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It does not need two: Assessing physiological linkage from videos across the valence dimension

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Abstract

The phenomenon of physiological linkage describes similar fluctuations of two individuals' physiology, for example, the cardiac inter-beat interval (IBI). Physiological linkage is a well-documented occurrence in research settings of interacting dyads but the literature on non-interacting dyads, that is, someone watching a video of another person, is sparse. The current study investigated whether physiological linkage, based on IBI, occurs from watching videos where strangers report about personal (neutral, positive, negative non-traumatic, and negative traumatic) experiences. Videos were produced with six individuals and then presented to observers ($N=26$). Time-frequency-domain cross-wavelet analyses supplemented by threshold-free cluster enhancement (TFCE; to account for multiple testing) showed significant physiological linkage between the IBI of observers and persons in the videos for 16 out of the 21 tested videos. Although significant physiological linkage also emerged for neutral videos and positive, negative valence videos led to such associations more reliably. This study shows that physiological linkage can be investigated in highly controlled conditions based on video stimuli paving the path for experimental manipulation in future research. Furthermore, due to the provision of information on time and frequency, the use of cross-wavelet analysis is encouraged to learn more about factors modulating physiological linkage. The current study presents the next step toward identifying psychophysiological causal and modulating factors of physiological linkage.

KEYWORDS

IBI, physiological linkage, synchronization, time-frequency analyses, videos

Physiological linkage is proposed to be associated with emotional contagion and empathy (Preston & De Waal, 2002), and is assumed to affect health in interpersonal conflict and social support (Reed et al., 2013), making the phenomenon of interest to many researchers and applied fields. Physiological linkage is defined as assimilation in physiological fluctuations in the same or opposing directions between two interacting individuals. For example, the cardiac inter-beat interval (IBI) of two individuals or their skin conductance level (SCL) can assimilate or fluctuate in similar ways and thus show high associations. This phenomenon is sometimes also termed physiological synchrony or concordance. The first studies, which empirically examined physiological linkage, focussed on dyads with strong existing bonds, for example, psychotherapist and client (Di Mascio et al., 1955; Di Mascio et al., 1957; Malmo et al., 1957). Physiological linkage has also vastly been empirically investigated in dyads of other strong bonds, such as spouses (Levenson & Gottman, 1983) or romantic partners in general (literature review by Timmons et al., 2015). Since the phenomenon was first introduced to the scientific community, it has been investigated across a range of relationships among familiar and unfamiliar people, such as dyads of mother and child, friends, strangers, and also group and team interactions (see literature review by Palumbo et al., 2017).

A commonality in the aforementioned literature is that physiological linkage was simultaneously measured in participants. It is important to note that participants were interacting live and in person, which allows participants to influence each other. This approach is necessary to address research questions on physiological linkage involving inter-dyad characteristics of variables related to relationships, for example, the relationship status, the attachment style, or the communication style. A challenge inherent to an in-person interaction approach is to control these relationship characteristics. Another challenge is to control the direction of linkage (i.e., who is linking to whom) and investigate physiological linkage uninfluenced by the back-and-forth influence inherent to interactions. In addition, interacting dyads can show a great degree of inter-dyad variability in the nature of the interaction. Investigation of physiological linkage in an individual outside of a synchronous interaction may be advantageous for the identification of causal and/or modulating factors and could expand the knowledge on physiological linkage. An experimental approach with standardized stimuli would allow the systematic manipulation of variables and enable investigation of mechanisms and factors underlying and modulating physiological linkage. An advantage of being able to investigate physiological linkage asynchronously with controlled stimuli would also be that participant recruitment is facilitated, as recruitment of and appointment scheduling with dyads poses challenges. Ultimately, using controlled stimuli in an asynchronous manner could provide a simplified way to identify a person's susceptibility to physiological linkage with clinical implications. For example, a susceptibility to physiological linkage could put therapists working with trauma survivors at risk for the development of secondary traumatic stress. Identification of such susceptibility would allow for preventative measures to be applied. However, with the literature presented having applied interactive approaches, the question arises whether physiological linkage can even occur when individuals are not interacting live and in person but are exposed to standardized stimuli (of strangers).

To our awareness, there are only a handful of published studies where stimuli, rather than live interacting dyads, were used to assess physiological linkage. Of these few studies, most showed video material to participants of individuals familiar to participants, again including the relationship factor and allowing for inter-dyad variability. For example, an early study conducted by Gottman and Levenson (1985) used video recordings of spousal interactions to investigate physiological linkage (based on IBI, SCL, and finger pulse). The spouses were asked to recount recent events after a multiple hours-long separation in one condition and to discuss a marital problem in another. Physiology was measured in both spouses and the interaction was video-recorded. A few days later, the participants watched the video recordings of their dyadic interaction while their physiology was again recorded. A strong linkage of the physiology between one spouse in the original situation and when watching their own interaction on video was found and this result was interpreted as the participants re-living the interaction. In Gottman and Levenson (1985), the video might have served as a prompt to remember the situation that was video-recorded, including the physiological responses. This is similar to a study conducted by Zerwas et al. (2021), where female friend dyads were each placed in a stressful situation taken from the Trier Social Stress Test (Kirschbaum et al., 1993). That is, participants were each asked to give a speech but with only a very brief preparation time. Participants were video-recorded during the speech and their physiology (IBI, SCL, and finger pulse) was recorded. Afterward, each participant watched the speech of their friend on video while their physiology was measured again. In Zerwas et al. (2021), physiological linkage was also demonstrated to occur when watching a video. Similar to Gottman and Levenson (1985), both participants had experienced the same situation and could have re-experienced the situation with similar physiological responses while watching the videos. To assess physiological linkage without the potential of re-experiencing a situation driving the linkage, studies using a new sample of participants (i.e., mere observes of the videos) are needed.

Only two studies (that we are aware of) have implemented such a mere observer condition where participants were also strangers to the individuals in the videos, that is, excluding individual relationship characteristics and re-experiencing a situation as influencing factors. Levenson and Ruef (1992) added to the study by Gottman and Levenson (1985) by showing the video recordings of the interacting couple to strangers while measuring their physiology (IBI, SCL, and finger pulse). That study found physiological linkage with the target spouse, suggesting that the observers linked their physiology to the target individual in the video. There was a degree of triangulation, as the observer watched a video of two interacting individuals. In a more recent study, the physiological linkage was also measured based on standardized video stimuli but featuring only one person in the video, thus, controlling the interaction, individual relationship, and re-experiencing a situation aspect. Jospe et al. (2020) asked participants to tell autobiographical stories of emotional experiences while they were video-recorded and their physiology (HR) was measured. The video recordings were then shown to a new sample of observing participants (strangers to the video-recorded participants) while their physiology was measured. The results showed physiological linkage, demonstrating that individuals are not required to interact live, have had the same situational experience (i.e., video production), or know the stimulus person for physiological linkage to occur.

The two studies showed that observers can link their physiology to (unfamiliar) individuals in videos. It should be noted that the video production by Jospe et al. (2020) was non-categorical. That is, participants were asked to tell stories without specifically instructing participants to report a positive or negative event. Although the stories selected for their study included predominantly either negative or positive reports, the reported emotional content was nonetheless mixed within stories, that is, varied along the affective valence dimension from unpleasant to pleasant (Russell, 1980). Whether physiological linkage to one (unfamiliar) person in a video can be seen for reports of content that is pre-defined as positive, negative, and neutral in affective valence is an open research question. In case this were possible, future research could investigate the phenomenon of physiological linkage, causing and modulating factors, in experiments with highly controlled video stimuli of specific valence categories.

Traditionally and predominantly, physiological linkage is investigated using either 'time-domain analyses' (e.g., cross-correlation in Coutinho et al., 2021) or 'frequency-domain analyses' (e.g., cross-spectral analysis in Schmidt et al., 2012). The aforementioned video-based research on physiological linkage applied time-domain analyses. Time-domain analyses provide information on the extent to which two signal series (plotted: x-axis = time, y-axis = amplitude) behave synchronously to each other over pre-defined time windows. Time-domain analyses produce an aggregated value, for example, the covariance or its standardized form, the Pearson correlation. Frequency-domain analyses (such as power spectral density) divide the covariance into frequency components, thus, providing information on the speed or rhythm of the covariation (plotted: x-axis = frequency, y-axis = amplitude). It is important to note that in the spectral domain, covariance magnitude is independent of phase shift. (Phase shift denotes how far the wave of a signal is shifted horizontally in comparison to its usual position or the comparison signal; see Figure S1 for illustration). In the time domain, sine waves of equal wavelength have a covariance of zero when shifted by a quarter of the wavelength. However, in the spectral domain, sine waves always have the same covariance magnitude, independent of the magnitude of the shift based on their spiral shape and rotation behavior around the origin. Consequently, the distance from zero is equal at any given moment. Therefore, physiological linkage measured in the frequency (and 'time-frequency', see second next paragraph) domain can be described as *synchronous change following a certain rhythm* rather than *synchronous change in the same direction*. High physiological linkage at a certain frequency equates to both signals having high (absolute) covariances with complex sine waves at the identified frequency. These covariances can be caused by visible oscillation cycles in the signals, partial cycles (e.g., HR increases or decreases), or signal properties that appear only after decomposition by frequency (e.g., RSA oscillations overlaid and hidden by larger Mayer-waves[1]).

The autonomic control system underlies HR fluctuations (Saul, 1990). A decomposition of the HR by frequency can be highly informative, as the three specified frequency bands differentially represent parasympathetic versus sympathetic activity, allowing us to relate physiological processes to observed fluctuations. That is, HR fluctuations in the HF band generally reflect parasympathetic activity and are predominantly related to respiration (e.g., RSA with fluctuations at 0.15–0.40 Hz equivalent to wavelengths of 2.5–6.67 s; Berntson et al., 1997). Fluctuations in the LF band generally involve both sympathetic and parasympathetic activation. Blood pressure regulation constitutes a typical example of HR fluctuations in the LF band (e.g., the baroreflex with fluctuations at 0.10 Hz equivalent to a 10-s wavelength; Moak et al., 2007). The VLF band mainly reflects sympathetic activity with thermoregulation as an associated process (Fleisher et al., 1996). Investigation of physiological linkage by frequency band can provide information on underlying common or opposing physiological processes in the pair of investigation.

When dyadic interactions of individuals are being investigated, information on the frequency as well as the

[1]Slow arterial pressure oscillations are called Mayer-waves (Julien, 2006).

strength of linkage at specific points in time where physiological linkage is occurring can be of particular interest. Cross-wavelet analysis, a time-frequency-domain approach, can provide information on both time and frequency of linkage, that is, it can reveal fluctuations in synchrony over time. Wavelet transform is the mathematical operation underlying cross-wavelet analysis where a signal is divided into different scale components (phase widths) on the *y*-axis, thus, covering varying frequencies. Two signal series can be tested for association across the length of the time series on the *x*-axis producing magnitudes of association (e.g., the strength of physiological linkage); for each step, the wavelet window is shifted across the signals. For more detail and a tutorial on the analysis, see Issartel et al. (2015). Cross-wavelet analysis, thus, identifies not only if physiological linkage occurred but also when it occurred in time, which can provide clues on mechanisms driving physiological linkage.

Published research has effectively used cross-wavelet spectral analysis to investigate the dyadic linkage of arm movement (Issartel et al., 2007; Issartel et al., 2015) and movement within an unstructured dyadic conversation (Fujiwara & Daibo, 2016). Likens and Wiltshire (2021) used the ECG data from a study on cognitive collaboration in pairs (Ahonen et al., 2016) and demonstrated, using cross-wavelet analysis (on IBI data; see also de Boer & Karemaker, 2019), that individuals move in and out of synchrony over time. To date, cross-wavelet analysis has not been used to investigate non-interacting dyads (to our awareness).

The current study sought to test whether physiological linkage can be effectively assessed from controlled stimuli within a laboratory-based experiment. Cross-wavelet analysis was used to assess if the physiological linkage of observers to video stimuli occurred; time- and frequency-domain measures (Pearson correlation and power spectral density, respectively) were used in addition to be able to compare the results to the findings from the cross-wavelet analyses. More specifically, it was assessed whether physiological linkage can be induced by videos containing reports of pre-defined affective valence categories (neutral, positive, negative non-traumatic, and negative traumatic). Cross-wavelet analysis allows to provide information on the frequency range and specific video contents where significant physiological linkage occurs, potentially providing useful information for future research on mechanisms associated with physiological linkage. The videos were created to be in the standard format of experimental stimuli, that is, participants were filmed face-forward, giving the impression of directly speaking to any observer of the recorded videos. It was hypothesized that physiological linkage would take place for reports of all valence categories, that is, that observers would link their physiology to the individuals in the videos.

1 | METHOD

1.1 | Participants

The current research project was approved by the Kantonale Ethikkomission Zurich (BASEC: 2019-02476) and carried out in accordance with the Declaration of Helsinki. Participants were recruited via different online platforms, word-of-mouth, black boards, university mailing lists, and from a pool of previous participants who gave permission to be invited for future study participation. Inclusion criteria for both reporting and observing participants were males and females aged 18–55 years, normal or corrected-to-normal vision, native-speaking Swiss-German/German, or equivalent fluency. Exclusion criteria for both reporting and observing participants were current medical condition or intake of medications with influence on psychophysiological measurements (e.g., beta-blocker). In addition, participants for the video production had to have experienced at least one traumatic event in their past. To avoid adverse reactions to the video recording procedure, these participants were required to not demonstrate current clinically relevant suffering from trauma-induced symptoms. Thus, a score below 28 on the Post-Traumatic Diagnostic Scale (Foa, 1995; Foa et al., 2016) was required; see Questionnaires section. Exclusion criteria for participants who watched the videos were a self-reported diagnosis of a psychiatric disorder and, in case they had experienced a trauma, a Post-Traumatic Diagnostic Scale score >27. Additional exclusion criteria for these participants were having taken part in the video production, a beard covering the cheeks where zygomaticus facial muscle site electrodes were attached and Botox injections in the corrugator facial muscle site. Videos were recorded with six participants (2 males and 4 females) between 19 and 47 years of age ($M=28$, $SD=13$).

A required sample size calculation was conducted for permutation tests to assess physiological linkage corresponding to two-tailed parametric tests of sample means against zero. Since the main aim of the study was to test whether physiological linkage occurs in a unidirectional setup, a meaningful effect size (medium to large) was specified. The same effect size was expected for all frequency bands. With an alpha level of $a=.05$, and a required test power of $b=.80$, sample size analysis with G*Power (Faul et al., 2007) indicated a required sample size of 24 participants to detect medium to large effects (effect size of $d=0.60$). A sample of 26 participants (12 males, 14 females) aged between 19 and 30 years ($M=23$, $SD=3$)

watched the videos. Participants were compensated for participation with CHF 20 per hour.

1.2 | Physiological measuress

Based on previous studies on physiological linkage involving videos (Jospe et al., 2020; Levenson & Ruef, 1992), IBI was used as the primary measure to assess physiological linkage in the current study. (SCL was also assessed but there was insufficient statistical power to conduct meaningful analyses). A standard lead II ECG was recorded with one electrode below the right collarbone, one electrode below the left rib cage, and a ground electrode below the left collarbone. The electrode placements were equal for both reporting and observing participants and disposable gel electrodes were used. The g.tec system (g.HIAMP amplifier and g.RECORDER) was used for physiological data recording during the video production, using standard passive electrode leads for the ECG. The sample rate was 1200 Hz.

Observers' EMG responses were assessed as a measure of valence to assess alignment with the stimulus categories. Facial EMG was recorded from the m. corrugator supercilii facial muscle site (associated with negative valence) and the m. zygomaticus major facial muscle site (associated with positive valence). The Biopac MP150 system with EMG100C modules in combination with the BioNomadix wireless system and Acqknowledge (Version 4.4.1) software were used for physiological data acquisition of observing participants. Pairs of shielded Ag-AgCl EMG electrode leads per facial muscle site were used with a 4 mm recording diameter, filled with saline conductive gel, and attached to the skin (according to the guidelines by Fridlund & Cacioppo, 1986) with double-sided adhesive rings. An unshielded ground electrode was placed on the forehead. The EMG data were recorded with a bandpass-filter (10–500 Hz) and a 50 Hz notch filter was applied. The sample rate was 1000 Hz across measures with a BN-RSPEC transmitter and receiver and BN-EL45 leads for the ECG.

1.3 | Self-report ratings

It was assessed whether reporting individuals were experiencing affective states congruent with the four stimulus categories and whether the stimuli elicited affect in observers. Using Psychopy (Version 3.2.4; Peirce et al., 2019), self-report ratings were obtained on visual analogue scales (0–100) from reporting and observing participants (at baseline and after each report/video). The rating scales were valence (i.e., unpleasant to pleasant), arousal (i.e., calm to active), and emotion-specific ratings of five negative emotion-related terms (helpless, sad, angry, anxious, stressed) and five positive ones (secure, energized, touched, joyful, hopeful). The German words were: hilflos, traurig, wütend, ängstlich, gestresst, geborgen, belebt, gerührt, freudig, zuversichtlich. Observing participants were further presented with a self-formulated single item after each video to assess subjective affect linkage as a subjective validation of the video categories. The question was: How much did you feel the emotions of the person in the video within yourself. [Wie sehr haben Sie die Gefühle der Person im Video bei sich gespürt?]. A VAS rating scale ranging from not at all (=0) to extremely (=100) was applied.

1.4 | Questionnaires

The German version of the Post-Traumatic Diagnostic Scale (Wittmann et al., 2021), which is based on the Diagnostic and Statistical Manual of Mental Disorders Version 5 (APA, 2013), was used to assess whether participants had experienced a trauma and if so, their current symptom severity. The Post-Traumatic Diagnostic Scale assesses the type of trauma an individual experienced and the current symptom frequency as well as severity across 20 items.

For exploratory purposes, six a-priori selected items taken from the Emotional Contagion Scale (Doherty, 1997; German translation by Falkenberg, 2005) were used in the application of the video stimuli part of the study. The results will not be reported.

1.5 | Video production

Individuals who expressed interest in participating in the video production were sent study details. Afterward, a telephone screening was conducted to check the inclusion and exclusion criteria. As part of this procedure, the Post-Traumatic Diagnostic Scale (Wittmann et al., 2021) was filled out with the interested individuals during the phone call. Individuals had to fulfill criterion A of the Diagnostic and Statistical Manual of Mental Disorders Version 5 (APA, 2013) for a post-traumatic stress disorder: direct exposure to or witnessing death, actual or threatened serious injury, or actual or threatened sexual violence. Individuals who met all eligibility criteria were invited to the laboratory. Upon arrival at the laboratory, the individuals were asked to provide written consent permitting the use of the created video stimuli for research purposes.

In the video production, instructions about the video production were given by a psychotherapist (the last author) who sat in the control room next to the laboratory where the participant was seated. Participants saw the therapist via a webcam. Participants sat in front of a large projection screen, where a small camera was unobtrusively placed behind a tiny hole in the screen. Participants saw the therapist on the screen and heard her through speakerphones. The therapist saw the participants through a small recording device (Blade Samurai), which was coupled with a recording microphone, and heard participants through a headset. The set-up of a camera (Marshall CV502-M) behind a screen was chosen for participants to speak to the therapist rather than looking directly into a camera. This set-up mimicked a face-to-face setting while allowing video-recording with participants front-facing the camera.

Participants were informed by the experimenter that their arousal (via ECG and EDA) was measured as an indicator for present affect after which the electrodes were attached. Afterward, a 3-min resting baseline was recorded timed using Psychopy (Version 3.2.4; Peirce et al., 2019) while the participant sat in the laboratory followed by the affect and emotion self-report ratings. The video production followed and started with positive and negative experience reports (without any traumatic content). For the traumatic report, the psychotherapist asked the participants whether they were ready for the trauma recall and informed the participants again that they can withdraw consent or take a break at any time.

For every recording, prior to talking about an event, participants were asked to recall and immerse themselves in the event they were going to report about. The aim was to help participants remember details of their events and to induce corresponding emotional states. For this purpose, standardized instructions were verbally given to participants by the therapist before each video recording. The instruction for participants can be found in Appendix S1. Participants who felt comfortable with closing their eyes followed the instructions with eyes closed.

Each video recording was started after the instruction was given and participants spoke freely without any verbal feedback from the therapist. However, the therapist showed signals (e.g., nodding) that are commonly used during interactions to demonstrate to the participant that she was listening. A pilot investigation on dyadic physiological linkage conducted in our lab showed less pronounced or even absent physiological linkage when participants were talking without pausing. Participants were therefore instructed to pause speaking (around 2–18 s). (This procedure was introduced after the completed video production with the first reporting participant). To ensure that participants would allow their emotions to surface (especially during the reporting of traumatic events) rather than suppress their emotions, participants were instructed to turn their attention to their body and subjective feelings during these pauses. If participants forgot to pause, the therapist signaled non-verbal reminders. This was done approximately after 2–3 sentences and particularly after mentioning emotional content. Each participant reported about a neutral, positive, negative (non-traumatic), and negative-traumatic experience. Self-reported affect and emotion ratings of participants' current state were obtained at baseline and after each report. ECG was recorded throughout. The electrodes were removed after the last report was video-recorded. Before participants left, the therapist asked about their well-being and offered support if it was needed. Participants were financially compensated with 40 CHF for the duration of the video recording session (2 h).

The longer video clips (>5 min) were shortened in duration by cutting parts in the beginning and/or the end that were not essential to the understanding of the report in the video. The videos were converted in Handbrake from the original .avi (25 fps; 1920 × 1080) to .m4v to reduce the file size and assure playability as stimuli within the experiment to assess physiological linkage. The final videos had a frame rate of 25 fps and a resolution of 1280 × 720. Table 1 provides an overview of the video characteristics and contents of the reports. There are two negative videos for stimulus person 2 and no traumatic one, as the information provided in the video did not meet the criteria of a trauma as specified in the Diagnostic and Statistical Manual of Mental Disorders Version 5 (APA, 2013).

1.6 | Application of the video stimuli

Individuals who expressed interest in the study were sent study details. Afterward, a telephone screening was conducted to check the inclusion and exclusion criteria. As part of this procedure, the Post-Traumatic Diagnostic Scale (Wittmann et al., 2021) was filled out with the interested individuals during the phone call. Individuals who met all eligibility criteria were invited to the laboratory. Upon arrival at the laboratory, participants were again briefed about the study and written informed consent was obtained.

The ECG, EDA, and facial EMG electrodes were attached to the participants' chest, hand, and face. Participants were informed that they were being unobtrusively video recorded to be able to detect movement artifacts in the physiological data. A resting baseline of 3 min was obtained and timed with Psychopy (Version 3.2.4; Peirce et al., 2019), and the same affective and emotional ratings as in the video production were obtained.

Participants viewed all 24 video stimuli and the self-report ratings were obtained at baseline and after each video stimulus akin to the procedure during video production. The videos were randomized in order per participant

TABLE 1 Video stimuli characteristics.

SP	Sex		Neutral	Negative	Traumatic	Positive
1	Male	Content	Shopping at the supermarket	Strangers in home	Multiple rapes in childhood	Zoo visit
		Duration	01:05:00	03:17:00	05:35:00	01:34:00
		Valence	80	50	30	50
		arousal	85	80	85	80
2	Female	Content	Watching TV	Difficulties studying abroad	–	Graduation ceremony
		Duration	05:02:00	09:08:00		05:11:00
		Valence	50	20		91
		Arousal	50	60		71
		Content		Anorexia		
		Duration		05:01:00		
		Valence		30		
		Arousal		70		
3	Female	Content	Visiting a bakery	Difficulties with a roommate 05:03:00	Physical attack	Vacation with a friend
		Duration	04:42:00	37	06:49:00	05:00:00
		Valence	69	85	7	94
		Arousal	50		80	70
4	Female	Content	Living situation/location	Deadly illness of best friend's child	Sexual abuse by a relative	Trip with friends
		Duration	05:28:00	05:09:00	07:09:00	05:07:00
		Valence	80	79	30	79
		Arousal	18	20	51	48
5	Male	Content	Studying at university	Conflict with mother	Deadly accident	School excursion
		Duration	04:35:00	04:49:00	09:02:00	04:39:00
		Valence	66	77	74	84
		Arousal	38	74	66	70
6	Female	Content	Doing Christmas shopping	Foster horse getting sold	Attack and subsequent loss of vision	Oral exam with good outcome
		Duration	05:34:00	05:07:00	05:39:00	05:15:00
		Valence	100	50	50	99
		arousal	11	40	49	21

Note: The presented times represent the video duration in minutes and seconds after editing. The valence ratings ranged from unpleasant to pleasant (0–100) and arousal from low to high (0–100).

Abbreviation: SP, stimulus person.

and the experiment was programmed to offer short breaks after 6, 12, and 18 watched videos, which participants were allowed to skip by key press. Participants were blind to the valence category of the videos. After each video, participants were asked to state on a rating scale (0–100) how much they themselves felt the emotions of the person in the video ('subjective affect linkage'). The experimenter observed participants trough a webcam during the experiment and, for later data editing, took note of any artifacts (e.g., yawning) in the physiological data that occurred during the experiment. At the end of the experiment, participants rated themselves on the selected six items from the Emotional Contagion Scale (Falkenberg, 2005). Before leaving the laboratory, participants were financially compensated with 50 CHF for the total duration of 2.5 h.

1.7 | Data preparation

Pre-processing of the physiological data was conducted in Anslab (Version 2.6; Blechert et al., 2016) which runs on MATLAB. Since only results from cardiac activity and

EMG are reported in the results section of this manuscript, processing steps of SCL are not reported.

1.7.1 | Facial EMG

EMG signals were 28 Hz high-pass filtered, rectified, smoothed with a moving average width of 50 ms, and down-sampled to 100 Hz. The EMG data were corrected for artifacts (e.g., yawning) that were noted down by the experimenters during data collection. Such segments were classified as missing values and excluded from further analysis. Means were calculated with the cleaned data for the baseline period and the duration of each stimulus; the baseline mean was subtracted from the stimulus means. The resulting values belonging to the same valence category were averaged.

1.7.2 | ECG – IBI and spectral measures

After filtering of the ECG signal (40 Hz low-pass filter, 0.5 Hz high-pass), R-waves were identified automatically by Anslab and subsequently manually edited for artifacts, misses, false positives, and ectopic beats following established guidelines (Task Force of the European Society of Cardiology, 1996). For example, individual missed beats (up to 3) were visually inspected and inserted manually if the R-waves remained recognizable to the eye or otherwise interpolated based on neighboring beats. Wrongfully identified beats by the software were manually deleted. Based on the identified R-Waves, the instantaneous IBI was calculated for each recording and transformed into a time series equidistantly sampled at 4 Hz. The power-spectral density of all IBI signals was calculated using the Welch-method with a hamming window of 60 s (i.e., 240 samples) and a 50% window overlap of 30 s (i.e., 120 samples) to obtain estimates of the VLF, LF, and HF band power (as natural logarithms of the area under the curve of the power spectrum from 0.0033 to 0.04 Hz for the VLF band, 0.04–0.15 Hz for the LF band, and 0.15–0.40 Hz for the HF band according to the heart rate variability guidelines; Task Force of the European Society of Cardiology, 1996). IBI signals and their power spectra were averaged across stimuli within each valence category separately for reporting and observing participants. Means and standard deviations were calculated. Before conducting the linkage analyses, all IBI time series were standardized to have a mean of 0 and standard deviation of 1 to remove the influence of the global IBI level of each participant on the subsequent analyses. Extreme outliers (>3 *SD* above and <3 *SD* below the mean) in each time series were excluded and replaced with linear interpolations. Three stimuli were too short in duration for meaningful analysis (<5 min) and were excluded from the analyses on physiological linkage (i.e., the negative, neutral, and positive video of stimulus person 1). Thus, analyses were conducted for 21 cleaned and standardized stimuli. For each stimulus, 26 cleaned and standardized observer data were available for IBI-based linkage analysis.

1.7.3 | Physiological linkage

The physiological linkage between stimulus and observer was analyzed using cross-wavelet analysis. Cross-power spectra and Pearson correlations were calculated to supplement the cross-wavelet analysis. Cross-wavelet analysis of the IBI was performed using the Wavelet toolbox in MATLAB and a complex Morlet wavelet. The analyzed frequency range was selected to cover the three spectral bands most commonly investigated in studies on heart-rate-variability using 53 logarithmically spaced frequencies beginning at 0.0248 Hz and ending at 0.5 Hz, with 12 voices per octave. Central wavelet periods ranged from 40.3 s at 0.0248 Hz to 2.0 s at 0.5 Hz.

To avoid distortions due to edge-effects, results outside a cone-of-influence were discarded as suggested by Torrence and Compo (1998). The same set of frequencies was used for cross-spectral density estimation to enhance comparability. Cross-spectral density was estimated using the standard Welch-method with a hamming window of 60 s (240 samples) and a 50% window overlap of (30 s, 120 samples).

1.8 | Statistical analyses

1.8.1 | Observers' responses to the videos

It was examined whether watching the videos induced emotional states in observers by baseline-correcting the observer ratings provided after each video. That is, the baseline rating from each of the emotion items (10) was subtracted from the corresponding item rating provided after each video stimulus. One-sample *t* tests were conducted on these baseline-corrected ratings to test for significant changes of emotional states after watching each video. Means and standard deviations were calculated, averaged across stimuli belonging to the same valence category, for all measures (self-report ratings, facial muscle responses, and IBI).

1.8.2 | Physiological linkage

Cross-wavelet spectra, cross-power spectra, and (Fisher-transformed) correlations were averaged for each stimulus across the 26 observers to obtain average measures of association as index of physiological linkage. Cross-wavelet and cross-spectral analyses produce complex numbers. Of the (complex-valued) cross-wavelet spectra and cross-power spectra, the absolute values (or magnitudes) were calculated and used for statistical testing.[2] To obtain an empirical test distribution for these absolute values under the assumption of no physiological linkage between stimulus and observer time series (H_0), the absolute values of the described average measures of association were calculated for 2000 signed permutations of the data sets according to established permutation procedures (Good, 2000). That is, the sign of the association measures (Pearson correlations, power spectral density coefficients, and wavelet coefficients) was randomly multiplied for each participant by either 1 or −1 and the average association measures were recalculated (per stimulus). This was repeated 2000 times to generate the test distributions under H_0 (i.e., average association measure not different from zero). Real and imaginary parts were independently permuted; the same (random) sign was used for the real/imaginary part of the entire spectrum/wavelet of each participant.

Cross-power spectra magnitudes were then tested for significance by determining the proportion of permutations with higher magnitudes than in the original data set. Correlations were tested on both tails, and the tail with the lower proportion was used as an estimate of the *p*-value; since the test distributions were not symmetrical around zero, a test of the absolute values of the correlations would have been biased. These tests were carried out without correction for multiple testing since their number was moderate (21 correlations, 21 stimuli × 53 frequencies = 1113 tests for IBI). A significance level of $\alpha = .05$ was applied for these tests.

Cross-wavelet magnitudes, however, could not be tested without a more sophisticated correction of the inflation of Type I error, given the total of 1,226,526 tests performed (1102 samples × 53 frequencies × 21 stimuli = 1,226,526 tests for IBI). Therefore, Threshold Free Cluster Enhancement (TFCE, Smith & Nichols, 2009) was used, a modification of the cluster permutation test described by Maris and Oostenveld (2007) on the magnitudes of the cross-wavelet spectra and the permutations. In other words, this modification uses a sum over the entire range of possible cluster thresholds instead of an (arbitrary) fixed threshold and weighs each time-frequency-sample based on the number of thresholds where it is part of a cluster. Taken together, 21 (IBI) tests were performed. A significance level of $\alpha = .05$ was applied for these tests.

2 | RESULTS

2.1 | Reporting participants' responses

Reporting participants showed an IBI pattern in line with the valence categories of the reports. That is, the IBI was shortest during traumatic reports, followed by negative reports, and then positive reports, and was longest during neutral reports. Similarly, reporting participants displayed reduced LnHF and LnLF during traumatic reports. Means and standard deviations are reported in Table 2.

2.2 | Observer's responses

Table 2 displays the affective and emotion ratings of observers after watching each video; the arousal and valence ratings of the stimulus persons are presented in Table 1. Observers' valence ratings were broadly in line with the affective categories of the videos. A rating of 50 would represent the neutral midpoint of the rating scale. Thus, the valence ratings after watching the negative videos were in the negative to neutral range. The valence ratings after the neutral videos were slightly positive and the valence ratings after the positive videos were in the positive range. The valence ratings after watching the traumatic videos were in the negative range. The observers' arousal ratings after watching each video are also corresponding to their valence categories with ratings in the calmer range for neutral, a little more energized for positive and negative videos, and closer to the midpoint of the rating scale for traumatic videos. The baseline-corrected valence and arousal ratings showed general alignment with the stimulus valence categories. That is, valence ratings decreased

[2]Complex-valued association measures, such as cross-spectral coefficients or cross-wavelet coefficients, are two-dimensional in nature. That is, they have a so-called 'real' component and a so called 'imaginary' component. Consequently, greater/lesser comparisons between such measures cannot be made. However, greater/lesser comparisons are required for permutation testing when determining the proportion of permutations that (randomly) lead to 'greater' associations. Therefore, the two-dimensional measures needed to be transformed to a one-dimensional scale allowing to make such comparisons. Using the magnitude (i.e., absolute value) is advantageous, as it corresponds to determining the distance from the origin in the two-dimensional complex plane, discarding the direction information (so called 'phase'). Since averages of complex-valued association measures were tested, random variations between subjects will cause the average to fall close to the origin. Only consistent phases of individual association measures across subjects will have their average fall at a distance from the origin, and then this distance can be used for signed permutation testing against zero. An implication of this approach is that only phase-locked linkage (linkage with uniform phase-shift across the sample) can be detected. Non-phase-locked linkage (linkage with varying phase-shift across the sample) will be averaged out.

TABLE 2 Descriptive statistics for observers' and reporting participants' responses.

	Traumatic	Negative	Positive	Neutral
Observing participant				
Subjective affect linkage				
M	57.57	46.52	42.90	33.38
SD	23.30	24.22	25.29	23.88
Range	81.80	76.33	77.50	74.33
Corrugator facial muscle site				
M	0.0047	0.0032	0.0011	0.0016
SD	0.0009	0.0007	0.0003	0.0030
Zygomaticus facial muscle site				
M	−0.0003	−0.0002	0.0007	0.0002
SD	0.0002	0.0002	0.0003	0.0001
IBI				
M	822.06	817.56	804.26	815.25
SD	115.09	115.60	109.06	111.51
lnVLF				
M	16.185	16.165	16.132	16.161
SD	0.292	0.295	0.275	0.275
lnLF				
M	9.347	9.400	9.391	9.486
SD	0.524	0.505	0.496	0.428
lnHF				
M	7.339	7.417	7.396	7.388
SD	0.772	0.735	0.729	0.672
Reporting participant				
IBI				
M	620.61	638.42	650.20	678.51
SD	76.28	43.16	73.09	45.35
lnVLF				
M	15.494	15.690	15.725	15.809
SD	0.230	0.145	0.221	0.130
lnLF				
M	9.782	10.242	10.375	10.432
SD	0.656	0.437	0.210	0.146
lnHF				
M	6.988	7.626	7.893	7.957
SD	0.874	0.541	0.364	0.511

Note: For observing participants, their subjective affect linkage, EMG responses, IBI, and power per frequency band (HRV) are presented. For reporting participants, their IBI and HRV are presented.

strongest after the traumatic videos and the least after the positive and neutral videos; arousal ratings showed the opposite pattern; Table 3.

The change in emotional state from baseline to after watching each video was also in line with the valence categories of the videos. That is, negative videos (traumatic and non-traumatic) led to observers experiencing a reduction in happiness and an increase in negative valence emotions or feeling touched. Except for one report, neutral reports did not lead to significant increases in emotion ratings but made observers mostly feel less energized. After watching positive reports, participants reported to feel more touched and mostly lessened negative emotions.

The subjective affect linkage ratings were in line with the valence category of the reports, that is, on the lower part of the rating scale for neutral reports and the higher

TABLE 3 Observers' affective and emotion ratings.

VC	SP	VAL *M* (*SD*)	ARO *M* (*SD*)	BL-C VAL *M* (*SD*)	BL-C ARO *M* (*SD*)	DEC	INC
Negative	1	53.81 (25.58)	40.54 (20.60)	−31.88 (27.82)	−6.19 (25.82)	Happy t (25) = −5.00***	Angry t (25) = 3.87***
	2	46.08 (26.10)	41.15 (23.12)	−39.62 (27.29)	−5.58 (27.15)	Happy t (25) = −5.03***	Touched t (25) = 4.28***
	2	36.77 (27.53)	46.31 (24.07)	−48.92 (29.04)	−0.42 (20.21)	Happy t (25) = −6.87***	Sad t (25) = 5.53***
	3	44.08 (21.51)	41.23 (21.09)	−41.62 (26.30)	−5.50 (28.14)	Happy t (25) = −6.44***	Angry t (25) = 6.80***
	4	38.23 (19.57)	30.23 (17.83)	−47.46 (24.63)	−16.50 (26.74)	Happy t (25) = −6.68***	Touched t (25) = 6.67***
	5	48.27 (20.21)	39.08 (21.86)	−37.42 (21.47)	−7.65 (30.02)	Happy t (25) = −6.42***	Touched t (25) = 2.57*
	6	53.96 (22.90)	32.58 (22.15)	−31.73 (21.96)	−14.15 (29.75)	Happy t (25) = −5.89***	Angry t (25) = 4.02***
Neutral	1	68.19 (18.35)	31.31 (21.02)	−17.50 (21.10)	−15.42 (25.15)	Energized t (25) = −3.97***	–
	2	73.23 (19.40)	35.96 (24.93)	−12.46 (16.79)	−10.77 (28.90)	Protected t (25) = −3.27**	–
	3	66.23 (25.39)	25.88 (19.83)	−19.46 (23.83)	−20.85 (22.50)	Energized t (25) = −5.00***	–
	4	61.58 (23.43)	32.73 (17.83)	−24.12 (25.58)	−14.00 (31.98)	Energized t (25) = −5.35***	Touched t (25) = 2.58*
	5	67.00 (22.94)	20.42 (18.63)	−18.69 (20.13)	−26.31 (29.83)	Happy t (25) = −4.a42***	–
	6	63.92 (21.57)	28.46 (20.10)	−21.77 (23.11)	−18.27 (30.65)	Energized t (25) = −4.65***	–
Positive	1	69.27 (19.89)	33.88 (23.72)	−16.42 (23.79)	−12.85 (35.10)	Energized t (25) = −2.88**	Touched t (25) = 2.50*
	2	75.65 (21.65)	38.35 (24.65)	−10.04 (22.08)	−8.38 (33.49)	Helpless t (25) = −2.64*	Touched t (25) = 3.78***
	3	68.12 (24.72)	23.50 (16.77)	−17.58 (25.61)	−23.23 (30.92)	Helpless t (25) = −2.45*	Touched t (25) = 2.67*
	4	78.38 (18.67)	28.12 (20.90)	−7.31 (19.35)	−18.62 (27.91)	Stressed t (25) = −3.27**	Touched t (25) = 3.37**
	5	63.69 (24.37)	30.85 (21.29)	−22.00 (23.82)	−15.89 (31.40)	Happy t (25) = −3.31**	Touched t (25) = 2.41*
	6	73.31 (18.48)	46.96 (24.35)	−12.38 (16.16)	0.23 (17.37)	Happy t (25) = −2.09*	Touched t (25) = 2.96**
Traumatic	**1**	24.15 (24.43)	46.50 (26.53)	−61.54 (26.45)	−0.23 (32.51)	Happy t (25) = −8.85***	Touched t (25) = 7.84***
	3	33.58 (24.25)	46.73 (21.10)	−52.11 (28.38)	0.00 (32.21)	Happy t (25) = −7.97***	Angry t (25) = 6.19***
	4	33.35 (23.80)	40.12 (19.73)	−52.35 (28.30)	−6.62 (25.34)	Happy t (25) = −8.08***	Touched t (25) = 7.13***
	5	25.50 (22.63)	40.12 (27.17)	−60.19 (25.00)	−6.62 (27.39)	Happy t (25) = −9.21***	Touched t (25) = 8.04***
	6	42.85 (25.15)	39.27 (19.78)	−42.85 (27.62)	−7.46 (28.90)	Happy t (25) = −5.90***	Touched t (25) = −5.80***

Note: Highlighted in boldface are the stimuli for which, based on the cross-wavelet-spectra analyses, significant physiological linkage was found.

Abbreviations: ARO, observers' arousal rating after video; BL-C ARO, baseline-corrected arousal; BL-C VAL, baseline-corrected valence rating; DEC, observers' greatest decrease in emotion compared to baseline; INC, observers' greatest increase in emotion compared to baseline; SP, stimulus person; VAL, observers' valence rating after video; VC, valence category.

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

part of the scale for traumatic reports; Table 2 (see Table S1 for subjective affect linkage ratings per stimulus).

Observers' facial EMG responses also showed alignment with the stimulus valence categories with increased zygomaticus facial muscle site activity to the positive category and increased corrugator muscle site activity to the negative categories; Table 2 (see Table S2 for facial muscle responses per stimulus).

Observing participants had generally longer IBIs than reporting participants and showed similar spectral power across valence categories. Means and standard deviations are reported in Table 2.

2.3 | Physiological linkage: IBI

Significant IBI associations were found for 16 out of 21 tested videos. These 16 videos span all four valence categories included in this study. Significant associations predominantly occurred in the LF and VLF bands.

2.3.1 | Category: traumatic

Observers watching the traumatic video of stimulus person 1 showed significant physiological linkage in the LF with slight crossover into the VLF and HF bands of the cross-wavelet spectrum in the range of 0.033–0.173 Hz after TFCE correction for multiple comparisons (Figure 1b), most consistent with an effect lasting for 150 s and starting around second 105. The identified sequence of linkage corresponds to the section of the video where the individual is reporting about the multiple instances of rape they experienced and the context surrounding the incidents. The regional average wavelet coefficient was located in the upper left quadrant of the complex plane (Figure 1d), indicating a strong phase shift between the reporting individual and the observers. Phase shift denotes that the pairs' signal was at different points in their cycle at a specific time point, that is, shifted along the *x*-axis, which is illustrated in Figure 1e. A regional average located on the right side on the x-axis would indicate no phase shift/synchrony (0°) whereas a regional average on the left side on the *x*-axis would indicate counter-fluctuation (180°); please refer to Appendix S1 for illustration of phase shift and its relationship with regional averages in the complex plane. As can be seen in Figure 1e, the phase shift corresponds to almost counter-fluctuating IBI time series. Another significant physiological linkage cluster was identified for a later segment in the video in the LF band (0.040–0.086 Hz). This segment started around second 290, lasting for about 20 s, where the individual reenacted their bodily response when they realized, they were being sexually attacked again. The regional average wavelet coefficient was located in the lower left quadrant (Figure 1d), indicating marked phase shift between the reporting individual and the observers. Although the Pearson correlation (Figure 1c) did not identify the physiological linkage, the cross-power spectrum showed significant linkage for the same frequencies as the cross-wavelet spectrum (Figure 1a).

The traumatic report of stimulus person 3 showed no significant physiological linkage based on the Pearson correlation and the cross-wavelet spectrum, whereas the cross-power spectrum identified some physiological linkage at LF and HF. Given that the cross-power spectrum analysis does not provide timing information, the identified physiological linkage cannot be related to video content. The figure showing these results can be found in Figure S2.

The traumatic report of stimulus person 4 led to significant physiological linkage in the LF and HF bands (0.093–0.173 Hz) and lasted for approximately 30 s starting around second 15. This segment corresponds to the individual reporting about being invited into their relative's bed, and their sibling supporting the suggestion. The regional average was situated on the left side of the complex plane nearly on the x-axis indicating almost counter-fluctuation between observers and reporting participants. The second significant cluster identified with cross-wavelet spectrum analysis was situated in the VLF with a slight crossover into the LF band of the cross-wavelet spectrum (0.025–0.053 Hz) lasting for ca 105 s starting around second 45. This segment corresponds to the individual recalling the act of sexual abuse by their relative. The regional average was situated in the lower left quadrant of the complex plane indicating a marked phase shift between observers and reporting participants. The Pearson correlation did not show significant physiological linkage. The cross-power spectrum showed significant physiological linkage in the HF band. All results are visualized in Figure 2.

The traumatic report of stimulus person 5 led to significant physiological linkage in the VLF in the range of 0.025–0.038 Hz, starting around second 75 with an approximate duration of 125 s. During the period most compatible with the TFCE-cluster of the traumatic video, the individual was reporting about the moment right after their motorcycle accident, their physical pain, and seeing their injured relative lying on the ground. The regional average was situated in the lower left quadrant of the complex plane, close to the *x*-axis, indicating almost counter-fluctuation between observers and reporting participants. Physiological linkage in the VLF was found in the cross-power spectrum as well, but not in the Pearson correlation. All results are visualized in Figure 3.

During the traumatic report of stimulus person 6, a strong physiological association in the VLF reaching into the LF band (0.025–0.061 Hz) of the cross-wavelet spectrum of the IBI of the stimulus person and observers was found practically for the entire analyzed duration of the report. The stimulus person reported about the situation where they were hit by another person, fainted, and woke up without vision. The regional average was situated in the lower left quadrant of the complex plane indicating a marked phase shift between observers and reporting participant. Physiological linkage was clearly visible in the

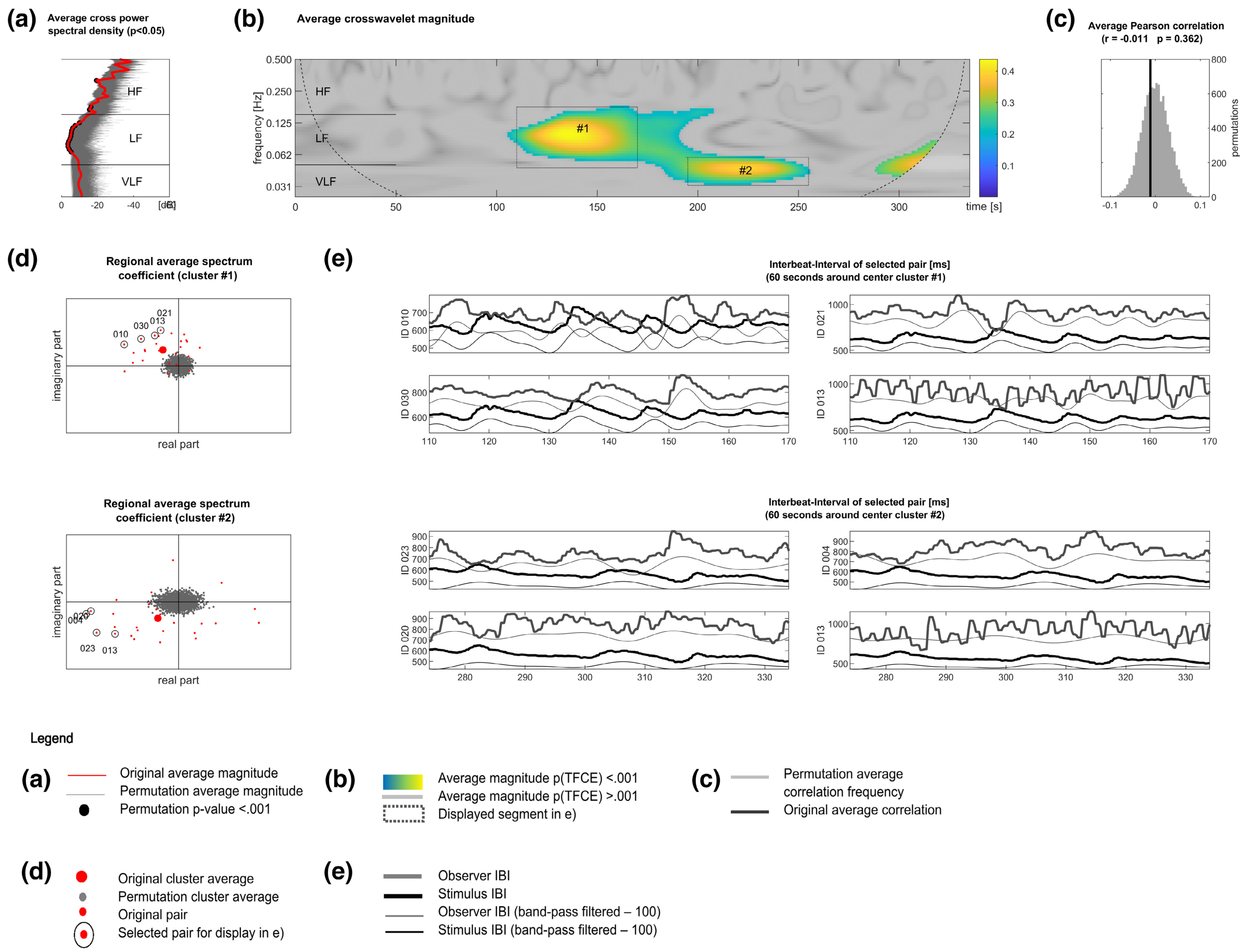

FIGURE 1 Stimulus person 1, traumatic report. Variation testing for the identified cluster shows a significant regional cross-wavelet spectrum average (=large red dot in d)), not visible in the Pearson correlation (c) and cross-power spectrum (a). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the four participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

cross-power spectrum, but not in the Pearson correlation. All results are visualized in Figure 4.

2.3.2 | Category: negative (non-traumatic)

Significant physiological linkage was found for stimulus person 2 during the report about the first negative event in the VLF and LF bands of the cross-wavelet spectrum. Cluster 1 was situated in the LF reaching into the HF band in the range of 0.073–0.173 Hz, starting around second 165, and lasting for around 30 s. The regional average was situated in the upper right quadrant of the complex plane indicating only a small phase shift (almost synchrony) between observers and reporting individuals in IBI changes. The significant cluster corresponds to the moment where the individual is reporting about realizing how far away all their loved ones were when they went oversees for educational purposes. The regional average was situated on the left side of the complex plane on the *x*-axis indicating counter-fluctuation. Cluster 2 was predominantly situated in the VLF band but also reached into the LF band (0.025–0.05 Hz) and lasted for about 180 s, starting around second 290. The regional average for this cluster was situated on the left side of the complex plane on the x-axis indicating counter-fluctuation. The significant cluster corresponds to the moment where the individual was reporting in tears how they realized they did not want to stay overseas, which also made them feel guilty recognizing their privilege. The Pearson correlation was positive and significant. The cross-power spectrum showed significant

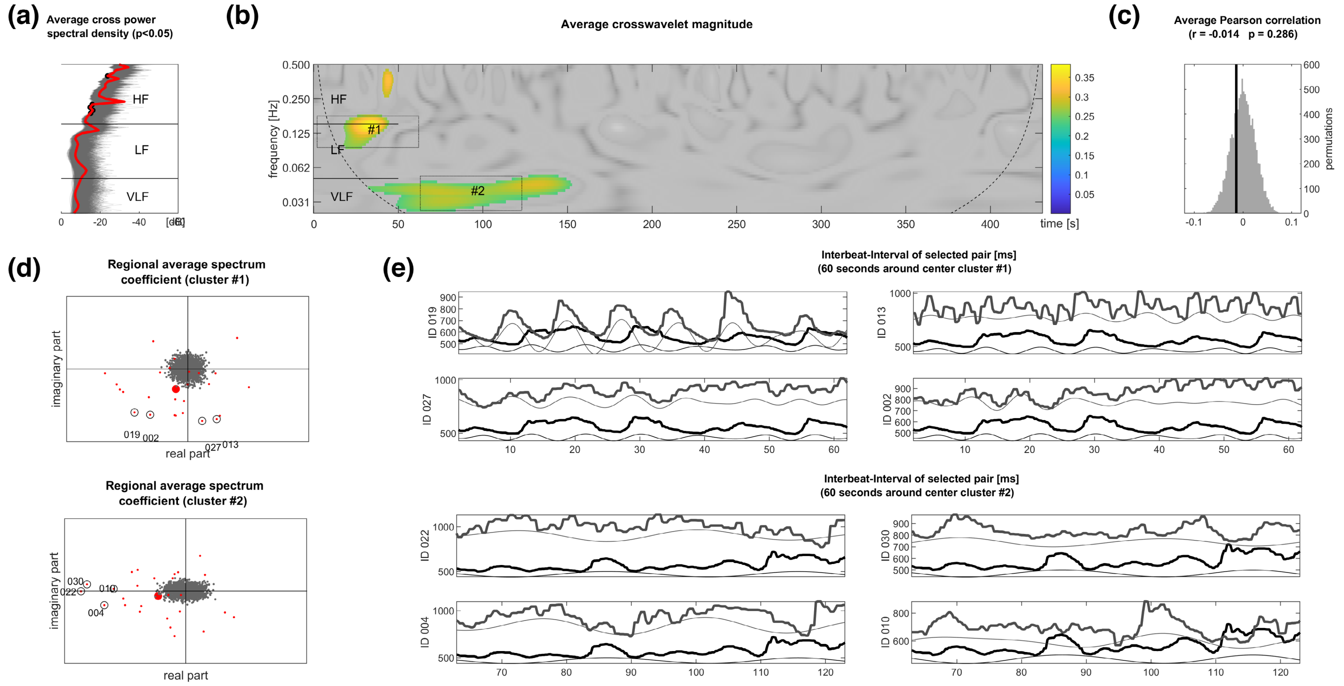

FIGURE 2 Stimulus person 4, traumatic report. The significant physiological linkage clusters are visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

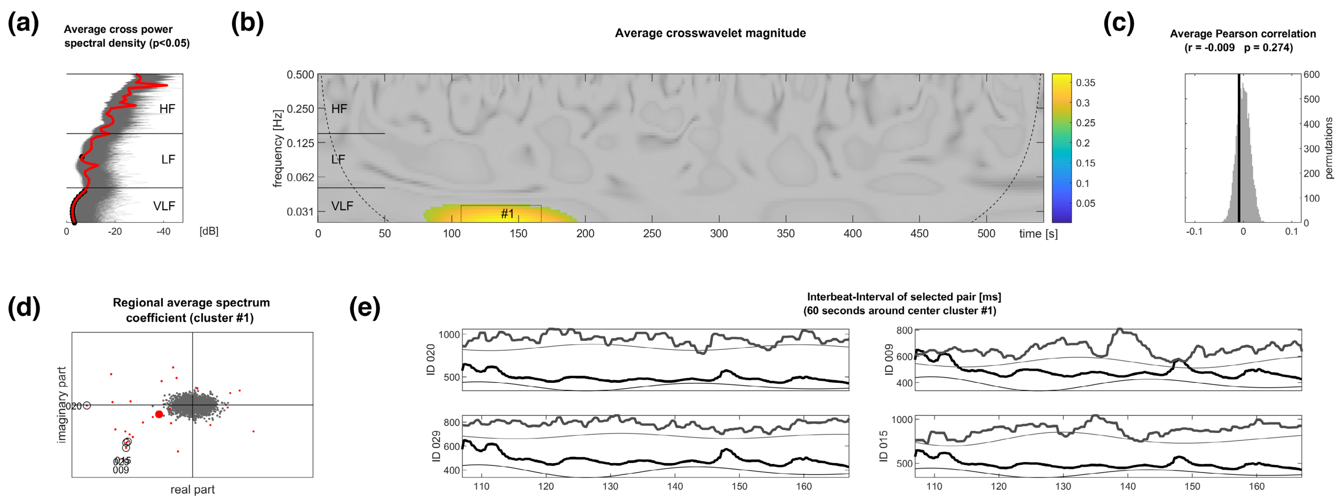

FIGURE 3 Stimulus person 5, traumatic report. The significant physiological linkage cluster is visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

physiological linkage at the VLF, LF, and HF bands. All results are visualized in Figure 5.

The second negative report by stimulus person 2 led to two significant clusters of physiological linkage in the cross-wavelet spectrum. Cluster 1 started around second 25 and lasted for approximately 15 s. This cluster stretched across the LF and HF bands (0.114–0.185 Hz) and corresponds to the moment when the reporting participant spoke about being constantly physically agitated as part of their anorexia nervosa. The regional average

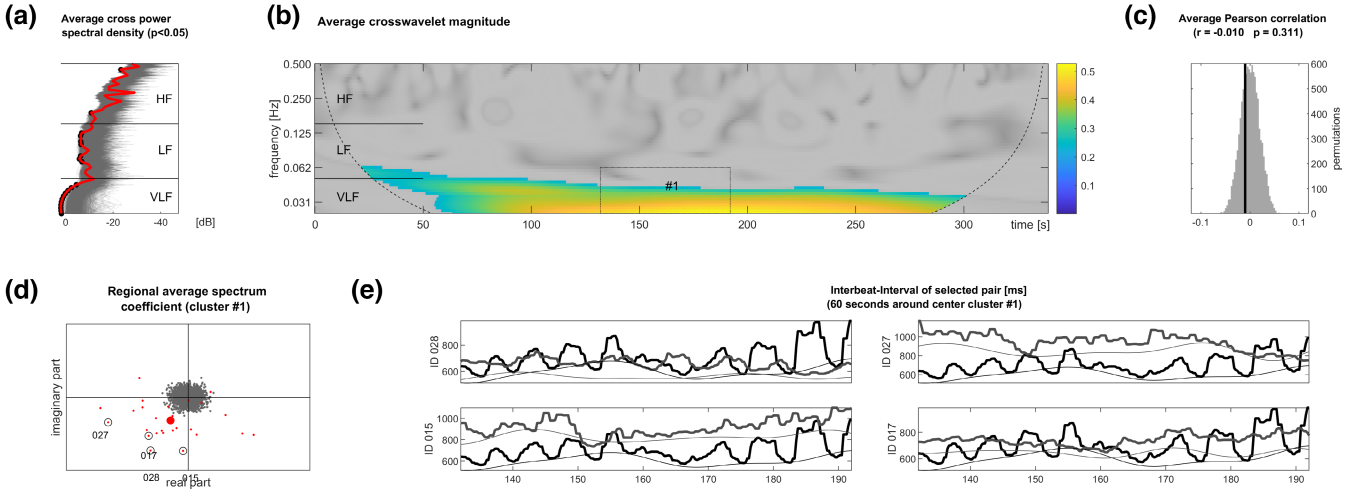

FIGURE 4 Stimulus person 6, traumatic report. The significant physiological linkage cluster is visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

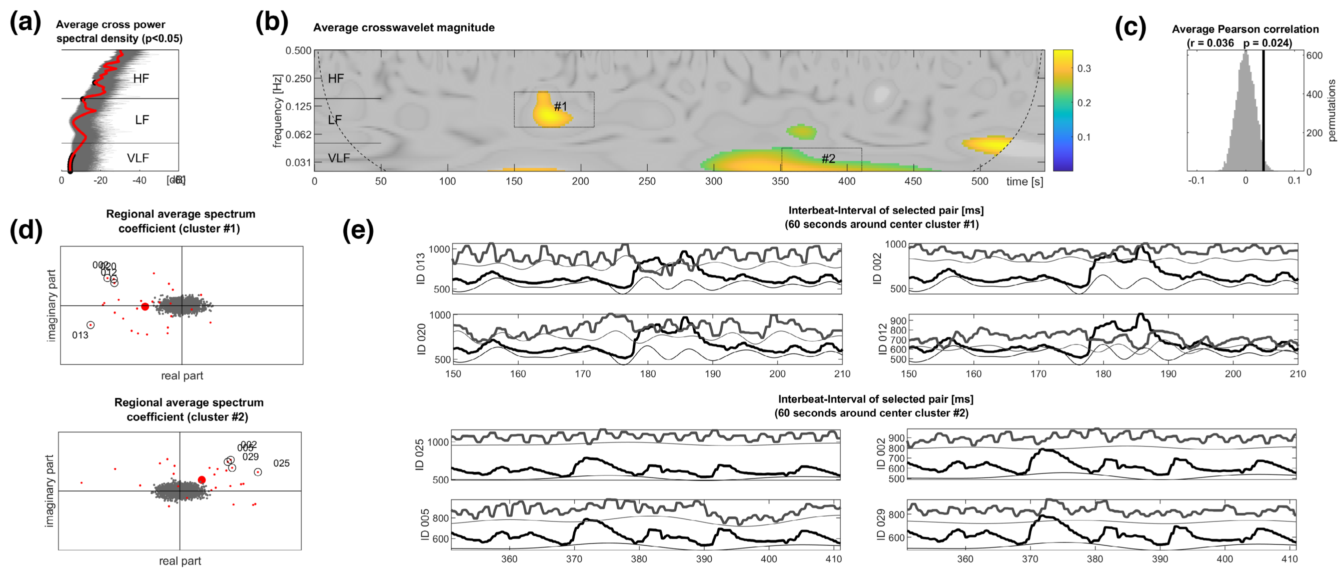

FIGURE 5 Stimulus person 2, first negative report. The significant physiological linkage clusters are visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

was situated in the left upper quadrant of the complex plane indicating a strong phase shift. Cluster 2 fell on the border of the LF and HF bands (0.122–0.150 Hz), started around second 235, and lasted for approximately 5 s. At this moment, the individual reported in tears how they preferred dying over gaining weight. The regional average was situated in the lower quadrant on the x-axis of the complex plane indicating a substantial phase shift almost counter-fluctuating. The Pearson correlation was negative and significant. The cross-power spectrum showed significant physiological linkage in the VLF, LF, and HF bands. All results are visualized in Figure 6.

The negative report by stimulus person 3 led to significant physiological linkage in the cross-wavelet spectrum in the LF band. Cluster 1 was in the range of 0.053–0.099 Hz, started around second 25, and lasted approximately 40 s.

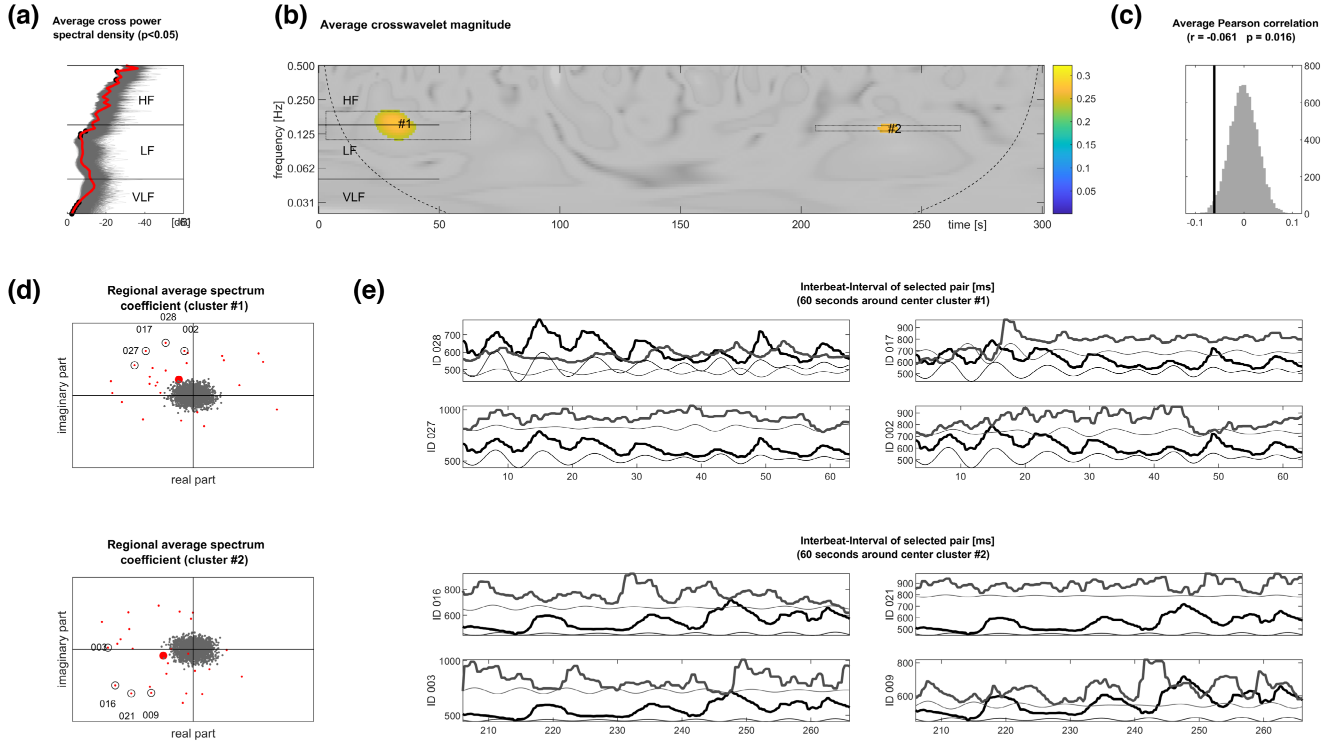

FIGURE 6 Stimulus person 2, second negative report. The significant physiological linkage clusters are visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

This segment corresponds to the individual reporting about being yelled at by another person. The regional average was situated on the left side of the complex plane on the *x*-axis indicating counter-fluctuation. Cluster 2 was in the range of 0.075–0.14 Hz, started around second 230, and lasted about 30 s. In this segment, the individual describes a scene in the dark hallway of their flat where the yelling was taking place. The regional average was situated in the lower left quadrant of the complex plane close to the *x*-axis indicating almost counter-fluctuation. The Pearson correlation was negative and significant. The cross-power spectrum showed significant physiological linkage in the VLF, LF, and HF bands. All results are visualized in Figure 7.

Significant physiological linkage was found for stimulus person 4 during the report about a negative event. The negative report led to a positive association in the VLF band in the range of 0.025–0.043 Hz with an approximate duration of 165 s, starting around second 75. The identified sequence corresponds to the section of the video where the person is reporting, under tears, about a friend's terminally ill child. The regional average cross-wavelet coefficient of the corresponding cluster was located in the upper right quadrant of the complex plane (Figure 3d), indicating only a small phase shift between the person in the video and the observers. Physiological linkage was not visible in the Pearson correlation but in the cross-power spectrum (VLF and HF). All results are visualized in Figure 8.

The negative report of stimulus person 5 led to significant negative associations in the VLF for almost the entire video duration in the range of 0.025–0.061 Hz (cluster 1) and the LF band in the range of 0.061–0.131 Hz with an approximate duration of 55 s (cluster 2). Physiological linkage was found in the cross-power spectrum as well, but not in the Pearson correlation. In the video, the first cluster corresponds to the stimulus person reporting about being in the car with a close relative. They stated that there was friction between the two and that the stimulus person caused a minor accident. The regional average was situated in the lower left quadrant of the complex plane indicating a marked phase shift between observers and reporting participant. The second sequence refers to the moment where the stimulus person mentioned verbally fighting with their close relative and described the damage to the vehicle. The regional average was situated in the upper left quadrant of the complex plane indicating a strong phase shift between observers and reporting participant. All results are visualized in Figure 9.

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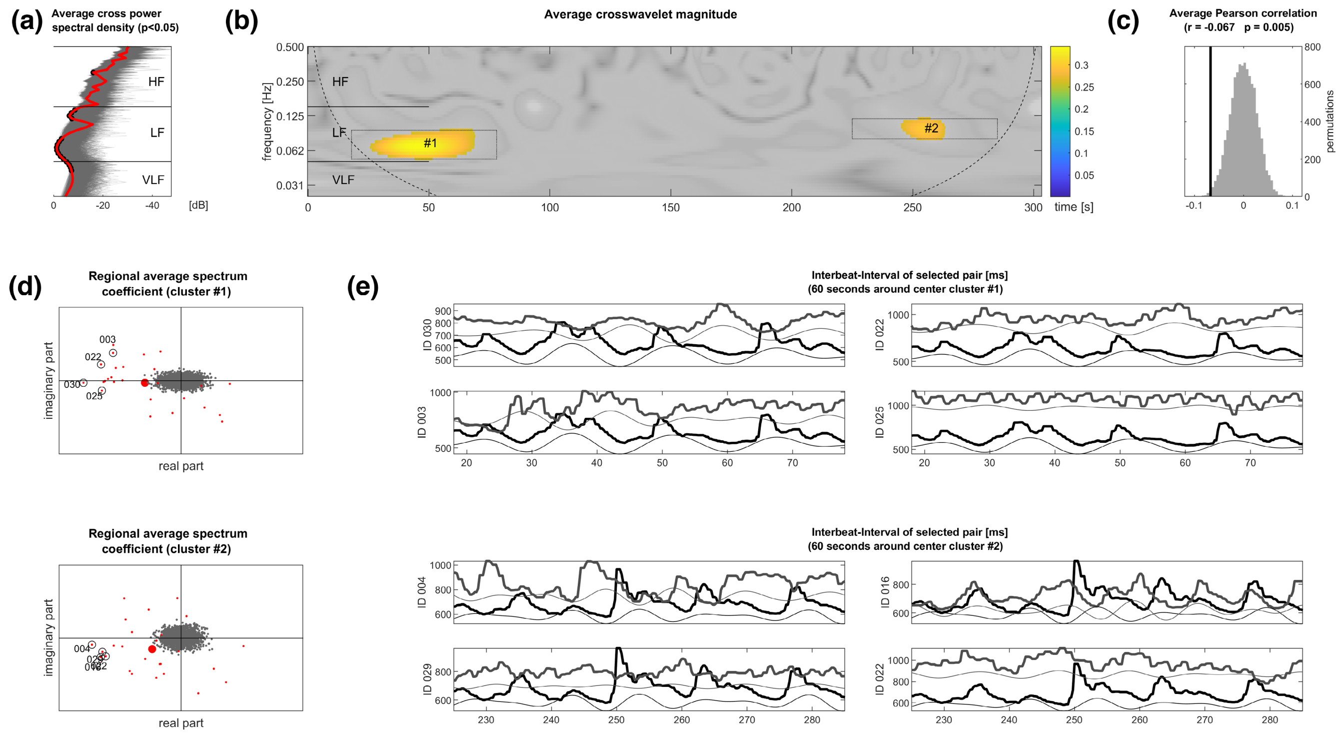

FIGURE 7 Stimulus person 3, negative report. The significant physiological linkage clusters are visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

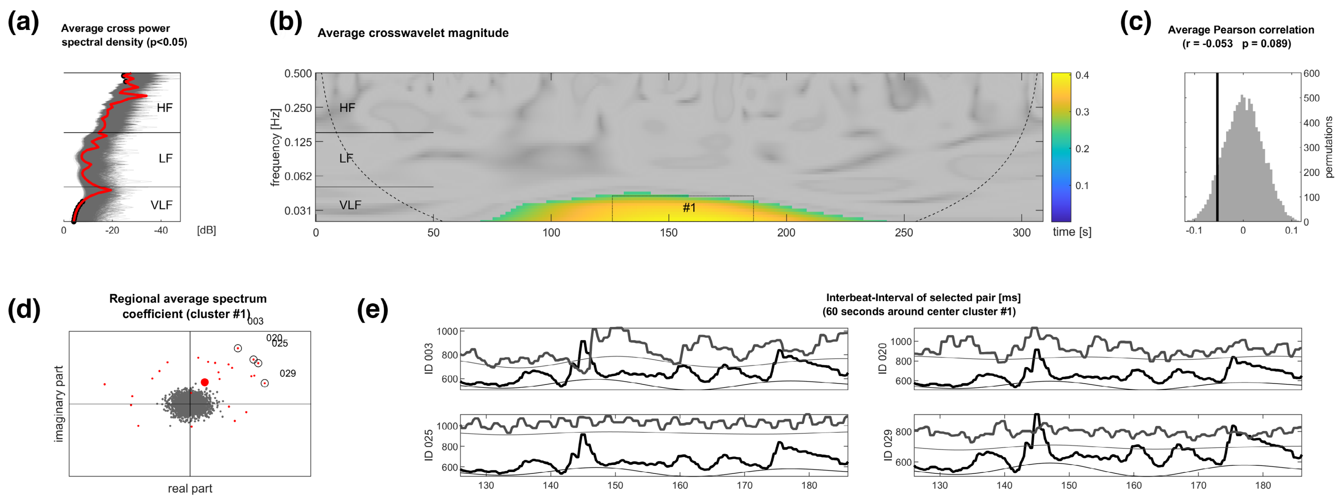

FIGURE 8 Stimulus person 4, negative report. The significant physiological linkage cluster is visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

The negative report of stimulus person 6 led to significant physiological linkage in the cross-wavelet spectrum. Cluster 1 was in the LF band in the range of 0.053–0.086 Hz, starting around second 80, and lasting approximately 65 s. This segment corresponds to the moment where the individual reported about receiving the

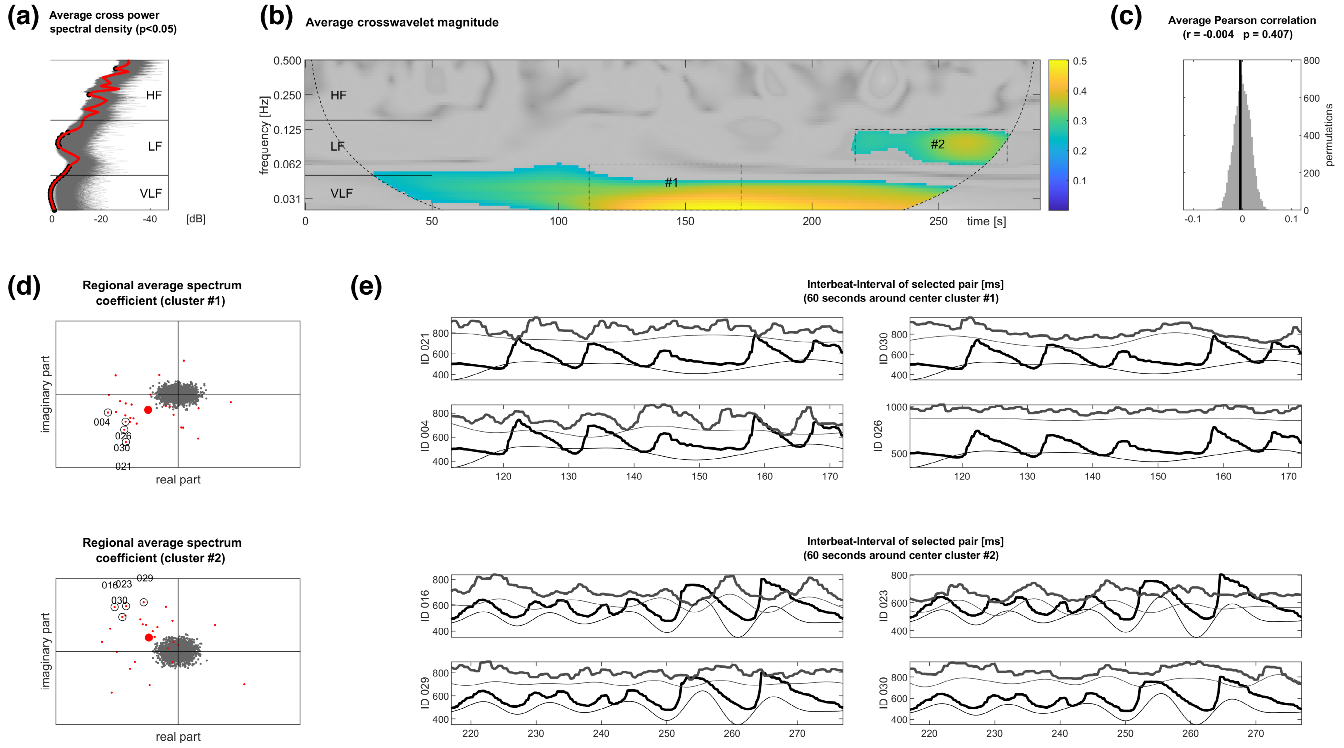

FIGURE 9 Stimulus person 5, negative report. The significant physiological linkage clusters are visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

news that they will no longer be allowed to take care of a foster animal and how this affected them. The regional average for this cluster was situated in the upper left quadrant of the complex plane almost on the y-axis indicating a small phase shift. Cluster 2 was in the VLF band in the range of 0.025–0.035 Hz, starting around second 50, and lasting for ca. 50 s. The segment corresponds to the individual sharing how they re-evaluated the aforementioned information. The regional average for this cluster fell into the lower half of the complex plane and right on the y-axis hinting at a small phase shift. The Pearson correlation was positive and close to reaching significance. The cross-power spectrum showed significant linkage in the VLF, LF, and HF bands. All results are visualized in Figure 10.

2.3.3 | Category: positive

For the positive report of stimulus person 2, significant physiological linkage was found based on the cross-wavelet spectrum in the VLF band (0.025–0.046 Hz) for a period of approximately 175 s and starting around second 30. The identified segment corresponds to the individual reporting full of joy about their prom. The regional average for this cluster was located in the upper right quadrant very close to the *x*-axis demonstrating close synchrony between observers and reporting participant. The Pearson correlation was positive and significant. The cross-power spectrum showed significant linage in the VLF, LF, and HF bands. All results are visualized in Figure 11.

The positive report of stimulus person 3 showed no significant physiological linkage based on the cross-wavelet spectrum, whereas the cross-power spectrum identified physiological linkage at LF and HF. The Pearson correlation was negative and close to reaching significance. The figure showing these results can be found in Figure S3.

For stimulus person 4, significant physiological linkage was found for the positive report in the LF to HF band (0.081–0.198 Hz) based on the cross-wavelet spectrum. The cluster started around second 35 and lasted about 35 s. The significant segment corresponds to the individual recalling a trip in nature together with friends. The regional average for the cluster fell in the upper left quadrant of the complex plane and close to the *x*-axis indicating a strong phase shift, almost counter-fluctuating. Although the Pearson correlation showed no physiological linkage, the cross-power spectrum showed linkage in the VLF, LF, and HF bands. All results are visualized in Figure 12.

The positive report of stimulus person 5 showed a cluster of physiological linkage in the cross-wavelet

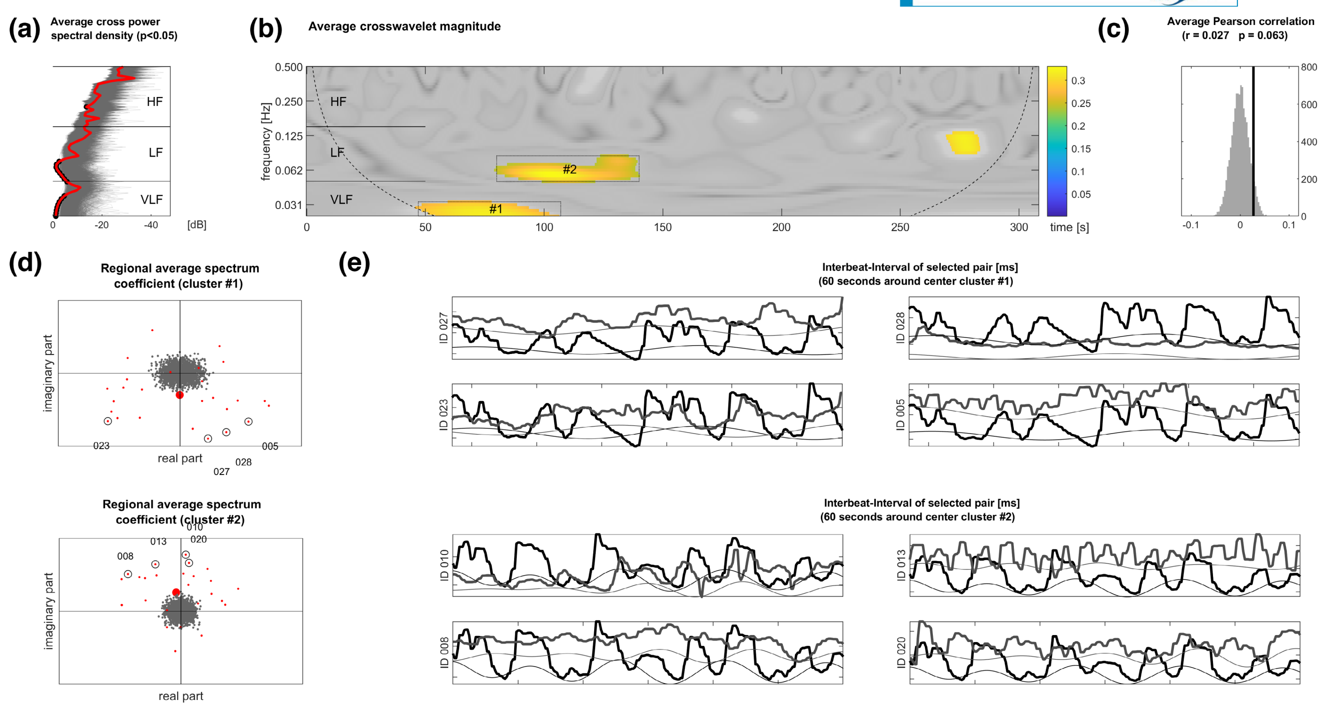

FIGURE 10 Stimulus person 6, negative report. The significant physiological linkage clusters are visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

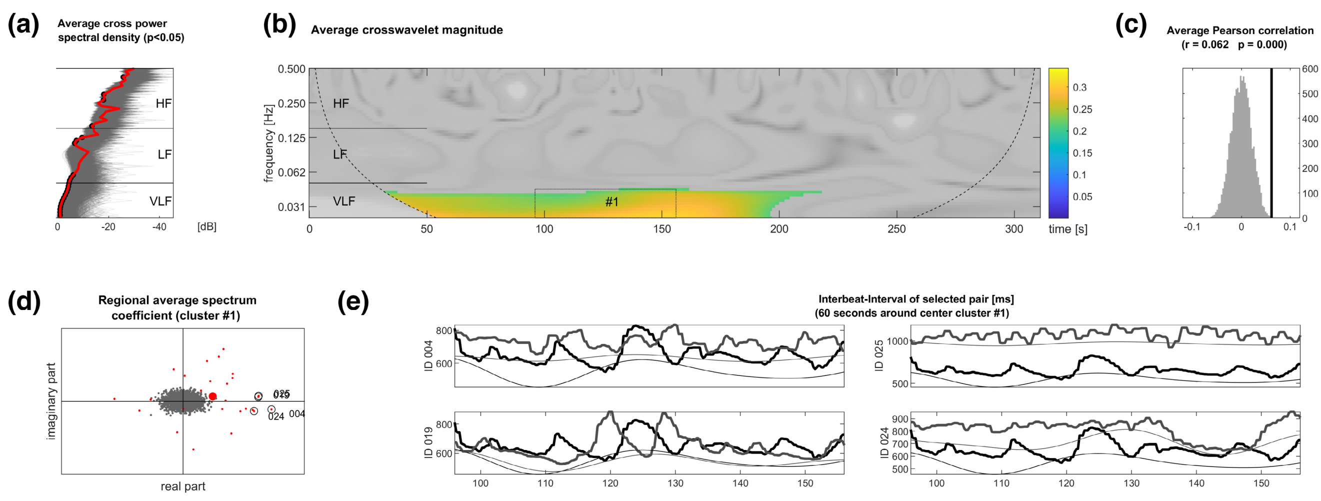

FIGURE 11 Stimulus person 2, positive report. The significant physiological linkage cluster is visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

spectrum in the VLF band in the range of 0.025–0.043 Hz. The cluster started around second 135 lasting for 110 s. This segment corresponds to the individual reporting about having a good time with their best friend, playing a game. The regional average was situated in the lower left quadrant of the complex plane indicating a marked phase shift between observers on reporting participant. The negative Pearson correlation was significant, and

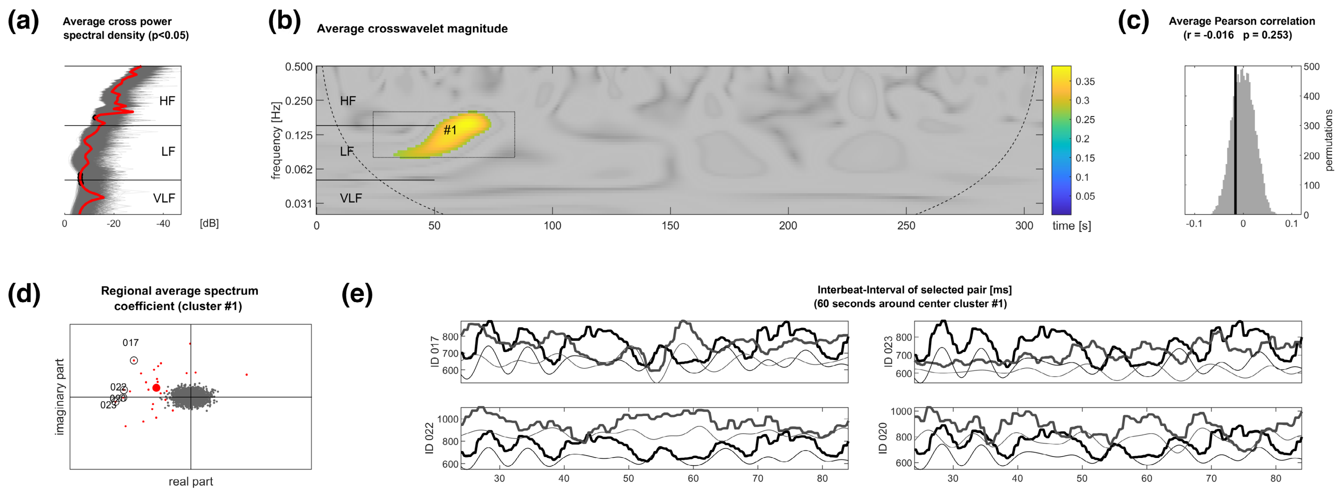

FIGURE 12 Stimulus person 4, positive report. The significant physiological linkage cluster is visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

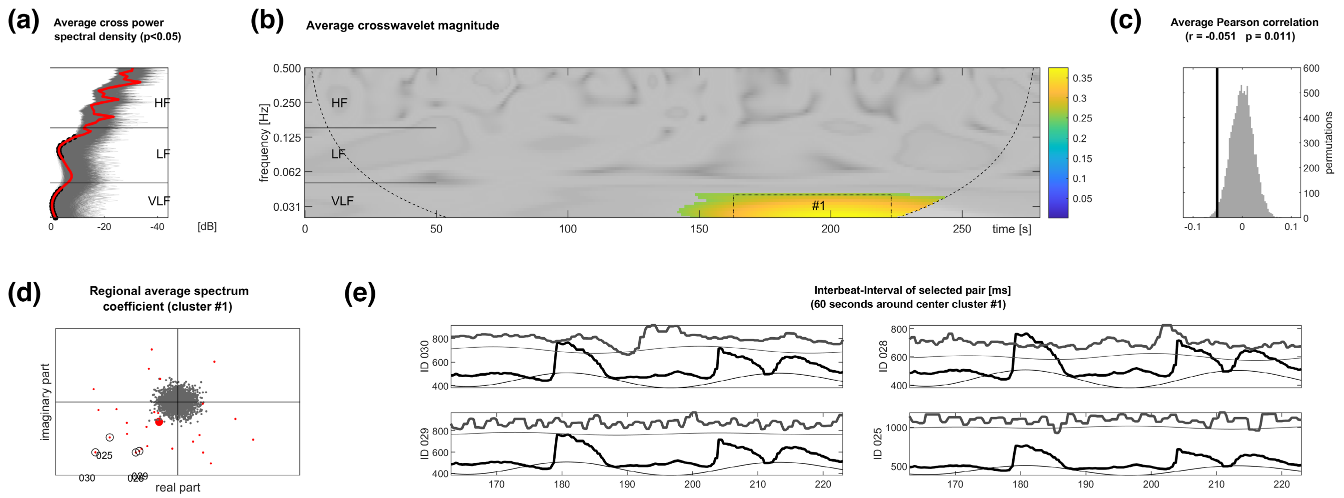

FIGURE 13 Stimulus person 5, positive report. The significant physiological linkage cluster is visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

the cross-power spectrum showed significant physiological linkage in the VLF and LF bands. All results are visualized in Figure 13.

The positive report of stimulus person 6 led to two significant clusters of physiological linkage based on the cross-wavelet spectrum. Cluster 1 fell in the VLF reaching into the LF band in the range of 0.025–0.053 Hz with an approximate duration of 80 s and starting around second 25. The identified segment corresponds to the individual reporting about nervousness in relation to an exam. The regional average in the complex plane was situated in the upper half and right on the y-axis indicating a smaller phase shift between reporting and observing participants. Cluster 2 stretches across the LF and HF bands in the range of 0.061–0.262 Hz and is of approximately 35 s durations, starting around second 255. This segment corresponds to the moment where the individual reported about a kind examiner and how this positively affected them. The regional average for cluster 2 was situated in the upper right quadrant of the complex plane

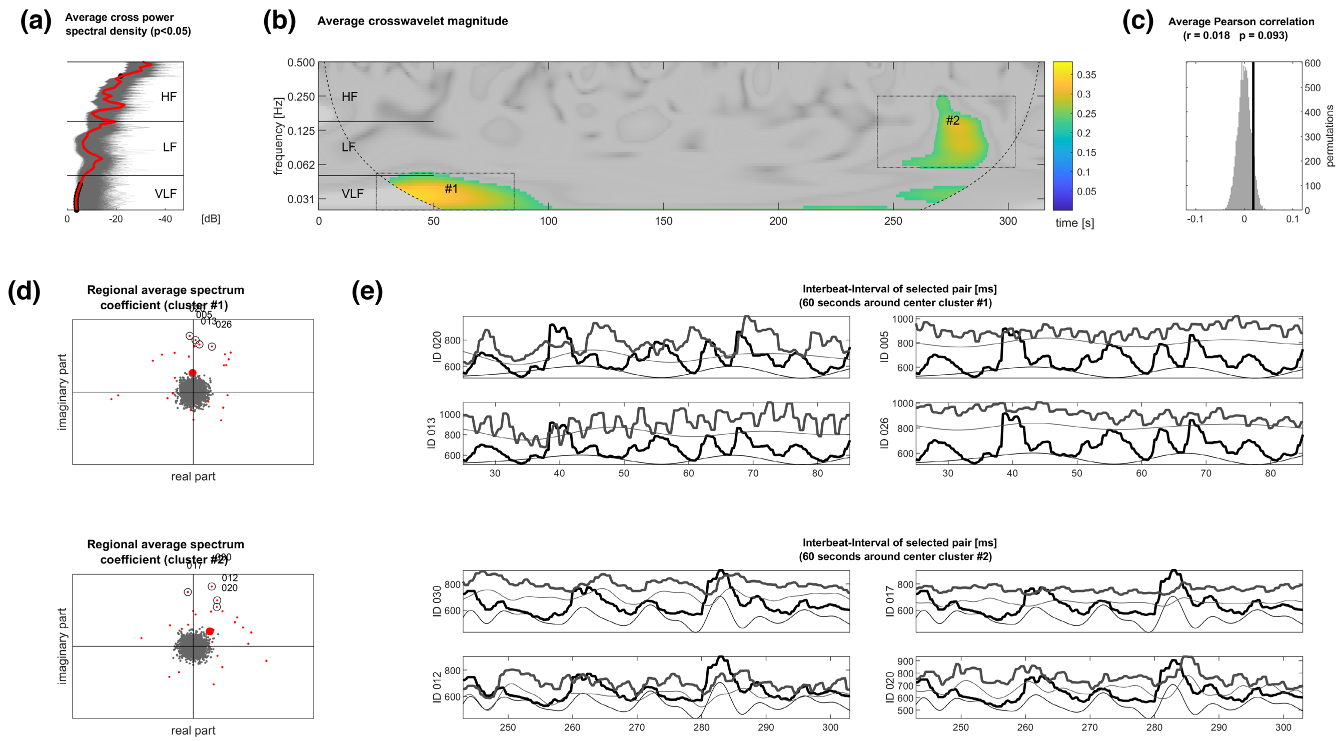

FIGURE 14 Stimulus person 6, positive report. The significant physiological linkage clusters are visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

indicating only a small phase shift between observers on the reporting participant. The Pearson correlation was not significant. The cross-power spectrum showed significant physiological linkage in the VLF and HF bands. All results are visualized in Figure 14.

2.3.4 | Category: neutral

Based on the cross-wavelet spectrum, there was no physiological linkage for stimulus person 2 during the neutral report. The Pearson correlation was also not significant. The cross-power spectrum showed significant physiological linkage in the HF band. The figure showing these results can be found in Figure S4.

During the neutral report of stimulus person 3, significant physiological linkage was found in the cross-wavelet spectrum in the LF with a crossover into the HF range (0.053–0.185 Hz). This segment started around second 70 and lasted for about 160 s. This period corresponds to the section in the video where the person reported about being in a café and describing tasty food and drinks. The location of the regional average spectrum coefficient in the upper left quadrant close to the x-axis indicates a strong phase shift with almost counter-fluctuation between the person in the stimulus and observers. The cross-power spectrum showed significant physiological linkage in the LF and HF bands. The negative Pearson correlation was highly significant. All results are visualized in Figure 15.

The cross-wavelet spectrum showed significant physiological linkage for stimulus person 4 during the neutral report in the LF band in the range of 0.075–0.140 Hz. The cluster started around second 50 and lasted for about 25 s. The segment corresponds to the stimulus person describing their current and desired living situation. The regional average was located in the left upper quadrant close to the *x*-axis indicating a strong phase shift with almost counter-fluctuation between the person in the stimulus and observers. The Pearson correlation was negative and close to significance. The cross-power spectrum showed significant physiological linkage in the VLF, LF, and HF bands. All results are visualized in Figure 16.

The neutral reports of stimulus persons 5 and 6 did not show any significant physiological linkage in the cross-wavelet spectrum. The Pearson correlations were also not significant. The cross-power spectrum of stimulus person 6 showed significant linkage in the HF band, whereas for stimulus person 6, there was significant linkage in the LF

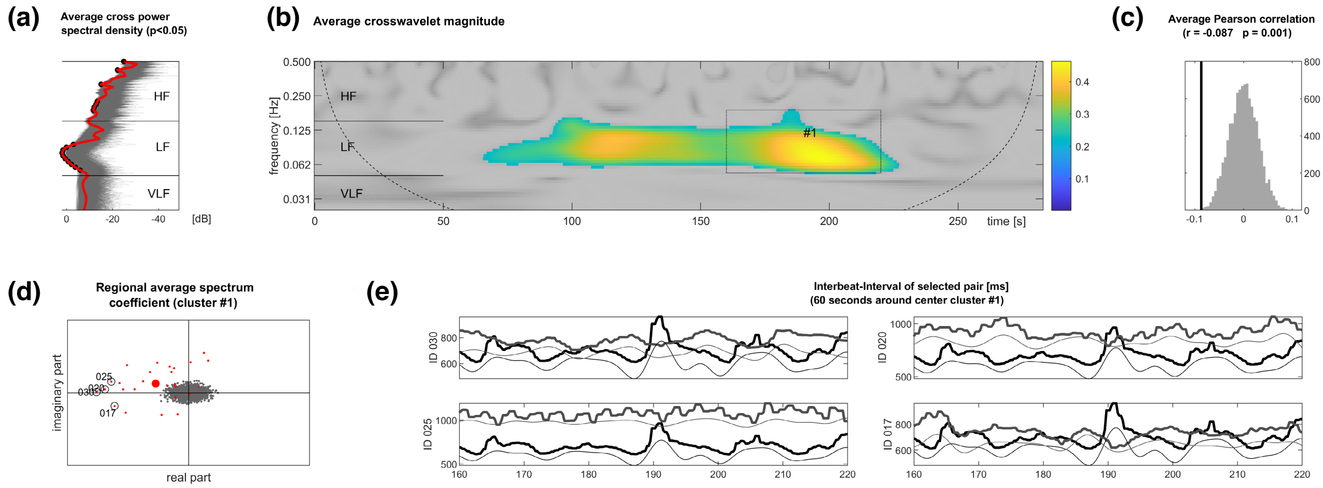

FIGURE 15 Stimulus person 3, neutral report. The significant physiological linkage cluster is visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

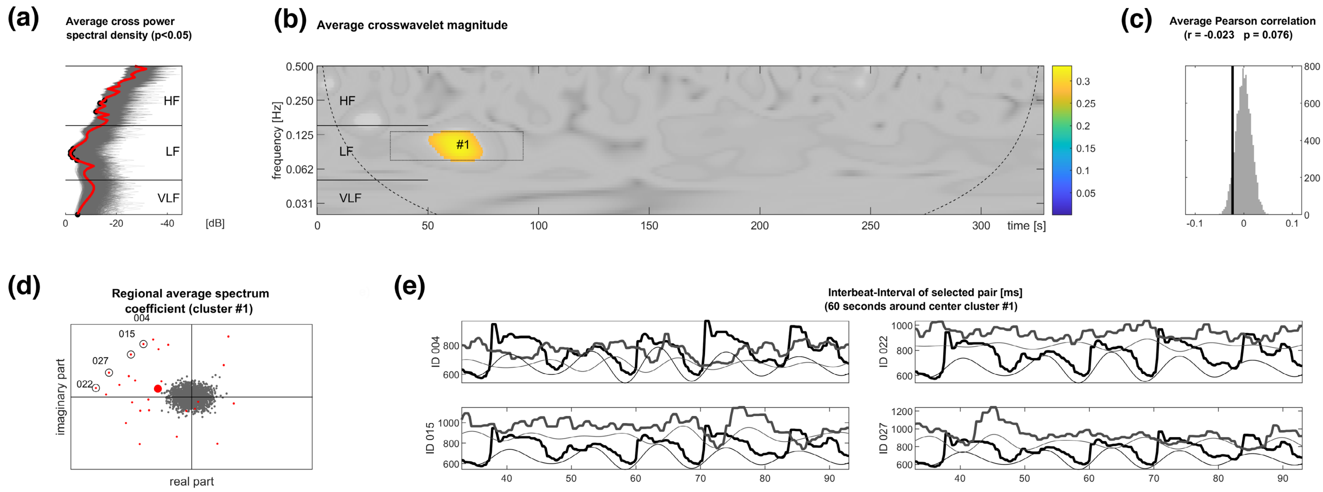

FIGURE 16 Stimulus person 4, neutral report. The significant physiological linkage cluster is visualized in (b). The cross-power spectrum is presented in (a) and the Pearson correlation in (c). The gray dots in (d) represent the variation averages (i.e., the test distribution for the large red dot). Each small red dot represents a pair of participants, that is, the stimulus person and one observer. The original and band-pass filtered IBIs of the participants with the strongest linkage effect are plotted for in (e): each plot shows 60 s, corresponding to the dotted box in the cross-wavelet spectrum in (b). From the filtered IBI, 100 was deducted to avoid overlapping of original and filtered data.

and HF bands. The respective figures with the results can be found in Figures S5 and S6.

3 | DISCUSSION

The current study investigated physiological linkage between observers and individuals in videos reporting about personal experiences that fit into the affective categories positive, neutral, and negative (non-traumatic and traumatic). Cross-wavelet analysis has proven to be a sensitive approach in identifying physiological linkage using standardized stimuli. In line with the hypothesis, periods of physiological linkage in the HR IBI were found across all affective categories (for 16 of 21 tested videos). Physiological linkage was found mainly in the VLF and LF bands but reached into the HF band. Employing a promising analysis approach, the current research demonstrates that (1) it is possible for an observing individual to link their physiology (based on HR IBI) to an unfamiliar person without time congruency, shared (live) experience, and signals only available in live interactions (e.g., signals of liking, attention, etc.) and (2) that this linkage is similar across observing individuals. That physiological linkage can be measured from videos of distinct affective valence categories (including neutral) opens up many research opportunities and should encourage the use of standardized stimuli to learn more about underlying mechanisms, functions, and effects of physiological linkage. In addition, cross-wavelet spectrum analysis demonstrated that physiological linkage is a heterogenous phenomenon that can occur across HR frequency bands associated with a variety of psychological and physiological processes. The current findings encourage further investigation of individual frequency bands in light of physiological linkage from videos.

3.1 | Physiological linkage and stimulus valence

The current study found physiological linkage during reports of all four stimulus valence categories. These findings are in line with previous reports of physiological linkage occurring for emotional and neutral reports in live interactions (Scarpa et al., 2018). Based on having detected physiological linkage across conditions (sad, happy, neutral), Scarpa et al. (2018) concluded that physiological linkage may be related to the simple presence of another person. This conclusion is in line with Golland et al. (2015) who found synchronization in IBI and EDA in (non-interacting) dyads watching positive and negative emotional movies together (see also Golland et al., 2014). Golland et al. (2015) concluded that the time-locked emotional events in the stimuli in addition to the presence of another person might be driving the synchronization. However, co-presence was not found to be necessary for physiological linkage in the current study. This raises the question of whether the emotional aspects of the reports in the videos play a major role in physiological linkage after all.

The current study found a greater number of significant clusters of physiological linkage for negative valence than for positive and neutral valence reports. This finding is in line with results from videos of physiological linkage being more likely to occur for negative than positive affect (Levenson & Ruef, 1992). Levenson and Ruef (1992) concluded that physiological linkage may be difficult to occur for positive emotions, as they lack a typical pattern of automatic nervous system activity that would be necessary for physiological linkage to occur. This conclusion could explain the current results of more clusters of physiological linkage for the negative videos than the other categories. An alternative explanation is that positive and neutral reports might be less engaging than negative reports given the negativity bias in attention allocation (Smith et al., 2003). Generally, affective information is more readily attended to when deemed significant with the amygdala being considered as the underlying neural structure (Pessoa, 2010). Steiger et al. (2019) reported that the two most intense movie scenes (out of six) their participants watched led to the greatest HR linkage across observers in their study. The latter result also supports the assumed role attention and affective significance play in physiological linkage. In addition, the positive reports in the current study did not reach a level of positivity to markedly increase observing participants' valence ratings compared to baseline, although the self-reported affect linkage was found to be similar for the negative and positive valence categories whereas lower for neutral reports. Based on the current results, it appears that high affective significance modulated by attention is a driving factor for physiological linkage. The averaged responses of the corrugator muscle in observers and IBI per stimulus valence category in reporting and observing participants in the current study seem to support this assumption, as more activation occurred for traumatic stimuli, which should have the highest affective significance and engage most attention. It remains for future research to investigate whether positive reports in videos, able to evoke more intense positive affect in observers and to engage more attention, would also lead to more physiological linkage.

3.2 | Physiological linkage and HR frequency bands

In addition to the upper and lower bounds of the HR, HR fluctuations can only vary in frequency in line with the structures and processes that elicit the changes (e.g., the Baroreflex around 0.1 Hz). Neural structures which could be involved in physiological linkage are afferents from the auditory system including the cochlea, medulla oblongata (cochlear nuclei, olivary complex, trapezoid body), midbrain (inferior colliculus), interbrain (medial geniculate body and auditory cortex), and the visual system including the retina, midbrain (superior colliculus), interbrain (lateral geniculate nucleus, pulvinar) and visual cortex (Kolb & Whishaw, 2015). The efferents regulating the heart rate are cortical areas, such as the medial prefrontal cortex and the insular cortex, subcortical forebrain areas including the hypothalamus and the amygdala, regions in the midbrain, such as the periaqueductal gray, and numerous areas in the medulla oblongata (Silvani et al., 2016). It should be noted that many of these areas are associated with emotion processing and the mirror neuron system

(Bonini et al., 2022), which could be underlying physiological linkage. Output from these structures is integrated with a baroreceptor, chemoreceptor, and group III/IV-muscle afferents in the nuclei of the medulla oblongata forming the sympathetic and parasympathetic outflow to the heart. This dual outflow, acting jointly with the intracardiac nervous system and thoracic ganglia, is assumed to coordinate the cardiac function on a beat-to-beat basis (Ardell et al., 2016).

The identified clusters of physiological linkage in the current study were mainly located in the VLF and LF bands. There were no identified clusters in the HF band although some LF clusters showed a slight crossover with the HF band up to 0.26 Hz (4 s). That is, fluctuations in IBI were overall very slow to slow with a maximum of 40 s (0.025 Hz) for one cycle of oscillation. As HF IBI changes are under parasympathetic control and commonly related to RSA (McCraty et al., 2009; McCraty & Shaffer, 2015), none of the identified physiological linkage clusters in the current study can be explained by RSA. This is in line with a study where participants listened to audio-visual narratives (not including emotional content) and found HR synchronization across listeners, which could not be explained by respiration (Pérez et al., 2021). (Note that in Pérez et al. (2021), synchronization with the stimulus was not investigated, only across observers). While LF oscillations are under sympathetic and parasympathetic control, fluctuations presenting in the VLF band are thought to be intrinsically created by the heart but modulated by efferent sympathetic activity (McCraty et al., 2009). According to McCraty et al. (2009), experiencing negative emotions or the presence of an emotional stressor can produce oscillations in the VLF band with co-occurring LF fluctuations based on the necessary blood pressure regulation. At the same time, these authors suggest that fluctuations in the VLF band can also result from mental focus (with little motor activity). With most physiological linkage clusters in the current study identified for negative reports (non-traumatic and traumatic), it can be assumed that these served as a stressor. Reporting individuals might have experienced distress due to speaking about highly personal experiences while being video-recorded and observers employed mental focus by listening to highly emotional reports, which in turn might have served as stressors for the observers.

3.3 | Physiological linkage and phase shift

Most of the identified clusters showed a strong phase shift with some showing counter-fluctuations (also called ‘anti-phase’), indicating that when the IBI of the person in the video was increasing, the observers' IBI was decreasing and vice versa. In the VLF band, fluctuations occurred over 26–40 s and a 180° phase shift would indicate that the IBI fluctuations between observers and reporting participants were shifted by 13–20 s. LF oscillations stretch 7–25 s with a 180° phase shift resulting in a difference of 3.5–12.5 s. It is noteworthy that sympathetic control has a delayed effect on the HR of up to 5 s (McCraty & Shaffer, 2015). Many identified clusters of physiological linkage in the current study were in the LF band and below a 180° phase shift and in VLF with small phase shifts. Consequently, these identified phase shifts could be explained by the delayed sympathetic HR modulation through sharing emotions involving sympathetic activation. For example, observing a reporting individual's anger towards a rapist could also elicit anger in observers with an increase in HR (see Kreibig et al., 2010). Activated reflexive feedback loops, for example involving the baroreflex due to the change in HR, could explain linked oscillations in IBI after emotion onset across participants.

Furthermore, the videos included continuous emotional reports. It is thus likely that multiple emotions occurring in the reporting individuals elicited either multiple shared emotional responses and/or (non-shared) emotional responses in observers. It is further possible that behavioral mimicry served as a trigger for physiological linkage across observers to the reporting participant. For example, it has been found that head tilts by 70° gradually increase the HR, even over a 90-s period (Borst et al., 1982). A slight change in the seating position in the reporting participant could have been mirrored by observing participants and caused physiological linkage in IBI in the VLF band. High levels of empathy have been found to facilitate behavioral mimicry (Chartrand & Bargh, 1999). Mirror neurons could also have been involved in physiological linkage, as mirror neuron activity has been associated with affective empathy (Nummenmaa et al., 2008), and physiological linkage is assumed to physiologically drive empathy (Levenson & Ruef, 1992). A more recent literature review further identified partial support for a role of the mirror neuron system in empathy (Bekkali et al., 2021). Notably, greater changes in HR were found in participants who self-reported higher empathy when watching an emotional movie (Steiger et al., 2019). Given the emotional content of the reports in the current study, empathy could have played a role in the results and should gain more attention in future research.

In addition, unconscious perceptual processes could be taking place. Biomedical engineering research has shown that standard PCs with RGB cameras can measure cardiovascular activity (e.g., blood pressure, HR) via photoplethysmography based on detected color changes in the face's skin due to pulse-induced artery extension (Wang et al., 2014). The human visual system might be able to extract this information as well and in combination with mirror neuron activity could lead to physiological linkage in cardiovascular activity. Future research could test this speculation by editing the skin color in videos while measuring HR in stimulus person and observers akin to the current study.

Phase shifts close to 180° can suggest a marked delay in the same physiological processes but also that opposing processes were taking place at the same time. Staying with the above example, the observation of experienced anger in the reporting participant in combination with the information on the context surrounding the elicitor may capture the attention of observers akin to an orienting response. It has been demonstrated that the orienting response includes a decrease in HR which is amplified for negative stimuli (Bradley et al., 2001). A reporting participant experiencing an emotion like anger leading to an increase in HR (Kreibig et al., 2010) might elicit an orienting response in observers, leading to a decrease in HR at similar times, which presents itself as counter-fluctuation in IBI. Such an occurrence could explain physiological linkage with 180° phase shifts where the IBI signal is synchronously moving in opposing directions. Whether via the shared processes (e.g., shared negative emotion) or non-shared processes with opposing effects on the HR, a greater phase shift in physiological linkage between reporting participant and observers likely indicates sympathetic HR modulation. Conversely, positive emotions appear to be related to the parasympathetic activity (McCraty et al., 1995) and parasympathetic modulation of the HR takes effect within 2 beats (McCraty & Shaffer, 2015). Physiological linkage clusters with minimal phase shift, as occurred for three positive stimuli in the current study, could thus be explained by parasympathetic modulation. As such, sharing of emotion might explain these clusters of physiological linkage we found for positive emotions. Although these explanations outline how the start of a physiological linkage cluster might have been caused, the sustained linkage over several oscillations could be explained by stimulus-driven pacing of reflexive feedback loops and intrinsic rhythms inherent to the cardiovascular system (e.g., the baroreflex).

That the current study found physiological linkage with opposing directions (i.e., phase shift) might seem in contrast to the most similar published study (Jospe et al., 2020) where positive associations were reported. However, methodological differences can explain the seemingly diverging result. Jospe et al. (2020) applied a time-series analysis approach and considered a lag of up to 10 s, selecting the lag with the maximum correlation value. With this approach, anti-phase linkage is unlikely to occur. The current study on the other hand calculated parameters in the spectral domain, where all types of phase shifts are considered valid, and phase shift is calculated as an additional parameter. It should be noted that Levensen and Ruef (1992), who also used video stimuli and of similar duration to the current study, reported negative (time-domain) associations for HR (albeit not reaching statistical significance). A negative association was also reported by Reed et al. (2013) for IBI linkage in interacting dyads, which again, did not reach statistical significance. Reed et al. (2013) also suggested using concurrent cardiac measures to examine physiological linkage instead of lags given the fast reactivity of these indices.

Furthermore, it should be noted that, given individuals move in and out of synchrony (Likens & Wiltshire, 2021) and linkage can take in-phase as well as anti-phase forms, calculating an average of association across the complete stimulus duration can average out effects, that is, periods of physiological linkage remain undetected. That averages can hamper effects is highlighted by the Pearson correlation results in the current study, which often did not detect associations that were revealed by cross-wavelet analyses. Consequently, the use of cross-wavelet analysis is encouraged (we are publicly providing the script underlying the analyses on OSF, doi 10.17605/OSF.IO/2XFGE; https://osf.io/2xfge), as it allows for examining the effects in individual frequency bands and identifies in-phase and anti-phase linkage for specific time periods.

Another methodological aspect important to consider, which can alter the signal and have an effect on results, is the applied filtering method. For example, strong low-pass filters (as used for instance in Jospe et al., 2020), creating smoother signals, may enhance correlations while likely removing fluctuations in the higher frequencies. To exemplify, had the current study used a moving average of 30 seconds, physiological linkage clusters in the LF bands would not have been detectable. Given these results, strong low-pass filters when investigating physiological linkage based on IBI should be cautiously applied.

3.4 | Physiological linkage and semantic stimulus content

The applied cross-wavelet analysis in the current study allowed to identify the segments where physiological linkage occurred and thus to examine the video content of these segments to derive potential semantic factors causing physiological linkage. It should be noted, though, that since the identification of such factors was not the aim of the current study, only speculations are presented in the following. Future research should *systematically* investigate factors within video stimuli that potentially cause physiological linkage.

The physiological linkage clusters with small phase shifts have in common that the identified moments are emotionally relatable. For example, reporting about positive experiences at the prom night, having to say goodbye to a foster animal, or missing loved ones who are far away. It is possible that relatable content facilitates sharing emotions. Future research should assess the extent to which observers related to the reports to shed light on the role of relating to an experience in physiological linkage.

Building onto the earlier mentioned role of attention for creating anti-phase linkage, it can be speculated that some of the positive and neutral videos in the present study (with smaller phase shift) appeared less interesting and, thus, evoked less attention than the negative and traumatic reports. For most of the videos where physiological linkage was found, it occurred in moments where the tension in the story rose and reached its climax, that is, telling the listener what had happened and what the consequences were. This is important, as links between certain cognitive activities (e.g., orienting, attention) and the autonomic nervous system are assumed. For example, heart rate deceleration has been found to be linked to attention (Thayer et al., 2009). Possibly, the moment of highest tension for the speaker is the moment capturing the most attention of the observer. Given that observing participants were unaware of the valence category of the stimuli, it is possible that the expectation for something 'bad' to be reported created counter-fluctuation for some neutral and positive stimuli. The connection between semantic content, expectations, and attention could explain the counter-fluctuating linkage in the current study.

The results of the current study suggest that attention might be a factor that is crucially involved in physiological linkage. This aligns with published literature reporting conscious processing to affect the timing of the HR implicating that attention plays a key role in HR modulation (Raimondo et al., 2017) as well as synchronization (Pérez et al., 2021). Synchronization across participants is the result of the stimulus being similarly processed across participants. Pérez et al. (2021) postulate that there are triggers in the stories participants of their study listened to, such as emotion and or semantics, which are causing physiological linkage in HR. These triggers can be single words or sentences and the valence or semantics attached to these. It should be noted that all traumatic stimuli in the current study caused anti-phase linkage and their shocking nature with attention allocation could be underlying. Consequently, observers might have been orienting towards the stimulus and showed opposing patterns in IBI. Future research should systematically vary the contents of the reports by the same stimulus person from boring to exciting and include a measure of attention (e.g., eye-tracking), interest (e.g., subjective ratings), and respiration. Since reporting style could also affect physiological linkage, future research should systematically vary styles within-speaker, for example, reporting in a monotonous voice versus with excitement as well as physiological characteristics (e.g., taking breaks vs. continuous speaking) of reporting.

In line with the interpretation that attention is linked to physiological linkage, few reports (including one neutral one) in the current study showed linkage in moments where the person in the video mentioned food or beverages. Salient stimuli capture our attention in a bottom-up manner (Corbetta & Shulman, 2002). Food and beverages are salient stimuli, inherent and intense motivators for humans, and might thus capture attention albeit unconsciously, which could explain the physiological linkage in those parts. That food has effects on implicit levels was shown by a study using a subliminal priming paradigm showing food versus mosaic stimuli where subsequent ratings of neutral face stimuli were more favorable in the food condition (Sato et al., 2016). Another study specifically showed that food items more rapidly captured visual attention than non-food items in a visual search task (Nummenmaa et al., 2011). Given that the laboratory session for observers spanned 2.5 h, it is even possible that participants were experiencing some degree of hunger or thirst, which might have served as an additional motivator drawing attention to the mentioning of foods and beverages (see Ilse et al., 2020). Future research could compare linkage to the same stimulus person when speaking about food versus items that are not related to the basic needs of humans.

3.5 | Limitations

This study has several limitations. Exactly which bodily processes were causing the physiological linkage is difficult to determine, and the answer may vary between as well as within sequences of linkage. The heart's frequency is affected by many different processes ranging from neural processes and the experience of stress and emotion to vagal processes like breathing or changing the body posture, which, in turn, alters the breathing pattern and blood pressure regulation (i.e., baroreflex). Second, we did not include a measure of respiratory activity. Given that breathing can influence the heart's frequencies, such a measure could provide useful information for interpretation. Third, reporting of the stimulus persons was unnatural in the sense that pausing while speaking was instructed. Although this instruction may have affected the results, the physiological linkage was also found for the stimulus person who was not instructed to pause. In addition, many clusters of physiological linkage stretched longer time periods (up to 280 s), far exceeding the length of the pauses. Based on the results from the current study, instructing pauses during video production does not seem to be indicated. Fourth, the current study was based on a small sample size to detect strong physiological linkage, but smaller significant physiological linkage effects might be present, which only larger samples would detect. Fifth, our analytical approach aimed to detect phase-locked linkage across the sample and not non-phase-locked linkage within the sample. Sixth, the current study required observing participants to undergo a lengthy experiment, which may have caused fatigue, affecting the results. Possibly, a shorter experiment duration might have resulted in linkage for more videos. Future research should thus either opt for a shorter design and/or include a measure of fatigue.

3.6 | Conclusion

Overall, the current results show that physiological linkage to reporting participants occurred across observing participants while watching videos of strangers reporting about personal experiences related to different valence categories. It does not seem necessary to interact live or to have experienced the situation in the video oneself for physiological linkage to occur. The current study, therefore, demonstrates that standardized stimulus material can produce the phenomenon of physiological linkage (across the valence dimension). Furthermore, the results of the current study suggest that physiological linkage (based on IBI) constitutes an umbrella term including multiple distinct elicitors (related to the stimulus) as well as physiological mechanisms that can demonstrate themselves in IBI linkage to the stimulus person and similarly across observers. Stimulus valence seems to affect whether physiological linkage occurs and the duration of physiological linkage. As physiological linkage occurred more reliably to negative stimuli, a strong influence of stimulus saliency can be assumed. The current study further demonstrated that standardized stimuli can effectively be used to investigate physiological linkage in a highly controlled experimental setting. The use of experimental manipulation (alongside dyadic interaction studies) is encouraged to further the understanding of physiological linkage. For example, findings of more pronounced physiological linkage from video without audio than from audio (Jospe et al., 2020) raise questions about the triggers producing the phenomenon, which should get explored further. Beyond semantic salience in the language (Pérez et al., 2021), non-verbal expression of emotion (gestures, body posture, facial expression etc.) or implicitly perceived changes in appearance (e.g., widening of arteries through the pulse in the face and resulting color changes similar to remote photoplethysmography; see Wang et al., 2014) could get investigated as triggers for physiological linkage by future research. Furthermore, standardized video stimuli can be applied in clinically relevant research, for example, when identifying factors that predict psychotherapy outcomes or variables related to the mental well-being of health personnel working with emotionally highly burdened patients.

AUTHOR CONTRIBUTIONS

Tanja S.H. Wingenbach: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; writing – original draft. **Peter Peyk:** Formal analysis; software; visualization; writing – review and editing. **Monique C. Pfaltz:** Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review and editing.

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DATA AVAILABILITY STATEMENT

The data and code underlying the IBI analyses are publicly available on OSF, doi 10.17605/OSF.IO/2XFGE (https://osf.io/2xfge). The videos can be obtained for research purposes (free of charge) by contacting the last author (Monique Pfaltz: monique.pfaltz@miun.se).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Supplementary materials.
Figure S1. Phase shift.
Figure S2. Stimulus person 3, traumatic report.
Figure S3. Stimulus person 3, positive report.
Figure S4. Stimulus person 2, neutral report.
Figure S5. Stimulus person 5, neutral report.
Figure S6. Stimulus person 6, neutral report.
Table S1. Subjective affect linkage.
Table S2. Observers' facial muscle responses per stimulus.

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