|z|$s < 0.23, $ps > .456$). Significant emotion-dependent dissociations were observed specifically for nonswitch trials. Under negative state, increased alpha-band synchronization was associated with shorter RTs ($\beta = -0.87$, $z = -2.69$, $p = .007$), replicating the pattern observed in production. Conversely, positive state showed a positive relationship, with higher synchronization correlating with longer RTs ($\beta = 0.87$, $z = 2.86$, $p = .004$), consistent with production modality findings.

The mixing model analysis demonstrated more complex patterns (Fig. 4d). Alpha synchronization in the neutral state no longer significantly predicted RTs for nonswitch trials in either linguistic context (all $ps > .348$). Under positive state, enhanced alpha synchronization was consistently associated with prolonged RTs in the single-language ($\beta = 0.78$, $z = 2.73$, $p = .006$) context, whereas the corresponding association in the mixed context was non-significant ($\beta = 0.58$, $z = 1.82$, $p = .069$). Moreover, context-specific relationships emerged in the negative state: in single-language contexts, higher alpha

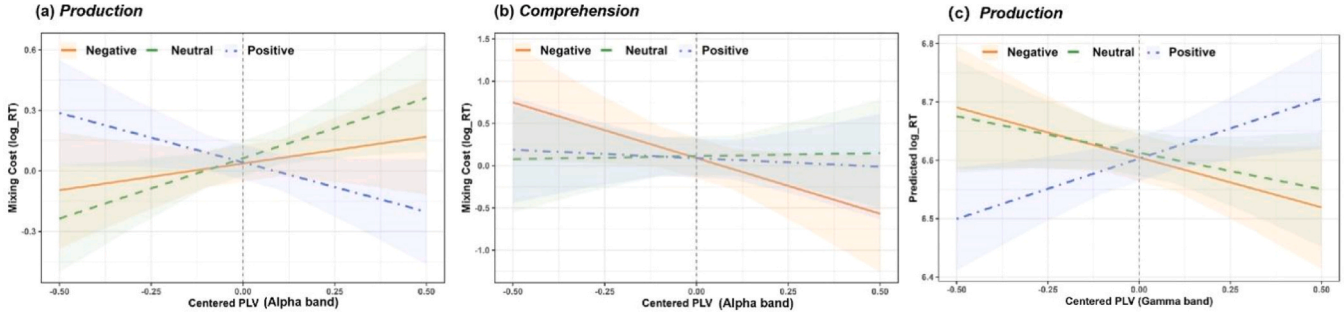


Fig. 5. The alpha interbrain synchronization effect on mixing costs in RTs (Log-transformed) in production (a) and comprehension (b) across three emotional states. The gamma synchronization effect on producer's RTs (Log-transformed) across three emotion states (c).

synchronization was associated with longer RTs ($\beta = 0.73$, $z = 2.20$, $p = .028$), contrasting with the pattern observed in production. No significant PLV–RT association was observed in the mixed context under the negative state ($\beta = -0.59$, $z = -1.72$, $p = .085$). As illustrated in Fig. 5b, the association between alpha PLV and mixing cost under the negative state was non-significant ($\beta = 1.32$, $z = 2.79$, $p = .059$).

3.3.3. Gamma synchronization (30–50 Hz): production

Analysis of gamma-band synchronization only revealed emotion-specific modulation patterns without trial type or context specificity. As illustrated in Fig. 5c, enhanced gamma synchronization under the positive state was associated with slower naming responses in producers ($\beta = 0.21$, $z = 2.58$, $p = .011$). In contrast, both negative and neutral emotional states showed non-significant inverse trends (negative: $\beta = -0.17$, $z = -1.69$, $p = .090$; neutral: $\beta = -0.13$, $z = -1.35$, $p = .177$).

3.3.4. Gamma synchronization (30–50 Hz): comprehension

The analysis revealed significant predictive effects of gamma-band synchronization in comprehension. In the switching model, nonswitch trials consistently demonstrated positive correlations between gamma synchronization and RTs across all three emotional states (neutral: $\beta = 1.11$, $z = 3.53$, $p < .001$; positive: $\beta = 0.86$, $z = 2.91$, $p < .001$; negative: $\beta = 1.36$, $z = 3.64$, $p < .001$), indicating that this synchronization-RT relationship remained stable regardless of emotional modulation (Fig. 6a). However, switch trials revealed emotion-dependent patterns: the neutral state showed positive associations ($\beta = 1.46$, $z = 3.37$, $p < .001$), negative state displayed inverse relationships ($\beta = -1.00$, $z = -2.36$, $p = .018$), while positive state showed no significant effects ($\beta = 0.14$, $z = 0.49$, $p = .624$). Furthermore, stronger synchronization in the negative state predicted smaller L1 switch costs ($\beta = -4.25$, $z = -4.97$, $p < .001$), while neutral and positive states showed no such association ($|z|$s < 2.28, ps $> .488$) (Fig. 6b).

The mixing model demonstrated more consistent positive predictive effects across emotional states (Fig. 6c). Under neutral state, enhanced interbrain synchronization correlated with longer RTs in both single-language ($\beta = 0.75$, $z = 2.081$, $p = .037$) and mixed contexts ($\beta = 0.84$, $z = 2.55$, $p = .011$). Negative state showed significant effects only in single-language contexts ($\beta = 2.23$, $z = 5.71$, $p < .001$), while the positive state exhibited no significant predictions in either context (all ps $> .337$). Moreover, stronger synchronization in the negative state predicted smaller L2 mixing costs ($\beta = 2.97$, $z = 4.35$, $p < .001$) (Fig. 6d), whereas no significant associations were found in the neutral ($\beta = 0.33$, $z = 0.46$, $p = 1.000$), or positive states ($\beta = -2.18$, $z = -3.18$, $p = .066$).

Table 1 summarizes the emotion-dependent PLV–RT associations across production and comprehension. Overall, PLV–RT associations varied across emotional states, frequency bands, and switching versus mixing contrasts, indicating that the behavioral relevance of interbrain PLV was not uniform. Analyses based on derived cost measures were broadly consistent with these slope patterns: stronger synchronization was associated with smaller L1 switch costs and smaller L2 mixing costs under negative emotion, whereas comparable cost-level associations were weaker or absent under neutral and positive emotion.

4. Discussion

The present study examined whether induced emotional states altered the association between interbrain synchronization and behavioral performance during a controlled dyadic bilingual task. Three main findings emerged. First, both negative and positive emotional states were associated with faster overall responses than the neutral state in production and comprehension. In production, both emotional states also reduced mixing costs, whereas in comprehension the mixing-cost reduction was limited to the positive state and was primarily observed in L1. Switch costs were not reliably modulated by emotion. Second, PLV–RT associations differed across emotional states. Under neutral emotion, stronger PLV was often associated with slower responses, whereas several corresponding associations were more negative under the negative condition. Third, the positive condition produced a more heterogeneous pattern across roles, frequency bands, and task contrasts. The clearest and most robust condition difference was observed for producer alpha PLV, for which the slope was more negative under

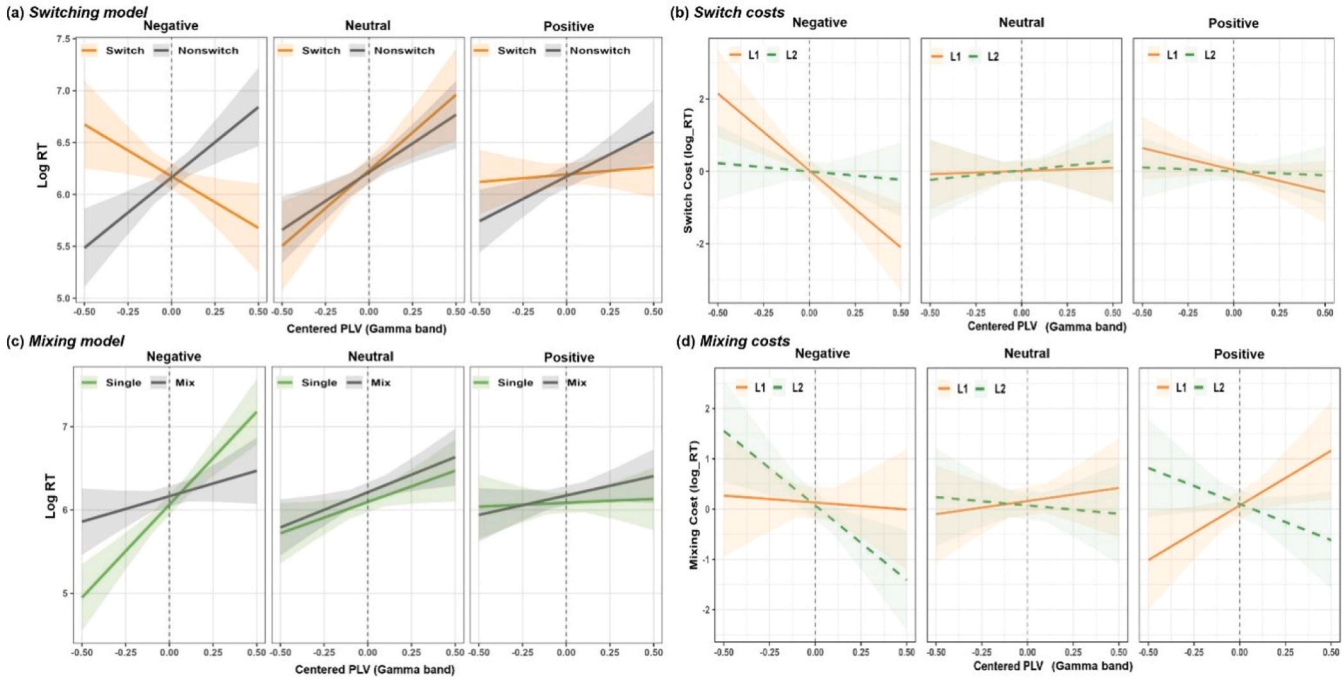


Fig. 6. The gamma interbrain synchronization effect on comprehender's RTs (Log-transformed) across three emotional states. The interaction effect between centered PLV, emotional state and trial type in switching model on RTs (a) and switch costs (b). The interaction effect between centered PLV, emotional state and context in mixing model on RTs (c) and mixing costs (d).

Table 1
The relationship between interbrain synchronization and RTs across Production and Comprehension.

	Language Production	*Language Comprehension*
Alpha synchronization		
Emotion × PLV	Neg (-); Neu (+); Pos (ns)	Nonswitch: Neg (-); Neu (ns); Pos (+)
Language × Type × Emotion × PLV	L1 switch cost: Pos (+)	Switch costs: ns
Context × Emotion × PLV	Mixing costs: Neu (+), Pos (-)†	Mixing costs: Neg (-)†
Gamma synchronization		
Emotion × PLV	Neg (-)†; Neu (ns); Pos (+)	Neg (ns); Neu (+); Pos (+)
Language × Type × Emotion × PLV	Switch costs: ns	L1 switch cost: Neg (-)
Language × Context × Emotion × PLV	Mixing costs: ns	L2 mixing cost: Neg (-)

Note: '-' represents the significantly negative relationship in the emotional states, while ' + ' indicates a significantly positive relationship surviving from the Tukey correction. Neg = Negative state; Neu = Neutral state; Pos = Positive state.

negative than neutral emotion and was partially reproduced in the emotion-blind all-pairs sensitivity analysis.

These findings indicate that the association between interbrain phase synchronization and bilingual performance was not uniform across emotional states. Importantly, PLV is a correlational and functionally nonspecific measure. The present results therefore do not establish that stronger synchronization directly caused either greater coordination demand or more efficient interpersonal coordination. Instead, they show that emotional state moderated how cross-brain phase consistency covaried with individual behavioral performance.

4.1. PLV–behavior associations under neutral and negative emotion

Under neutral emotion, stronger alpha PLV was associated with slower production responses in mixed-context nonswitch trials and with larger mixing costs. In comprehension, stronger gamma PLV was similarly associated with slower responses across several task conditions. These positive slopes indicate that greater cross-brain phase consistency covaried with slower behavioral performance under the neutral condition.

One possible explanation is that stronger PLV accompanied greater shared monitoring or compensatory engagement when coordination was more demanding. Kurihara et al. (2022), for example, found that interbrain synchronization increased when interpersonal tapping became less stable, suggesting that stronger coupling can accompany greater effort to maintain coordination rather than better performance itself. In the present task, dyads with slower responses may likewise have engaged more strongly with the shared production–comprehension structure.

However, shared monitoring cannot be separated from common sensory and temporal input in the present design. Producer and comprehender followed the same trial sequence and event timing, and the comprehender heard the producer's spoken response on every trial. Speaker–listener synchronization can partly arise from speech-related neural entrainment (Pérez et al., 2017), while time-locked task events can provide a common temporal basis for synchronization even when coupling also varies with social engagement or performance (Reinero et al., 2021). The neutral-state associations may therefore reflect a combination of shared task timing, auditory processing, attentional entrainment, partner monitoring, and interpersonal coordination. Because RT indexed individual performance rather than the quality or stability of dyadic coordination itself, the most direct conclusion is that stronger PLV was associated with slower responding under neutral emotion.

Relative to the neutral state, the negative state produced more negative PLV–RT associations in several analyses. In the alpha band, stronger synchronization under negative emotion was associated with faster production responses on switch trials and faster comprehension responses on nonswitch trials. In the gamma band, stronger synchronization was also associated with smaller L1 swtich costs and smaller L2 mixing costs in comprehension. These patterns indicate that greater cross-brain phase consistency was associated with more favorable behavioral performance under the negative than the neutral condition

This difference is compatible with the possibility that the negative state altered how shared attention, temporal prediction, or partner monitoring covaried with performance. Negative emotion may also have changed vigilance, motivational intensity, response variability, or sensitivity to task cues, any of which could affect both PLV and RT. The results therefore do not demonstrate that synchronization became intrinsically more efficient or more task focused under negative emotion. They instead show that the direction of the PLV–behavior association differed between the negative and neutral conditions.

Experimental stimulation studies show that manipulating cross-brain phase relationships can affect joint behavior, but these effects are highly specific. In-phase 20 Hz dual-brain stimulation improved the initiation, but not the later maintenance, of synchronized tapping (Novembre et al., 2017). In-phase 6 Hz stimulation enhanced interpersonal learning in another study, with spontaneous movement synchrony partially mediating the behavioral effect (Pan et al., 2021). In contrast, Szymanski et al. (2017) found that active hyper-tACS reduced dyadic drumming synchrony relative to sham and noted that neural entrainment was not directly verified. These mixed findings caution against inferring from the present correlational PLV results that stronger synchronization caused faster bilingual performance.

The emotion-blind all-pairs sensitivity analysis provided partial support for the producer alpha finding. In both the switching and mixing models, the PLV–RT slope was significantly more negative under negative than neutral emotion. However, the positive neutral slope observed in the emotion-sensitive-pair analysis was not consistently reproduced, and the corresponding pattern was not uniformly observed for comprehenders or in the gamma band. The findings therefore support a condition-dependent difference in the PLV–RT association, rather than a general shift from costly to efficient coordination.

4.2. Heterogeneous PLV–RT associations under positive emotion

The positive state produced a less consistent pattern. In the alpha band, stronger PLV was associated with slower production responses on switch trials but faster responses on nonswitch trials, resulting in a larger estimated switch cost. In comprehension, stronger alpha PLV was associated with slower nonswitch responses, in the opposite direction to the corresponding negative-state association. Gamma-band associations were more limited and also differed across production and comprehension.

These results do not indicate that positive emotion uniformly facilitated or disrupted interpersonal coordination. Positive emotion shortened mean RTs relative to neutral emotion, but this overall facilitation was not accompanied by a consistently more favorable PLV–RT relationship. Mean behavioral performance and PLV–behavior covariance may therefore reflect partly different aspects of task processing. Faster responses could arise largely from changes within each participant, while PLV remained sensitive to shared timing, auditory entrainment, partner monitoring, or other interpersonal processes.

A broader and more flexible attentional mode provides one possible

account of the variable associations under positive emotion (Dreisbach & Goschke, 2004; Fredrickson et al., 2003). Such a state could support overall response speed while reducing the consistency with which neural alignment tracked specific control demands. However, this interpretation is post hoc. Positive emotion has also been associated with stronger interbrain synchronization and better coordination in other cooperative tasks (Y. Li et al., 2022), suggesting that its relationship with interbrain synchronization depends on the task, behavioral measure, and neural index under examination. The present findings therefore support a heterogeneous, condition-dependent pattern rather than a general claim that positive emotion either improved or impaired dyadic neural coordination.

4.3. Frequency-band patterns and role-specific patterns

Alpha- and gamma-band PLV both showed emotion-dependent associations with behavior, but their profiles were not identical. Alpha effects were observed in both production and comprehension, and the clearest negative–neutral difference occurred in producer alpha PLV. Gamma effects were more role- and condition-specific. In comprehension, positive PLV–RT associations were observed across several non-switch conditions, whereas stronger condition differences emerged for switch and mixing contrasts. Gamma findings in production were more limited.

These frequency-specific patterns should be interpreted descriptively. Within-brain alpha activity has been associated with attentional gating and functional inhibition (Jensen & Mazaheri, 2010; Klimesch, 2012), whereas gamma activity has been linked to salience detection and integrative processing (Garcia-Garcia et al., 2010; Matsumoto et al., 2006). Cross-brain PLV in the same frequency ranges does not necessarily inherit these functional interpretations. The present results therefore do not demonstrate that alpha and gamma PLV implement distinct interpersonal control mechanisms. They show only that emotion-dependent PLV–behavior associations differed across frequency bands and interlocutor roles.

The role differences are also theoretically informative. Producers selected and articulated the target language, whereas comprehenders monitored the producer's output and made an animacy judgment. Although both partners shared the same task timing and communicative sequence, their control requirements were not identical. Variation across production and comprehension is therefore expected and argues against treating interbrain synchronization as a single, role-independent index of shared control. The most defensible conclusion is therefore associative: the relationship between PLV and behavioral performance varied across the induced emotional states, with the clearest negative–neutral difference appearing in producer alpha PLV. These findings do not establish that stronger PLV caused more efficient coordination or that the observed differences were uniquely driven by emotional valence.

4.4. Implications for dyadic bilingual control

The present findings have several implications for theories of bilingual language control and interpersonal coordination.

First, the results suggest that transient emotional states may influence how the control demands described by the Adaptive Control Hypothesis are expressed within a dual-language context (ACH; Green & Abutalebi, 2013). The emotional manipulation should not be treated as an additional interactional context in the ACH, and a brief induction cannot demonstrate long-term adaptation. Instead, the language environment may establish recurrent demands on goal maintenance, interference control, monitoring, and task engagement, while the current emotional state influences how these demands are reflected in behavior and dyadic neural activity. Emotional state may therefore operate as a proximal influence nested within the broader interactional context.

The language-specific mixing-cost results provide some indication of which aspects of control may have been affected. In production, L2 mixing costs were no longer reliable under either negative or positive emotion, whereas L1 mixing costs remained present. This pattern suggests that emotional facilitation did not reduce bilingual control demands uniformly across languages. One possible explanation is that the induced emotional states changed preparation or contextual monitoring for the less dominant language. However, the present data cannot distinguish these processes from changes in language activation, response selection, or general task readiness. The persistent L1 mixing cost should likewise not be treated as direct evidence of inhibition. In comprehension, the mixing-cost reduction was more restricted, occurring primarily for L1 under positive emotion, further indicating that emotional effects depended on both language and interlocutor role.

Second, the results support a view of bilingual control that extends beyond language selection by an isolated speaker. Previous joint-switching research has shown that language produced by one person can influence the subsequent control processes of another person (Gambi & Hartsuiker, 2016). Hyperscanning research has further associated language-control demands during cross-language communication with synchronization between speakers and listeners (H. Liu et al., 2019). In the present study, PLV–RT associations were observed in both production and comprehension, although their direction and consistency varied across emotional states and task conditions.

These findings suggest that control in a dyadic bilingual task involves at least partly distinct processes for the two interlocutors. Producers must select and produce the target language, whereas comprehenders must monitor the producer's output, identify the spoken language, and prepare an appropriate response. A dyadic account should therefore distinguish self-language selection from partner-language monitoring and from the temporal coordination imposed by the shared task. The findings do not establish that the same language-control operation was literally shared across two brains. Rather, they show that dyad-level phase coupling covaried with individual performance in a manner that depended on emotional state and interlocutor role.

Finally, the findings distinguish the magnitude of interbrain synchronization from its behavioral association. Negative and positive emotion both facilitated overall behavioral performance relative to neutral emotion, but they produced different PLV–RT patterns. Thus, neither stronger PLV nor faster mean responding has a fixed theoretical meaning when considered in isolation. Models of dyadic bilingual control should specify the emotional state, task demand, interlocutor role, and frequency band under which neural coupling is associated with behavioral performance.

4.5. Limitations and future directions

Several limitations should be noted. First, the controlled task did not capture the full dynamics of natural bilingual conversation. Producer and comprehender roles remained fixed, language choices were externally cued, and the comprehender performed an animacy judgment rather than engaging in spontaneous language selection. The constrained response sequence also lacked reciprocal turn-taking and real-time negotiation of language choice. In addition, emotion was induced at the block level, which captured a sustained affective context but not the rapid emotional fluctuations that may occur during natural dialog. Future studies should examine whether the observed PLV–behavior patterns generalize to more interactive settings with role alternation, spontaneous language choice, and continuous measures of emotional change.

Second, PLV measures phase consistency but does not indicate the direction of influence between partners. It remains unclear whether emotional state changes which partner leads the interaction or whether information flow is bidirectional. Directed connectivity methods, such as Granger causality or transfer entropy, could clarify this issue. Third, the present design did not independently manipulate emotional valence and arousal. Consequently, differences among the negative, neutral, and

positive conditions cannot be attributed specifically to valence, arousal, or their interaction. Future studies could use an orthogonal manipulation of valence and arousal to clarify which affective dimension drives changes in interbrain synchronization and its association with behavioral performance. Finally, the sample comprised intermediate Chinese–English bilinguals with limited naturalistic code-switching experience. Whether the emotion-dependent PLV–behavior patterns observed here extend to highly proficient bilinguals or communities with habitual interactional switching remains an open question.

5. Conclusion

The present study shows that emotional state moderates the association between interbrain synchronization and behavioral performance during dyadic bilingual production and comprehension. Under neutral emotion, stronger PLV was generally associated with slower responses, whereas several corresponding associations were more negative under the negative condition. The positive condition produced a more heterogeneous pattern across roles, frequency bands, and task contrasts. These findings indicate that emotional context shapes how cross-brain phase consistency covaries with bilingual performance.

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CRediT authorship contribution statement

Shuang Liu: Methodology, Investigation, Data curation. **Dongxue Liu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xiaoxuan Li:** Data curation. **Shutong Lv:** Data curation. **Junjun Huang:** Data curation. **Baoguo Chen:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Lu Jiao:** Resources.

Declaration of Generative AI and AI-assisted technologies in the writing process

Statement: The author(s) did not use generative AI technologies for preparation of this work.

Declaration of Competing Interest

We have no known conflict of interest to disclose.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2026.109371.

Data availability

Data and analysis scripts: primary data and all analysis scripts are publicly available (Retrieved from osf.io/tmy8z)

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