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Negative Emotions Disrupt Intentional Synchronization During Group Sensorimotor Interaction

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Emotions play a fundamental role in human interactions and trigger responses in physiological, psychological, and behavioral modalities. Interpersonal coordination often entails attunement between individuals in various modalities. Previous research has elucidated the mechanisms of interpersonal synchronization and the emotions aroused by joint action: cardiac activity aligns in disputing marital couples, spectators share enjoyment in observing live dance performances, and joint finger-tapping evokes positive emotions. However, little is known about the impact of emotions on intentional interpersonal synchronization. To address this problem, we conducted an experiment in 2022 asking 60 participants to engage in a three-way finger-tapping synchronization task. We systematically induced emotional states (positive, neutral, and negative) with social comparison feedback using success–failure manipulations. An analysis of behavior synchronization using the Kuramoto order parameter revealed that negative emotion induction significantly diminished time spent in synchrony compared to positive induction. Moreover, the results exposed incremental struggles in attaining higher levels of synchronization (Q2–Q3) after the induction of negative emotions. These outcomes further substantiate the necessity of integrating the indices of agents' emotions into interpersonal synchronization and coordination models. We discuss the implications of this work for research on interpersonal emotion in joint action and applied outcomes in emotion-aware technologies and interventions.

Keywords: emotion, interpersonal synchronization, joint action, Kuramoto order parameter

In the course of biological and cultural evolution, emotions have become an instrument for social attunement. Negative emotions indicate animosity and lead to withdrawal from undesired interactions with extraneous groups (Rozin et al., 2009). In fact, the human brain is hardwired for the Us/Them dichotomy (i.e., distinguishing

between people of their kind and others), and negative emotions are fundamental in widening the gap between Us and Them (Sapolsky, 2017). There is some evidence that negative emotions can be beneficial. For instance, Lerner and Tiedens (2006) suggest that anger can facilitate decision-making to achieve desired outcomes by overcoming hesitation and overanalyzing. Moreover, people seek to increase anger as an instrumental emotion to improve individual performance in a confrontational context (Tamir et al., 2008). The key issue is that negative emotions are not inherently dysfunctional but can sometimes induce functional behaviors adapted to the specific context (Parrott, 2001). Positive emotions, in turn, act as a social glue. Adopting postures and behavior has the adaptive value of strengthening the affiliation with others, its allure, which ultimately leads to the improvement of evolutionary fitness (Lakin et al., 2003). Evolution reinforced congruent interpersonal behavior with pleasant sensations since imitating the movements of a person from the Us category activates the dopaminergic system (Losin et al., 2012). Considerable research efforts have been dedicated to investigating the influence of emotions on individual cognitive processes and behavioral responses.

However, emotions are triggered by an event in a person's environment, where interactions with other people play a key role. Some theoretical models are shifting the paradigm for emotion researchers from intraindividual study to an interpersonal realm. For instance, the temporal interpersonal emotion systems model (Butler, 2011) advocates that relationships between people operate as dynamic systems, characterized by a close interconnectedness of elements of the system, dependency on initial conditions and the system's past states, that all together give rise to an emergent property of self-organization, expressed in emotions that control

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the stabilization of behavior (i.e., morphostatis) or transition to another state (i.e., morphogenesis). Similarly, the emotions as social information model (van Kleef, 2009) puts forward expressions of emotions and subsequent appraisal processes in the form of inferences or affective reactions of the observer to explain how emotions regulate social interactions. In the model, social-relational (e.g., type of relationship, cultural norms, focus on a person or situation) and information-processing factors (e.g., cognitive implication) moderate the interpersonal effects of emotion. Finally, the sociodynamic model of emotions (Mesquita & Boiger, 2014) postulates that social interactions and emotions represent an integral and inseparable system. The model emphasizes that emotions do not exist a priori but rather emerge in interaction as functional and context-adapted constructs that form and shape interactions over time. The presented models illustrate the emerging trend toward the systematic study of emotions within interpersonal social dynamics, representing the “dark matter” of social neuroscience—not directly observable but an existing matter (Ayache et al., 2021; Schilbach et al., 2013). Our recent work (Bieńkiewicz et al., 2021) has shed light on the lacuna of empirical evidence on the effect of emotion on interpersonal rhythmic interactions in order to substantiate and enrich interpersonal emotion models.

Differentiating Emotion From Other Affective Constructs

Affect is an umbrella term encompassing various constructs such as emotion, feeling, and mood (Scherer, 2005). Russell and Barrett (1999) aptly drew an analogy by comparing the differentiation between emotion and other affective constructs to the parable of the blind men and an elephant. The analogy illustrates that the various affective constructs are merely different classes of events of the same underlying phenomenon. *Emotion* represents a multimodal and multicomponent process that entails a clear appraisal of an event that elicits a reaction of relatively short duration, triggering responses at behavioral, psychological, and physiological modalities (Sander, 2013). *Feeling*, on the other hand, is a single-component process that represents only the subjective experience of an emotional episode (Scherer, 2005). *Mood* does not have a clear antecedent, is less intense, and typically lasts longer than emotion (Beedie et al., 2005). And yet, all of the affective constructs discussed here¹ can be characterized in terms of valence.

Changes in valence serve as a necessary condition for changes in emotional states; however, changes in valence alone do not necessarily signify the emergence of an emotion (Quigley et al., 2014). Historically, the use of the word valence has been associated with the experience of positive or negative emotions that are inherently good or bad, leading to a “moralization of valence” (Colombetti, 2005). In fact, there are many dichotomies regarding how to classify positive and negative emotions, such as good–bad, right–wrong, pleasure–pain, approach–avoidance, and many others (Solomon & Stone, 2002). In this light, joy can be categorized as good, as right, or as one that brings pleasure, whereas anger can be categorized as bad, as wrong, and as one that causes pain. Each discrete emotion is characterized by a set of specific behavioral expressions. For instance, joy is often accompanied by smiling and laughter, while anger is commonly associated with furrowed brows and clenched fists. However, in contrast to this structuralist framework, we embrace here the functionalist perspective that views emotions as relevance detectors, guiding individual behaviors in the

environment through strong action tendencies (Campos et al., 1989; Frijda et al., 1989; Sander et al., 2003). It is this distinguishing feature, along with the multimodal and multicomponent process, that sets emotions apart from other affective constructs.

Investigating the Influence of Emotions on Interpersonal Synchronization

Collective effervescence serves as a compelling example of the interplay between emotions and rhythmic joint action. Coined by Durkheim and Fields (1995), collective effervescence describes the synchronization of intensities of individual emotional experiences resulting from participation in collective gatherings and rituals. Emotional contagion enables shared excitement in which people mimic and synchronize with other people’s facial expressions, vocalizations, postures, and behavior (Hatfield et al., 1994). Importantly, mere sharing of physical space is not sufficient for the emergence of collective effervescence (Xygalatas et al., 2011), and personal involvement modifies the affective response (Fischer et al., 2014). For example, audience enjoyment of live dance performances in three out of four choreographic sessions was found to predict the perceived synchronization of performers’ movements (Vicary et al., 2017). In a series of studies, Páez et al. (2015) empirically demonstrated the beneficial effect of collective effervescence on positive affect. Recently, Pizarro et al. (2022) conducted a meta-analysis of the influence of collective effervescence on, among others, emotions, and the authors further confirmed the beneficial effect on positive emotions. Nonetheless, the meta-analysis evidenced the absence of a meaningful influence of collective effervescence on negative emotions. Important to note is that studies reviewed by Pizarro et al. (2022) did not experimentally manipulate collective gatherings in which negative emotions were induced.

One area of research that provides evidence of detrimental associations between synchronization and emotion is dyadic conversation and conflict. For example, Gates et al. (2015) established a positive association between respiratory sinus arrhythmia and the number of conflicts in marital couples. The mere act of conflict implicates the collision of opinions and reduces behavioral synchronization (Paxton & Dale, 2013). Although, behavioral attunement during conversations about recurrent disagreements in long-term married couples correlates with shared affect (Otero et al., 2020). Conceivably, the nature of the conversation influences interpersonal attunement. For instance, mutual regulation of cardiac activity emerges in romantic couples during social support discussions when one partner attempts to regulate emotions verbally by supporting another partner (Zee & Bolger, 2023).

To date, only a few studies have explicitly targeted the causal effects of emotions on between-person synchrony. Paxton and Dale (2013) examined the convergence of interpersonal behavior during dyadic conversations under two counterbalanced experimental conditions: an affiliative condition, in which participants discussed the media they liked, and an argumentative condition, in which participants discussed a topic on which they had strong but conflicting opinions and were instructed to persuade their

¹ It is important to acknowledge that these three constructs do not encompass the entirety of affect. In addition to mood, emotion, and feeling, there are other constructs to consider, including preferences, affect dispositions, interpersonal stances, temperament, and sentiments, among others.

interlocutor. The authors did not find conclusive evidence for the effect of emotions on behavioral convergence but acknowledged the necessity for further research. In their following study, Main et al. (2016) explored dyadic conflict interaction between mothers and adolescents, entailing a verbal confrontation over an intense topic of disagreement. Unlike the previous experiment, the authors did not systematically manipulate different emotional conditions but only explored negative emotion context (i.e., argument discussion). Human raters quantified positive, negative, and neutral emotional expressions using the specific affect coding system during the interaction. The results demonstrated co-occurrence patterns between mothers and adolescents in both negative and positive displays, indicating emotional synchrony. By contrast, Tschacher et al. (2014) investigated five counterbalanced interactions: two conversations that promoted cooperation (i.e., developing a shared position and its justification to persuade an imaginary third person), two conversations that stimulated competition (i.e., debates over arguments from the same list and debates where one participant gets a weak list of arguments and the other receives strong ones), and one fun task to create engaging and humorous atmosphere (i.e., composing a five-course meal consisting of meals and beverages that neither of the participants likes). The authors found positive associations between emotions and synchrony in dyadic conversations and used Granger causality to investigate the direction of the causal relationship between emotions and interpersonal synchrony. The results revealed the predominant effect of interpersonal synchrony on emotion rather than vice versa. Notwithstanding the evidence, the authors recognized that causality evaluation was limited to temporal inference and that future studies should induce emotions experimentally.

Balancing Ecological Validity and Challenges in Selecting Emotion Elicitation Methods

The three abovementioned studies used dyadic conversation as an experimental paradigm. However, as a method of inducing emotions, dyadic conversation suffers from low experimental control (Levenson, 2003). In general, the choice of the emotion induction method is “a frustrating trade-off between ecological validity and experimental control” (Levenson, 2003, p. 217). To overcome the problem of low experimental control, Fujiwara and Daibo (2018) systematically manipulated emotions using video clips that the authors preselected in a pilot study for the Japanese population. The results did not support the hypothesis of an effect of emotion as the precursor of synchronization. However, the emotion elucidation method can explain the absence of meaningful results. In fact, emotional video clips suffer from low ecological validity (Levenson, 2003). Standard methods of emotion elicitation (e.g., photos, music, and films) fail to induce emotions reliably across different people. Indeed, people vary in their sensitivity to different stimuli (Joseph et al., 2020). To illustrate, while for some people the image of a spider can be a highly arousing stimulus, for others, the spider is neutral. This poses a methodological challenge in finding a standardized and reliable emotion induction method.

Social psychological methods based on deception can effectively circumvent awareness bias and generate reliable emotional responses through psychological realism in the laboratory (Harmon-Jones et al., 2007). To remedy the problem of low ecological validity and low experimental control, we have recently developed an emotion induction procedure based on success–failure manipulations (Smykovskyi

et al., 2022). In this type of induction, feedback on one’s own success or failure and the person’s participation in emotion-eliciting situations reinforce the emotional response (Nummenmaa & Niemi, 2004). Therefore, to enhance the personal relevance of the stimulus (to induce emotions), we incorporate individuals in the induction process and provide personalized performance feedback.

To increase standardization of the induction procedure among different people, we did not aim to induce any basic emotions, such as anger or sadness. In fact, after the same negative performance feedback, it is possible to induce anger in some participants as much as sadness in others. Moreover, Nummenmaa and Niemi (2004) warned that success–failure manipulations do not reliably target discrete emotions but instead produce discernible changes in the valence dimension of emotional states. For this reason, we decided to approach emotion elicitation in terms of different dimensions. Specifically, we expected that success manipulations would result in positive emotions and failure manipulations in negative emotions through changes in valence. Given the conceptualization of the emotion presented above, we adopt here a multimodal approach. Specifically, in addition to measuring behavioral (i.e., finger-tapping) and psychological responses to emotion induction, we examine a well-documented perspective of interpersonal cardiac activity (e.g., Gates et al., 2015; Konvalinka et al., 2011).

The Present Investigation

The results of our previous study (Smykovskyi et al., 2022) revealed that positive emotion induction fostered spontaneous synchronization and led to longer time maintained in synchronization (i.e., time-in-sync [TIS] metric). It remains an open question whether the emotional effect can also be observed in an intentional synchronization scenario. Finger-tapping provides an appropriate experimental paradigm for investigating intentional synchronization. While some studies assessed the effects of interpersonal finger tapping on emotional response (e.g., Rabinowitch & Cross, 2019; Zhang et al., 2016), the literature on the reciprocal effect is scarce. Addressing this issue is of pressing interest not only for fundamental science but also for human joint activity such as sports, military drills, and ensemble music performance, where intentionality underlies the ability to synchronize and generate potential positive consequences such as increased cohesion, empathy, and group efficacy.

Most interpersonal studies have examined dyadic social interaction while overlooking the emergent processes occurring at the group level (Dale et al., 2020). Namely, synchronization at the group level is not just the sum of its elements or the collection of pairwise relations. Instead, the group evolves, creating a “superorganism” that redefines the notion of an individual in the system and where the system becomes a new living entity (Emerson, 1939). In this context, a promising line of research is to identify the dynamics of entries and withdrawals from synchrony (e.g., Mayo & Gordon, 2020) and the process of coupling and uncoupling (e.g., Dumas & Fairhurst, 2021) that hints at group homology (i.e., how the geometry of group interaction–topology–changes over time; Zhang et al., 2020). Moreover, the group-level analysis provides a framework for empirical research into the effect of collective effervescence and the group-related tasks that are otherwise not accessible at the dyad level (Keltner & Haidt, 1999). This rationale gives rise to a relatively new research trend of group synchronization (e.g., Bieńkiewicz et al., 2023; Dale et al., 2020;

Fujiwara, 2016; Tomashin et al., 2022), which we follow in this article.

Human interpersonal synchronization can be considered through the mathematical lens of coupled oscillators, which are pervasive in many biological and physical systems (Feldman, 2007; Helm et al., 2012; Nordham et al., 2018; Yokoyama & Yamamoto, 2011; Zee & Bolger, 2020). However, Strogatz (2003) highlighted three constraints in approaching synchronization between humans as the study of coupled oscillators. First, human interactions are rich and variable in frequencies, while the science of synchronization is constrained to repeating the same constant frequency. Second, people are more influenced by their physical neighbors—and perceptual interaction (Bardy et al., 2020)—while the science of synchronization is constrained to all-to-all topology in which coupling is usually equally strong and shared between all oscillators simultaneously. Third, a reliable explanation of human behavior is challenging, while the science of synchronization requires a comprehensive explanation of the rules that govern interactions. Accordingly, an adaptation of the well-established Kuramoto model for human interaction has been proposed (Frank & Richardson, 2010; Richardson et al., 2012) and has been experimentally implemented using TIS and time-to-sync (TTS) metrics (Alderisio et al., 2017; Bardy et al., 2020; Calabrese et al., 2021; Smykovskiy et al., 2022). These metrics indicate the time spent in synchrony and the time needed to achieve the given synchronization level, respectively (see the Data Processing and Statistics subsection in the Method section for details on synchronization analysis).

Hypotheses and Contributions

In line with previous research (Smykovskiy et al., 2022; Tschacher et al., 2014), the specific hypotheses of the present article are that (a) the induction of negative emotions would result in lower synchronization scores than the neutral state (i.e., lower TIS and higher TTS metrics) and (b) the induction of positive emotions would result in higher synchronization scores than the neutral state (i.e., higher TIS and lower TTS metrics). Finally, the main contributions of this article are threefold:

- We propose a novel method of emotion elicitation based on success–failure manipulations using performance feedback and social comparison (see the Emotion Elicitation subsection in the Method section).
- We demonstrate that the emotion induction method is effective even when the experimental task holds little personal significance (see the Emotion Induction Effect on Interpersonal Finger Synchronization subsection in the Results section).
- We illustrate how the nature of the data can determine the choice of the synchronization measurement method. We juxtapose the results of Kuramoto order parameter values for behavioral and physiological modalities (see the Emotion Induction Effect on Interpersonal Heart Synchronization subsection in the Results section).

Method

Participants

Sixty adult students from various universities in Montpellier (33 females, 27 males, $M_{\text{age}} = 22.5$ years, $SD = 4.7$, range = 18–39)

participated in this study during 2022. They did not receive any benefit or form of financial or material compensation and reported no physical or mental disabilities.

We controlled for the rhythmic abilities and characterized participants' musical training in line with Rabinowitch and Cross' methodological approach (2019). A total of 39 people did not have any musical experience; 10 individuals played one musical instrument (singing included); 10 persons played two or more musical instruments; and one individual did not answer the question. Accordingly, no participants reported any difficulties in performing the rhythmical task.

Participants were randomly assigned into groups of three people (i.e., triads), and there were no prior acquaintances within either of the group members. Nine triads included only females, seven triads were composed of males, and four triads were mixed.

Before the start of the experiment, all participants read the information letter and provided written informed consent. The experimental procedure was approved by the local research ethics committee (EuroMov Digital Health in Motion, No. IRB-EM: 2106D).

Experimental Setup

The experiment was held in the Huyghens laboratory of the EuroMov Digital Health in Motion research unit. The experimental platform was set on the desktop of a round table with three chairs placed at equidistance from each other. Before starting the first trial, we verified the position of the chairs and table by aligning the furniture's legs with the marks on the floor. In this way, the furniture position was identical between different groups. Participants sat at a table in the same seat throughout all trials. To ensure a comfortable wrist position during the experiment, we fixed foam pads serving as wrist props on the table (placed at the vertices of an equilateral triangle with a side of 30 cm, see Figure 1 for illustration).

We used the Optitrack motion capture system for behavioral data acquisition. Five Optitrack Prime 13 cameras were calibrated daily prior to each experimental session. Calibration and data collection were conducted with a closed curtain to obtain the best conditions

Figure 1

The Experimental Setup With Three Participants Engaged in the Intentional Synchronization Task Consisting of an Air Version of Finger-Tapping (Without Contact Surface for the Fingertip)



Note. The persons in the photograph gave written consent to the publication of the photograph. See the online article for the color version of this figure.

for the motion capture cameras. We recorded movement at a sampling frequency of 120 Hz. One retroreflective marker was placed on each participant's index finger of a hand of their preference. Two participants decided to use their left hand and 58 participants opted to use their right hand. Data were inspected, preprocessed, and manually labeled in the Optitrack Motive Software (Version 2.0.0).

We used the Delsys Trigno Wireless Biofeedback System for physiological data acquisition. Specifically, we used wireless Trigno Avanti EKG biosensors to record cardiac activity at a sampling frequency of 2,148 Hz. Each participant positioned the biosensor according to the Delsys guide in a modified three-lead electrocardiogram (ECG) configuration. To ensure a high-quality signal, prior to affixing the biosensors, three sensor sites were cleaned to remove the dry dermis and skin oils. Then, the participants placed a V− electrode on the left side below the pectoral muscles on the lower edge of the rib cage and, in the same way, a V+ on the right side. They made sure that the electrodes were horizontally aligned. Finally, the sensor body was placed on the left side below the V− electrode. Raw ECG time series data were extracted with the Delsys EMGworks Software.

Moreover, to allow for the synchronous recording of physiological (Delsys Trigno) and behavioral (Optitrack) modalities, we used the Optitrack eSync 2 device connected to the Delsys Trigno Research + setup. In this way, starting a recording of Motive triggered an instantaneous recording of the three Delsys EKG devices.

The emotion induction was carried out using personal mobile phones. Prior to the experiment, participants were asked to bring their mobile devices charged. Emotions were induced using the Mentimeter website.² The website is designated for building interactive presentations with polls and questions. Personalized presentations were carefully prepared in advance for each participant. Before starting the experiment, we opened a browser window with three tabs with personalized presentations. Considering that the slides were changed manually, a simple Python code was created to facilitate the emotion induction procedure and perform it simultaneously for three participants. In fact, after a click of the letter R, the code produced a series of commands using keyboard shortcuts. Namely, Ctrl + 1 (open the first tab), right arrow (go to the next slide), Ctrl + 2, right arrow, Ctrl + 3, right arrow.

Emotion Elicitation

The emotion induction in the present experiment was performance feedback based on a comparison with the performance of two other group members. Participants were informed that there would be a subjective and an objective evaluation of their performance. The cumulative score of subjective and objective measurements would determine their place. Specifically, subjective evaluation consisted in ranking the triad members (including themselves) in relation to their task performance; objective evaluation entailed quantifying the performance with motion capture cameras. In reality, there were neither subjective nor objective results, and all the participants received manipulated and prepared in advance emotion induction stimuli. The cover story included subjective evaluation to ensure that participants were involved in the emotion-eliciting situation and objective evaluation to get participants to trust the performance feedback.

Notably, after each trial, all three participants received the same performance feedback, meaning that all participants were induced with all negative, neutral, or positive emotions. We asked the participants

to check their phones so other group members could not see their results.

Positive emotion induction was “[NAME] you are the BEST” (Figure 2A), and, correspondingly, negative emotion induction was “[NAME] you were chosen the WORST” (Figure 2C). The performance feedback had three key characteristics. First, to render the manipulations personal, we personalized Mentimeter presentations so that emotion induction slides started with the participant's name. Second, to increase the impact of manipulations, we carefully selected images from the open affective standardized image set (OASIS; Kurdi et al., 2017) of the same arousal level but of positive valence. Fireworks were chosen as a positive stimulus (valence was 6.27 and arousal was 4.98), and a house on fire as a negative stimulus (valence was 1.73 and arousal was 5.28). Third, to highlight the performance feedback, the words best and worst are in capitals.

However, it is tricky to induce a neutral state, that is, the control condition, with ranking performance feedback. Providing feedback about being in second place can be perceived as a negative emotional stimulus. To induce a neutral state, participants received ambiguous feedback “You are tied (best or worst) or in 2nd place” (Figure 2B).

Experimental Task and Procedure

Upon arrival at the laboratory, participants gave their written informed consent. All participants were naïve to the study's goal and were carefully informed that the experiment investigated how personality traits shape movement and interpersonal interactions. The specific purpose of investigating emotions was not revealed in order to avoid any explicit focus on the emotional reaction. Afterward, participants were equipped with the Delsys Trigno ECG sensor, and the experimenter visually examined the QRS complex using the Delsys EMGworks software to verify the accurate positioning of the Delsys electrodes. Then, a retroreflective motion capture marker was placed on each participant's index finger.

To get participants to trust the performance feedback (i.e., emotion induction), they and the experimenter ran a test of Mentimeter ranking on the mobile device and visualized the result on a screen. By doing so, participants were reassured that their ranking was, in fact, producing results.

Afterward, participants received a practice run of the process of answering questions. Specifically, after receiving the feedback on performance, participants were asked to answer three questions on their phones. Namely, the pleasure (Figure 3A) and arousal (Figure 3B) dimensions from the Self-Assessment Manikin (SAM) scale (Bradley & Lang, 1994), as well as the motivational consequences (Figure 3C) of emotion elicitation. Performance feedback and questions were displayed in French.

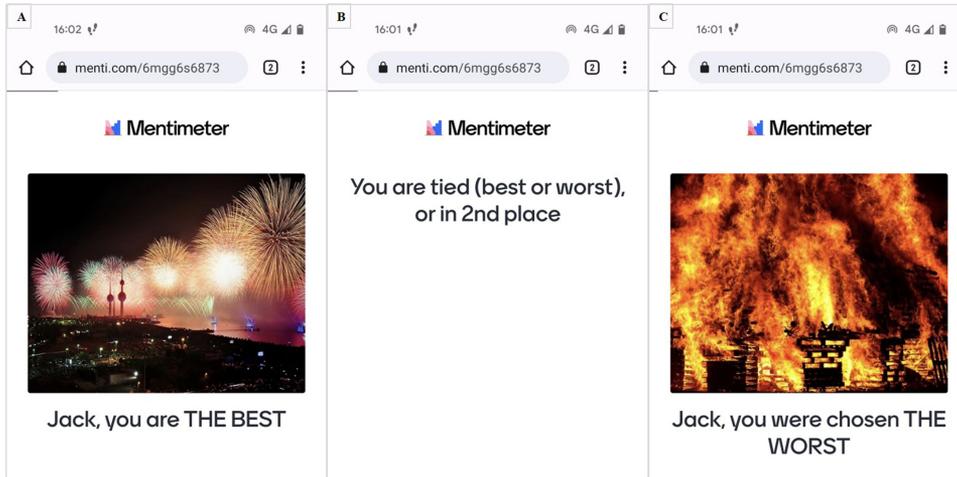
Experimental Task

Participants were asked to rest their wrists comfortably on the foam pad with their index fingers extended toward the middle of the table. The instruction was to synchronize vertical oscillations of the index finger with other group members. We choose not to tap on the table for two reasons. First, the afferent feedback from the hand to the muscles could influence motor command and rhythm production. Second,

²mentimeter.com.

Figure 2

Emotion Induction With Positive Feedback and Positively Valenced Image From the OASIS Database (A), Neutral State (B), and Negative Emotion Induction With Negative Valence Image From the OASIS Database (C)



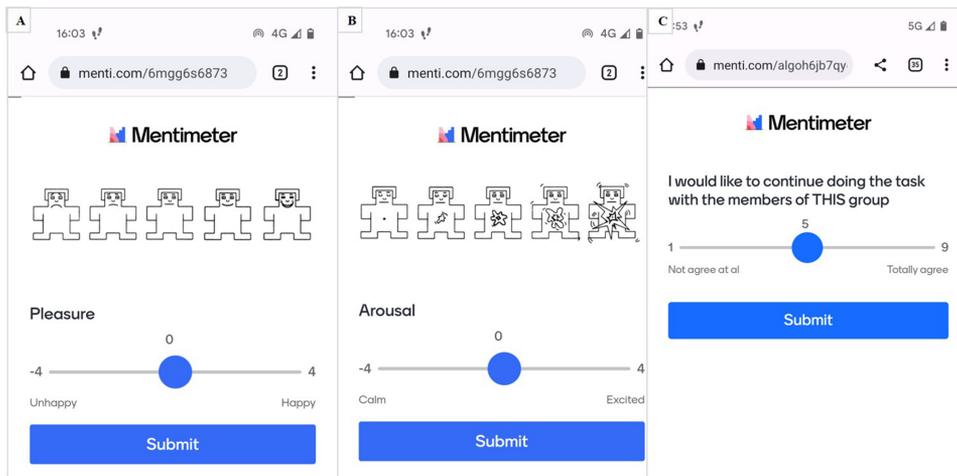
Note. OASIS = open affective standardized image set. From “Positive Emotions Foster Spontaneous Synchronisation in a Group, Movement Improvisation Task” by A. Smykovskiy, M. M. N. Bienkiewicz, S. Pla, S. Janaqi, and B. G. Bardy, 2022, *Frontiers in Human Neuroscience*, 16, 944241 (<https://doi.org/10.3389/fnhum.2022.944241>). CC BY. See the online article for the color version of this figure.

tapping on the table surface generates tactile-kinesthetic stimulation and creates noise, which improves the time-keeping precision by providing more sensory information (Drewing et al., 2002) and therefore biases the results of our task. To eliminate these potential biases, we chose a task of finger oscillations in the air. Finally, we asked participants not to communicate during the trials to avoid verbal or any other help to synchronize.

In this experiment, we investigated the effect of emotion on interpersonal synchronization. Thus, the first trial was excluded from the analysis because it was not preceded by emotion induction. In total, the participants completed 15 trials (five trials for each of the three experimental conditions), each trial lasting 20 s. There was a break of about 1 min between trials to rank the performances, get personal performance feedback (i.e., the same for all

Figure 3

Evaluation of the Emotional Consequences of (A) Pleasure and (B) Arousal, as well as the (C) Motivational Consequences Immediately After Each Emotion Induction



Note. From “Positive Emotions Foster Spontaneous Synchronisation in a Group, Movement Improvisation Task” by A. Smykovskiy, M. M. N. Bienkiewicz, S. Pla, S. Janaqi, and B. G. Bardy, 2022, *Frontiers in Human Neuroscience*, 16, 944241 (<https://doi.org/10.3389/fnhum.2022.944241>). CC BY. See the online article for the color version of this figure.

participants), and answer the three questions. The total duration of the experiment for a triad was about 45 min. Trials were randomized and counterbalanced to account for possible emotional after-effects. Specifically, we created two random orders of trials. Accordingly, we prepared two Mentimeter presentation templates of 75 slides each. Half of the triads performed the trials accordingly to the first order, and half performed the trials accordingly to the second order (Table S3 in the online supplemental materials). At the end of the experiment, the researcher debriefed the participants on the deception procedure and explained the necessity of such an experimental design.

Instruments

SAM

The SAM scale (Bradley & Lang, 1994) is a graphical and non-verbal measurement procedure that portrays human-like figures with different faces and sizes. Participants assess their subjective level of pleasure by selecting the matching facial expression of the figure and their level of arousal by choosing the corresponding size of the figure. Items are rated on a 9-point Likert-type scale ranging from -4 (*unhappy*) to 4 (*happy*) for the pleasure scale and from -4 (*calm*) to 4 (*excited*) for the arousal scale. We calculated the mean of each dimension. Internal consistencies in this sample ranged from 0.94 (*arousal*) to 0.96 (*pleasure*).

Motivational Consequence

To account for the dynamics of the approach and avoidance motivation (Elliot, 1999), we included a question “I would like to continue doing the task with the members of THIS group.” Given the low personal relevance of the task, we explicitly asked participants to focus on the part of the item that concerned their desire to participate in future activities with members of their triad. Item is rated on a 9-point Likert-type scale ranging from 1 (*not agree at all*) to 9 (*totally agree*). Internal consistency for the current sample was 0.82.

Data Processing and Statistics

Behavioral and Physiological Data Preprocessing

For the behavioral data, we performed a five-step process of identifying phase synchronization (see Smykovskiy et al., 2022). First, we extracted the raw velocities. Second, we locally detrended the velocity time series signals to bring the inflection points to 0. Third, we adjusted the local maxima to 1 and local minima to -1 and generated new sine-like time series. Fourth, we performed the Hilbert transform to extract phase time series. Fifth, we performed Kuramoto order parameter analysis to detect phase synchronization.

For the physiological data, we analyzed the most salient part of the ECG time series, that is, the QRS complex, to identify the R peaks. First, we detected R waves by using the sym4 wavelet. Then, we assigned 1 to the time stamps of the heartbeat occurrences and -1 to the midpoints between two successive heartbeats. This allowed performing the Hilbert transform for phase extraction and Kuramoto order parameter analysis for evaluating synchronization.

Synchronization Measurement

Given the movement phases (t) of a group of interacting people $k = 1, \dots, K$ in a given time interval $t = 1, \dots, T$ a metric to measure the group level of synchronization is the order parameter which is calculated as follows.

Firstly, each (t) represent a vector in 2D plane ($t = \exp(i \times \varphi_k(t)) = \cos(\varphi_k(t)) + i \times \sin(\varphi_k(t))$). This is a unit-length vector. Then, the mean (this is the group mean) of these vectors is calculated for every t :

$$\bar{x}(t) = \frac{1}{K} \sum_{k=1}^K x_k(t) = \frac{1}{K} \sum_{k=1}^K \exp(i \times \varphi_k(t)) \quad (1)$$

Finally, the order parameter is:

$$opmt(t) = |\bar{x}(t)| = \left| \frac{1}{K} \sum_{k=1}^K x_k(t) = abs(\bar{x}(t)) \right| \quad (2)$$

Intuitively, if all (t) “point” in the same direction, that is, (t) are similar, then $o(t) = |x(t)|$ will have values near to the maximal value of 1. On the contrary, if (t) are more dispersed, then (t) = $|x(t)|$ will be closer to 0 (the minimal value).

Main Synchronization Metrics

The Kuramoto order parameter was used to detect interpersonal synchronization (e.g., Alderisio et al., 2017; Bardy et al., 2021; Calabrese et al., 2021). Specifically, two metrics evaluated the synchronization dynamics of movement in and out of synchrony during the trial and the time needed to reach the specified synchronization level: TIS and TTS.

The first metric (i.e., TIS) was evaluated based on the interquartile range (IQR) principle and was calculated separately for each triad for all its trials. In essence, when the data points are arranged in ascending order, the lower quartile—Q1 synchronization level—spans the threshold above which 75% of data points are, the median—Q2 synchronization level—includes the highest 50% of data points, and the upper quartile—Q3 synchronization level—covers the 25% of the highest values. The interpersonal finger synchronization levels across different triads were calculated for Q1 ($M_{Q1} = 0.72$ years, $SD_{Q1} = 0.14$, range = 0.41–0.90), Q2 ($M_{Q2} = 0.86$ years, $SD_{Q2} = 0.08$, range = 0.62–0.94), and Q3 synchronization levels ($M_{Q3} = 0.93$ years, $SD_{Q3} = 0.04$, range = 0.82–0.98). By contrast, interpersonal heart synchronization is characterized by lower scores of little variations for Q1 ($M_{Q1} = 0.35$ years, $SD_{Q1} = 0.01$, range = 0.33–0.36), Q2 ($M_{Q2} = 0.53$ years, $SD_{Q2} = 0.02$, range = 0.48–0.56), and Q3 synchronization levels ($M_{Q3} = 0.77$ years, $SD_{Q3} = 0.02$, range = 0.74–0.81). TIS values range from 0 to 20 s, indicating the total time above the specified synchronization level. Time spent in synchrony in seconds is an intuitive and more easily interpretable metric than the Kuramoto order parameter, which ranges from 0 to 1.

As in our previous study (Smykovskiy et al., 2022), the weak synchronization level is of primary interest in this experiment. This is the first criterion for evaluating the dynamics of moving in and out of synchrony which includes the most significant amount of data (i.e., 75% of the highest-order parameter values). Incidentally, the word weak is essential for describing the synchronization of oscillators in the field

of nonlinear dynamics (e.g., Pikovsky et al., 2001). Indeed, Strogatz (2003) stipulated weak coupling as a condition for synchronization. Humans can be viewed as weakly coupled oscillators that are distinct from mediumly coupled (e.g., humans with haptic contact such as walking hand in hand) and strongly coupled oscillators (e.g., car wheels connected by the car axle). However, to avoid confusion with coupling, we renamed the term weak synchronization level to Q1 synchronization level. Moreover, we analyze the levels of synchronization Q2 and Q3 for comparison between levels as different states uncovering group interaction.

The second metric (i.e., TTS) calculated the time required to attain the specified synchronization level (i.e., Q1, Q2, or Q3) and stay above the level for a specified amount of time. Namely, in line with our previous study (Smykovskyi et al., 2022), we selected a threshold of 3 s (Table S2 in the online supplemental materials). To illustrate, if a triad in a given trial reached the Q3 synchronization level, stayed above it, and then dropped before the 3-s threshold, it is considered that the triad did not achieve the TTS Q3. TTS values can range from 0 s, which means that the group could not reach the specified level of synchronization and, crucially, stay over it for 3 s, to up to 20 s, the participants instantly reached the given level of synchronization and remained synchronized throughout the whole trial.

Transparency and Openness

An a priori power analysis was conducted using G*Power Version 3.1.9.7 (Faul et al., 2009) to estimate the required minimum sample size to test the study hypothesis. The statistical test for repeated measures within factors analysis of variance (ANOVA) was chosen. Given our past research examining associations between emotions and interpersonal synchronization, we anticipated a large effect (Smykovskyi et al., 2022). The input parameters were: the effect size $f = 0.40$ was selected to obtain a large $\eta_p^2 = 0.14$, with a significance criterion $\alpha = .05$, power = .80, one group (repeated measures design), and three measurements (experimental manipulations are positive emotion vs. neutral state vs. negative emotion). The results revealed that the minimum required sample size was $N = 12$. Therefore, with an obtained sample size of $N = 20$, the current study is adequately powered.

A total of 20 triads completed 15 trials each. One trial of synchronization between three individuals produced one synchronization score for the behavioral modality and one for the physiological modality. In total, we collected 300 behavioral and physiological scores each. However, one movement trial (out of 300) was corrupted due to technical problems. No problems were found in the collection of physiological data. Statistical analyses were performed using RStudio (Version 4.1.1, R Foundation for Statistical Computing, Vienna, Austria). This study's design and its analysis were not preregistered. Deidentified data and analysis code can be accessed at <https://osf.io/5qa4j/>. Finally, this article was conceived in accordance with Journal Article Reporting Standards (Kazak, 2018).

It is important to determine the distributions of each variable to choose the appropriate statistical method (i.e., parametric or nonparametric test). Our sample size was $N = 20$ triads. We used the Shapiro–Wilk normality test because it is suited for small sample sizes of $N < 50$ (Mishra et al., 2019). The results of the Shapiro–Wilk normality test were verified by visually examining the QQ plots and the absence of extreme outliers (using the boxplot method,

the troublesome values are above $Q3 + 3 \times IQR$ or below $Q1 - 3 \times IQR$). Before implementing the repeated measures ANOVA, we verified the equality of variances between groups with Mauchly's test of sphericity. If the assumption of sphericity was violated, then the conservative Greenhouse–Geisser correction was applied and reported. Separate one-way repeated measures ANOVA were run on the three metrics of synchronization (i.e., Kuramoto order parameter, TIS, TTS) with appropriate post hoc comparisons (i.e., *t*-test comparisons with the conservative Bonferroni correction) to detect meaningful differences between experimental conditions.

In the case of finding statistically significant differences in synchronization between conditions of emotion induction, certain healthy skepticism is necessary (Schmidt et al., 2012). Indeed, spurious chance and accidental coupling can be potential biases, and therefore it is crucial to perform a pseudo-synchrony test to account for chance synchrony (Bernieri et al., 1988; Moulder et al., 2018). This procedure consists in generating new triads, or pseudogroups, by shuffling order parameter time series from all triads and all trials and conducting statistical tests. In the absence of significant differences in pseudogroups, we confirm that the obtained results are not accidental.

The repeated measures design accounts for interindividual variability by demonstrating different effects of experimental conditions in the same subjects. However, in their recent work, Weissgerber et al. (2015) shed light on some limitations of presenting and analyzing data in repeated measures design. In particular, bar plots mask idiosyncratic changes across different experimental conditions and mislead readers by suggesting that groups are independent. In addition, the authors depicted various distributions of the paired data, resulting in identical bar plots. Lastly, Weissgerber et al. (2015) demonstrated that quantifying and visualizing differences between paired measurements unveils experimental changes across subjects. We follow their suggestion to unmask our distributions of data and produce violin plots and differences between paired measurements.

Results

This study investigated the effect of systematically manipulated emotional states on interpersonal synchronization across different modalities (i.e., behavioral, psychological, physiological) in a finger-tapping task.

Emotion Induction Effect on Interpersonal Finger Synchronization

Emotion Induction Effect on Order Parameter

A nonparametric Friedman test of differences among repeated measures between negative emotion ($Mdn = 0.79$, $IQR = 0.09$), neutral state ($Mdn = 0.82$, $IQR = 0.10$), and positive emotion ($Mdn = 0.84$, $IQR = 0.08$) was conducted and rendered a chi-square value of 18.20 which was statistically significant ($p < .001$) indicating that there were significant differences between at least two emotion induction conditions. A large effect size was detected ($W = 0.54$).

Pairwise Wilcoxon signed-rank test revealed statistically significant differences in order parameter values between negative emotion and neutral state ($Z = 23$, $p = .004$); negative emotion and positive emotion ($Z = 3$, $p < .001$); but not between neutral state and positive emotion ($Z = 46$, $p = .080$). The results indicate that order parameter

values were significantly more disrupted after negative induction than after neutral and positive inductions.

Emotion Induction Effect on TIS

A two-way repeated-measures analysis of covariance (ANCOVA) was performed to examine the effects of two independent variables, emotion and synchronization levels, on TIS, after controlling for motivational consequences. Descriptive statistics on the main synchronization metrics of different levels are presented in Table S1 in the online supplemental materials. There was a statistically significant interaction between synchronization level and emotion on the TIS, $F(4, 170) = 15.99$, $p < .001$, $\eta_p^2 = 0.27$. This indicates that the effect of emotion on TIS depends on the level of synchronization and vice versa.

The effects of emotion, $F(2, 170) = 113.97$, $p < .001$, $\eta_p^2 = 0.57$, and synchronization levels, $F(2, 170) = 695.20$, $p < .001$, $\eta_p^2 = 0.87$, were both statistically significant. However, the effect of the covariate variable, motivational consequence, was not significant, $F(1, 170) = 0.01$, $p = .917$, $\eta_p^2 = 0.00$. While the simple main effects of emotion were statistically significant at all levels of synchronization ($p_{Q1} < .001$, $p_{Q2} < .001$, $p_{Q3} < .001$), the simple main effects of motivational consequences were all negligible ($p_{Q1} = .759$, $p_{Q2} = .893$, $p_{Q3} = .844$). These results demonstrate that motivation does not explain the variance of the TIS metric.

Post hoc pairwise *t*-test comparisons with Bonferroni correction for Q1 synchronization level revealed that negative emotion was not statistically significantly different from the neutral state ($p_{\text{bonf}} = 0.202$, 95% confidence interval [CI] = [-1.63, 0.06]); negative emotion was significantly different from positive emotion ($p_{\text{bonf}} = 0.006$, [2.68, -0.71]); but no significant difference was found between the neutral state and positive emotion ($p_{\text{bonf}} = 0.163$, [-1.84, 0.02]).

Post hoc pairwise *t*-test comparisons with Bonferroni correction for Q2 synchronization level revealed that negative emotion was statistically significantly different from the neutral state ($p_{\text{bonf}} = 0.001$, 95% CI = [4.24, -1.45]); negative emotion was significantly different from positive emotion ($p_{\text{bonf}} < 0.001$, [5.20, -2.52]); but no significant difference was found between the neutral state and positive emotion ($p_{\text{bonf}} = 0.324$, [-2.27, 0.24]).

Post hoc pairwise *t*-test comparisons with Bonferroni correction for Q3 synchronization level revealed that negative emotion was statistically significantly different from the neutral state ($p_{\text{bonf}} < 0.001$, 95% CI = [6.67, -4.21]); negative emotion was significantly different from positive emotion ($p_{\text{bonf}} < 0.001$, [7.52, -4.96]); but no significant difference was found between the neutral state and positive emotion ($p_{\text{bonf}} = 0.468$, [-1.93, 0.33]).

Taken together, the post hoc results across different synchronization levels indicate that participants' time spent in synchrony significantly deteriorated after negative emotion induction. Moreover, Figure 4A depicts that with the transition to higher synchronization levels, the disruptive effect of negative emotion induction on TIS becomes increasingly more salient. Conversely, while the induction of positive emotions contributed to time spent in synchrony and yielded the highest scores across all synchronization levels, the gain was not substantial compared to neutral induction.

We performed a pseudo-synchrony check to test whether the obtained results were due to chance. After shuffling trials, the repeated measures ANOVA did not detect a significant main effect

of emotion, $F(2, 38) = 0.45$, $p = .643$, $\eta_g^2 = 0.02$. This outcome confirms that the TIS results are not spurious.

Differences Between Paired TIS Measurements

Given the recommendations of Weissgerber et al. (2015), we demonstrate violin plots with differences between paired measurements for time intentionally spent in synchrony (Figure 4B). The median differences between emotion induction pairs are measured in seconds and represent the Q1 level for negative-neutral ($Mdn = -0.87$), negative-positive ($Mdn = -2.30$), and neutral-positive ($Mdn = -0.88$); Q2 level for negative-neutral ($Mdn = -3.19$), negative-positive ($Mdn = -4.20$), and neutral-positive ($Mdn = -0.37$); Q3 level for negative-neutral ($Mdn = -5.55$), negative-positive ($Mdn = -6.48$), and neutral-positive ($Mdn = -0.75$) emotion. Notably, all medians have a negative sign. In addition to negative medians, the distributions are skewed toward negative values. These outcomes reveal that the results for all three pairs of emotions are consistent, albeit to varying degrees, with our hypothesis regarding the expected effects of emotion induction.

However, not every triad was prone to emotion induction by the same token. Indeed, there is a curious pattern comparing paired differences between the neutral and positive emotion induction pairs (Figure 4B). In fact, some pairs (e.g., neutral-positive Q1 and Q2 levels) have no data points around the median. This illustrates that our sample can be bimodal. In essence, the neutral and positive paired differences visualization shows two types of groups: the groups with paired differences far below the median that reacted in accordance with our hypothesis and the other group with paired differences far above the median for whom emotion induction had an opposite effect. This represents a promising avenue for uncovering individual sensitivity to emotion induction procedure, meaning to what extent some individuals are prone to a particular emotion induction.

Emotion Induction Effect on TTS

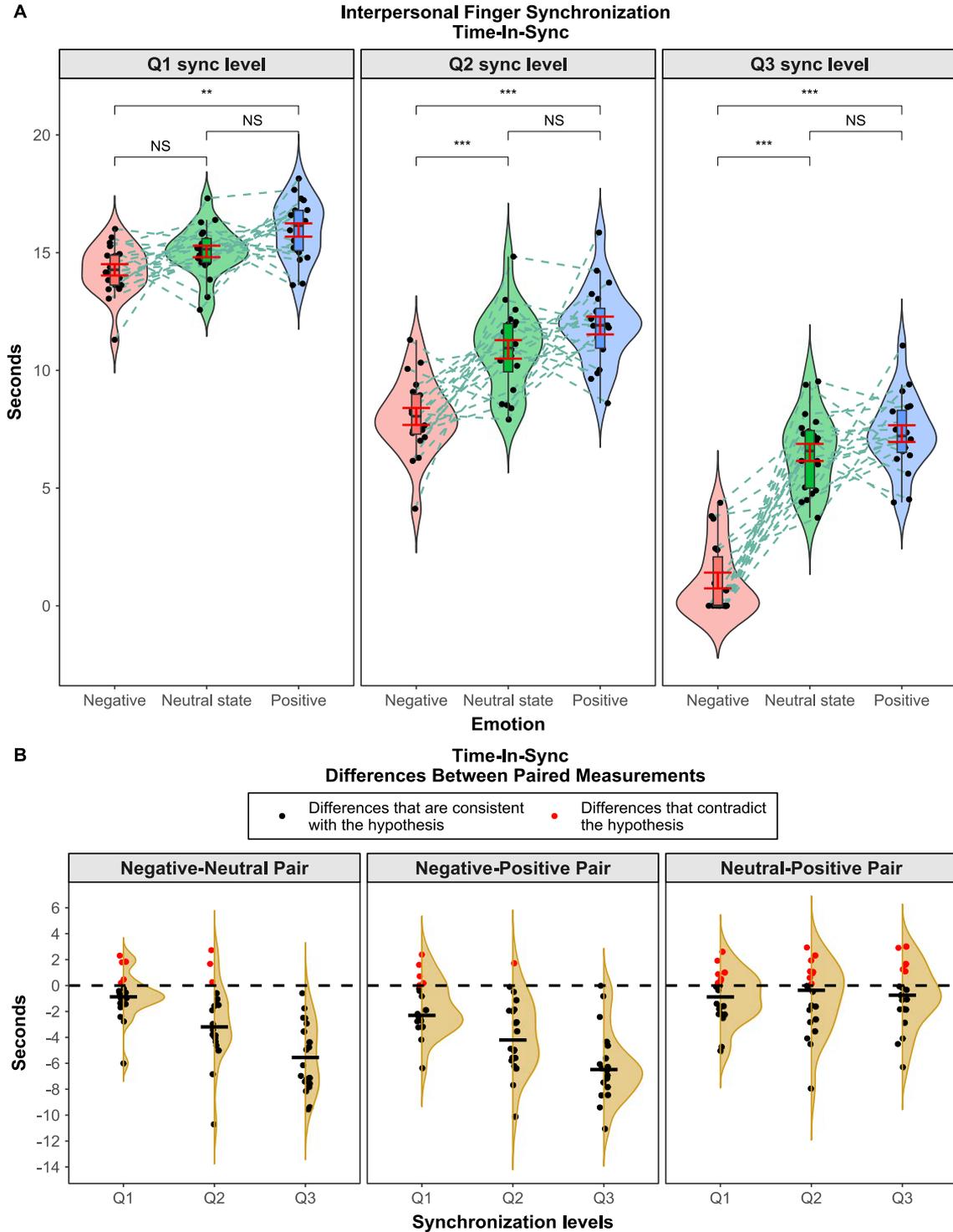
A two-way repeated-measures ANCOVA was planned to examine the effects of two independent variables, emotion and synchronization levels, on TTS, after controlling for motivational consequences. However, we could not perform the analysis because (a) while all the triads achieved a Q2 synchronization level after the neutral state and positive emotion inductions, eight triads did not attain the Q2 level after negative emotion induction and (b) while almost half the triads did not attain the Q3 level after the neutral state and positive emotion induction, none attained the Q3 level after negative induction creating a fully missing variable (Figure S1 in the online supplemental materials). This result further consolidates and stresses the perturbing effect of negative emotion on interpersonal finger synchronization.

Emotion Induction Effect on Pleasure, Arousal, and Motivational Consequences

A nonparametric Friedman test of differences among SAM pleasure repeated measures between negative emotion ($Mdn = 1.73$, IQR = 1.95), neutral state ($Mdn = 2.00$, IQR = 1.62), and positive emotion ($Mdn = 2.47$, IQR = 1.05) was conducted and rendered a chi-square value of 7.06 which was statistically significant ($p = .029$) indicating that there were differences between at least two different emotion induction conditions. A small effect size was detected ($W = 0.18$).

Figure 4

The Impact of Emotions on Movement is Illustrated by (A) TIS Violin Plots for Q1, Q2, and Q3 Synchronization Levels and (B) Differences in Paired TIS Measurements Depicted Using Flat Violin Plots



Note. (A) The red error bars are quantified with the standard error of the mean. Each triad's data points are connected with dashed lines. (B) The black dashed line indicates the hypothesis threshold, where the values lower than 0 align with the hypothesis (black data points), and the values above 0 contradict the hypothesis (red data points). The black vertical crossbars indicate medians of emotion pairs. TIS = time-in-sync; Q1 = first quartile; Q2 = second quartile (median); Q3 = third quartile; NS = non-significant. In the print version, the error bars colored in red will appear in a lighter shade. See the online article for the color version of this figure.

* $p < .05$. ** $p < .01$. *** $p < .001$.

Pairwise Wilcoxon signed-rank test of differences among SAM pleasure values revealed statistically nonsignificant differences between negative emotion and neutral state ($Z = 46, p = .087$); significant differences between negative emotion and positive emotion ($Z = 35, p = .022$); and nonsignificant differences between the neutral state and positive emotion ($Z = 38.5, p = .073$). The results indicate that SAM pleasure values were significantly improved after positive emotion induction and diminished after negative emotion induction.

A nonparametric Friedman test of differences among SAM arousal repeated measures between negative emotion ($Mdn = 0.90, IQR = 1.58$), neutral state ($Mdn = 1.00, IQR = 1.63$), and positive emotion ($Mdn = 1.03, IQR = 1.68$) was conducted and rendered a chi-square value of 2.18 which was statistically nonsignificant ($p < .336$) of a small effect size was detected ($W = 0.06$). This outcome suggests that the emotion induction manipulations did not produce self-conscious and substantial changes in arousal.

A nonparametric Friedman test of differences among motivational consequences repeated measures between negative emotion ($Mdn = 6.78, IQR = 0.92$), neutral state ($Mdn = 6.97, IQR = 1.17$), and positive emotion ($Mdn = 7.03, IQR = 0.97$) was conducted and rendered a chi-square value of 9.66 which was statistically significant ($p = .008$) indicating that there were differences between at least two different emotion induction conditions. A small effect size was detected ($W = 0.24$).

Pairwise Wilcoxon signed-rank test performed on motivational consequences revealed statistically nonsignificant differences values between negative emotion and neutral state ($Z = 69, p = 1.000$); significant differences between negative emotion and positive emotion ($Z = 19, p = .021$) and between the neutral state and positive emotion ($Z = 20, p = .014$). These results indicate that motivational consequence values were significantly enhanced after positive emotion induction.

Emotion Induction Effect on Interpersonal Heart Synchronization

Emotion Induction Effect on Order Parameter

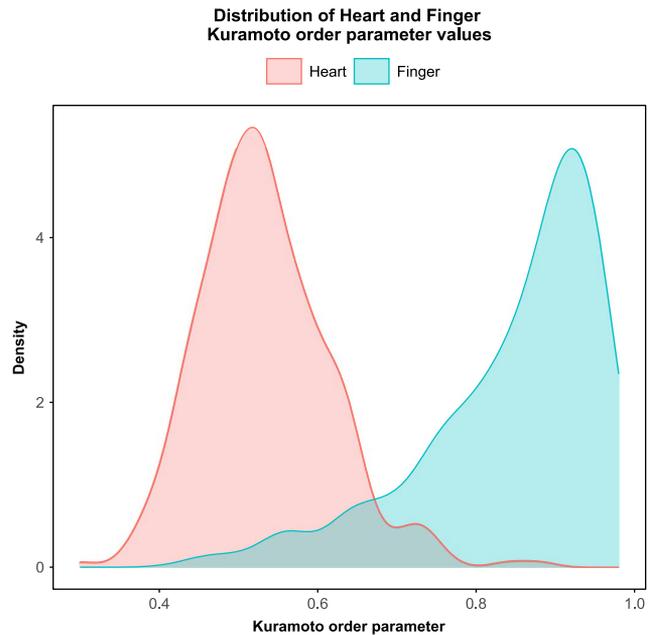
A nonparametric Friedman test of differences among repeated measures between negative emotion ($Mdn = 0.55, IQR = 0.04$), neutral state ($Mdn = 0.55, IQR = 0.03$), and positive emotion ($Mdn = 0.55, IQR = 0.02$) was conducted and rendered a chi-square value of 18.20 which was not statistically significant ($p = .522$) and of a small effect size ($W = 0.03$). These results reveal no significant differences between different emotion induction conditions.

Finally, the Kuramoto order parameter values for interpersonal synchrony for physiological modality were considerably lower than one found for behavioral modality (Figure 5). A Wilcoxon rank-sum test conducted on trial medians indicated that the finger order parameter values, $Mdn = 0.88$, were statistically significantly higher than the heart order parameter values, $Mdn = 0.53, W = 86,988, p < .001, \hat{r}_{\text{rankbiserial}} = 0.94, 95\% \text{ CI } [0.91; 0.96], n_{\text{obs}} = 599$. The implications of this finding are further discussed.

Emotion Induction Effect on TIS

Mauchly's test of sphericity indicates that the assumption of sphericity has been violated, $\chi^2(2) = 0.64, p = .019$. Therefore,

Figure 5
Density Plots Demonstrating Distributions of Trial Median Values of Heart and Finger Order Parameters



Note. See the online article for the color version of this figure.

the repeated measures ANOVA with Greenhouse–Geiser correction conducted between negative emotion ($M = 14.92, SD = 0.46$), neutral state ($M = 14.76, SD = 0.45$), and positive emotion ($M = 14.90, SD = 0.68$) did not reveal a significant main effect of emotion induction on TTS, $F(1.47, 27.99) = 0.34, p = .651, \eta_g^2 = 0.02$.

Emotion Induction Effect on TTS

Repeated measures ANOVA conducted between negative emotion ($M = 5.64, SD = 2.71$), neutral state ($M = 5.85, SD = 3.77$), and positive emotion ($M = 5.52, SD = 2.99$) did not reveal a significant main effect of emotion induction on TTS, $F(2, 24) = 0.56, p = .577, \eta_g^2 = 0.03$.

Discussion

Behavioral Modality

The current study examined the effect of emotion induction based on success–failure manipulation on intentional interpersonal synchronization. Results indicated that negative emotion induction substantially perturbed intentional finger synchronization. The results of three measures contributed to this conclusion. First, the negative emotion induction considerably reduced the raw order parameter values relative to the neutral state and positive emotion. Nevertheless, there were no significant differences between the neutral state and positive emotion.

Second, negative emotion induction shortened the time spent in Q1 synchronization—TIS measure—relative to positive emotion by 2.3 s. Although TIS post hoc pairwise comparisons confirmed the significant differences only between negative and positive

emotion inductions, differences between paired measurements demonstrated alignment with our hypothesis for the other two emotion induction pairs. Indeed, the neutral state improved the TIS values after negative emotion and positive emotion improved the TIS values after neutral state induction by almost 1 s for each pair. Moreover, TIS Q2 and Q3 synchronization levels (Figure 4A) depicted that, like in order parameter values, the negative emotion induction significantly shortened time spent in synchrony relative to both neutral state and positive emotion. In line with the Q1 order parameter results, neither the Q2 nor Q3 synchronization levels exhibited meaningful differences between the neutral state and positive emotion.

Third, the time necessary to attain synchronization—TTS measure—was not significant for either of the synchronization levels. Nevertheless, the higher the synchronization level, the more prominent the difficulty in attaining synchronization after the induction of negative emotions (Figure S1 in the online supplemental materials). As a matter of fact, while all the triads reached the Q2 synchronization level after the induction of a neutral state and positive emotion, almost half of the triads did not reach the Q2 level after negative emotion induction (Table S1 in the online supplemental materials). Remarkably, no triad achieved a Q3 synchronization level after the negative emotion induction.

Hypothesis 1: The induction of negative emotions will result in lower synchronization scores than the neutral state (i.e., lower TIS and higher TTS metrics).

We examined whether negative emotion induction leads to synchronization impairment and generates the lowest synchronization scores of the three experimental conditions. Supporting Hypothesis 1, we demonstrate a consistent results pattern between order parameter values and TIS concerning dropped synchronization scores after negative emotion induction. We noted an absence of significant effect in the TIS pseudo-synchrony check, as well as difficulties in attaining synchronization for TTS Q2 and Q3 levels after the induction of negative emotions, which we conclude as confirmation of our first research hypothesis. One possible explanation for the finding is that the processing of negative emotions increases cognitive load. Motivation and individual cognitive resources moderate interpersonal emotional effects, in which mental effort is positively associated with the predictive power of affective reactions (van Kleef, 2009). Moreover, increased cognitive demand for negative emotions, such as anxiety, hindered fluid cognition, and the ability to process the demands of unusual tasks and offered innovative solutions (Moran, 2016). However, in the present experiment, the task of cyclic sensorimotor interaction did not require a creative mental effort but exploited concentration to a greater extent. Moreover, if negative emotions are the cause, then mental efforts associated with processing positive emotions should not increase. Yet, positive emotions have also been found to intensify mental efforts (Um et al., 2012). For these reasons, the cognitive load explanation is not entirely convincing in this experiment, and future research should explore in depth the triangular relationship between participants' cognitive resources, synchronization task requirements, and the mental effort associated with processing different emotions.

Hypothesis 2: The induction of positive emotions will result in higher synchronization scores than the neutral state (i.e., higher TIS and lower TTS metrics).

In line with our previous study (Smykovskiy et al., 2022), we verified whether positive emotion strengthens synchronization and generates the highest synchronization scores. We did not detect a statistically significant improvement in positive emotion induction with respect to the neutral state. One explanation is that the intentional nature of the task allows for different outcomes. In contrast with our previous study, an improvisational task in which participants spontaneously synchronized, the present experiment was more controlled, and the synchronization of movement oscillations was performed intentionally. Possibly, while spontaneous synchronization is more prone to changes in positive emotion, intentional synchronization is more sensitive to negative emotion. However, we lean toward another explanation, which is a difference in the perceived relevance of emotion induction. In fact, in our preceding study, the participants were engaged in an activity they considered personally relevant (i.e., dancing for dancers). For this reason, the emotion induction based on success–failure feedback was conceivably high. By contrast, the activity of the present study (i.e., finger-tapping) was not considered personally relevant. Improving the relevance of emotion induction will potentially enhance the magnitude of differences. Indeed, despite the absence of a significant effect, positive emotion induction yielded the highest synchronization scores across all major indicators (i.e., order parameter, TIS Q1, TIS Q2, TIS Q3). This exploration suggests that the higher the perceived relevance of emotion induction, the greater the effect on movement synchronization, at least up to a certain threshold.

Psychological Modality

Some readers may challenge our view by insisting that the observed effects on behavioral modality can be due to an improved motivation to perform the task and not due to emotion induction. Social psychologists clearly distinguish motivation and emotion as separate theoretical constructions. However, it is unrealistic to separate the two entities in practice. In fact, motivation and emotion use the same neural circuitry (Lang & Bradley, 2010). Moreover, the insistence of some theories (e.g., Frijda et al.'s 1989 action tendencies) on motivation to engage in specific activity (i.e., anger to fight and fear to flight) further emphasizes the complexity of distinguishing these two theoretical constructions. Emotions are intrinsically motivational.

According to Elliot's (1999) approach–avoidance motivation distinction, the former entails inclination toward a desired stimulus, and the latter constitutes withdrawal from an undesired stimulus. Just as anger could incite aggressive behavior toward a source of danger, fear can incite moving away from the danger. More specifically to our study, while some might react to the personalized social feedback “[NAME], you were chosen the worst!” with anger and an amplified will to perform the task (i.e., approach), others might react with indifference, detachment and even sabotage (i.e., avoidance). That is why we introduced the motivational consequence question that detects the dynamics of approach and avoidance mindset. Moreover, motivation was used as a covariate of the TIS metric and yielded nonsignificant results. We found that, relative to the neutral state, the negative emotion induction did not deflect the will to engage in future activities. At the same time, participants reported higher approach scores after positive emotion induction. This is important because fostering the approach motivation allows for generating cohesive groups.

With respect to psychological dynamics captured with the SAM scale as a response to systematic emotion induction, we observed alterations in pleasure but not arousal scores. These results are consistent with our previous study (Smykovskiy et al., 2022) and are in line with previous literature (Joseph et al., 2020; Nummenmaa & Niemi, 2004). Evidently, the valence dimension can be robustly targeted with personalized success–failure feedback manipulations. Taken together with behavioral results, we conclude that the emotion induction of the present study was successful. Interestingly, unlike our previous study, the present results confirm a well-established negativity bias (Joseph et al., 2020; Rozin & Royzman, 2001). In the task of low personal relevance, negative emotion induction is more efficient and generates changes of higher magnitude than positive induction.

Physiological Modality

In relation to the effect of emotion inductions on physiological modality, synchronization scores of interpersonal heart activities were not meaningfully different. This result is consistent with our previous study (Smykovskiy et al., 2022). In our previous experiment, participants were standing and moving. In such a context, the movement typically affects to a greater extent the autonomic nervous system (ANS) rather than social comparison feedback. To control for the movement bias, the participants were seated in the present experiment. Indeed, gross movements were excluded, and participants only moved their index fingers. The present results corroborate that movement was not a bias in our previous study. The explanation is twofold.

On the one hand, we could interpret that the effect of emotion induction was not strong enough to produce discernable changes in heart rate activity. In fact, Wallot et al. (2016) already evidenced a lack of heart rate synchrony during a joint action activity. Notwithstanding the evidence, the authors emphasized the lack of strong emotional reaction to the task as a possible explanation for the absence of physiological sync. Indeed, when the emotional response is strong, such as the connection between relatives in a fire-walking ritual (Konvalinka et al., 2011), the between-person heart rate activity tends to synchronize. One of the future avenues of research on interpersonal synchronization is to determine the threshold of emotional intensity, after which one can detect cardiac attunement between people.

On the other hand, it is possible that the physiological response was indeed triggered. However, while order parameter analysis was suitable for identifying behavioral synchronization, it failed to detect physiological attunement. The evidence of between-person physiological synchrony is robust and was recently stressed in three literature reviews (Kazi et al., 2021; Mayo et al., 2021; Palumbo et al., 2017). Moreover, empirical evidence of heart rate synchronization during joint action is ample (e.g., Baranowski-Pinto et al., 2022; Lange et al., 2022; Tomashin et al., 2022). In our experiments, we performed the same Kuramoto order parameter analysis to homogenize the analysis across behavioral and physiological modalities. While movement variation can be considerable, heart rate changes are subtler and are bounded within physiological limits. Specifically, voluntary changes in movement can easily adjust interpersonal finger synchronization, but heart rate cannot change as dynamically because the changes are gradual and relatively slower. For instance, an adult American’s average resting

heart rate varies between 60 and 90 beats per minute (Osthega et al., 2011), and cardiac activity is characterized by small intrinsic variability (Constant et al., 1999). We demonstrated that the Kuramoto order parameter values are visibly diminished for physiological modality (Figure 5). Arguably, in addition to the phase analysis, the two most common techniques to detect synchronization are correlational and recurrence quantification analyses. While the former averages out the meaningful dynamics, which was shown to be the essence of synchronization (Mayo & Gordon, 2020), the latter could not be performed on our data due to insufficient data points—that is, heartbeats—during 20 s trials. Consequently, we encourage future research to establish synchronization-detection algorithms depending on the nature of the data.

Implications

From a theoretical perspective, this article produces empirical justification for including emotion in the human synchronization models to better understand interpersonal behavior and coordination. Our results empirically support Sapolsky’s (2017) claim that negative emotions constitute the mechanism for social detachment. In the long run, interpersonal emotion research will also contribute to the field of social opinion engineering (Bernays, 1928) through collective effervescence (Durkheim & Fields, 1995).

From an applied perspective, the results of this research can be used in the facilitation of autism spectrum disorder adaptations (Manders et al., 2021) and in techniques improving interpersonal bonding (Fuchs & Koch, 2014) by encouraging instances of congruent rhythmical behavior to generate shared positive emotions. Also, we have demonstrated the necessity of choosing an interpersonal synchronization detection analysis that is data-dependent (i.e., small intrinsic variability of cardiac activity and large variability of movements). Finally, these findings will contribute to the current technology trend that emphasizes the development of emotion-aware devices that promote student learning (Feidakis, 2016; Muñoz et al., 2020), facilitate decision-making on the battlefield environment (Lin et al., 2019), assists in healthy aging (Mieleszczenko-Kowszewicz et al., 2022) and more generally increases wellbeing and quality of life (Zhou et al., 2007).

Constraints on Generality

Our findings provide evidence of the emotional effect on rhythmic interaction in participants who were induced with success–failure manipulations. Given that this effect has been observed for a range of participants in a series of experiments on spontaneous and intentional synchronization in our laboratory, we expect our result to generalize to other contexts in which persons are engaged in rhythmical tasks as long as participants genuinely experience emotional states (i.e., the emotion induction method does not sacrifice ecological validity). One limitation of the present work is that the task is constrained. This was identified as a common weak spot of interpersonal coordination research (Bente & Novotny, 2020). While it is true that the present task is structured to movements only in one dimension, it allows for a controlled experimental design and a reliable answer to our research question of the effect of emotion induction on intentional group synchronization. Future studies shall focus on moving toward more naturalistic tasks. Finally, we expect that individual and cross-cultural differences

may moderate the observed experimental findings. In this study, we accounted for personality traits (i.e., neuroticism and extraversion), emotional contagion, and mood, but given the lack of significant explanatory contribution to the analysis, these variables were left out of the scope of this article.

Conclusions

In this article, we demonstrated that emotion induction altered participants' movement oscillations in an intentional finger-tapping task. Negative emotions influenced detrimentally interpersonal synchronization performance. This is a piece of empirical evidence that negative emotion may function as an instrument of restraint and protection, manifested by a tendency of withdrawal from undesired social interaction and revoking affiliation. Therefore, to unravel why and how humans synchronize, emotion is a key variable for seizing the dynamics of interpersonal coupling alongside perceptual interaction.

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