Frisson Waves: Exploring Automatic Detection, Triggering and Sharing of Aesthetic Chills in Music Performances

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Frisson is the feeling and experience of physical reactions such as shivers, tingling skin, and goosebumps. Using entrainment through facilitating interpersonal transmissions of embodied sensations, we present "Frisson Waves" with the aim to enhance live music performance experiences. "Frisson Waves" is an exploratory real-time system to detect, trigger and share frisson in a wave-like pattern over audience members during music performances. The system consists of a physiological sensing wristband for detecting frisson and a thermo-haptic neckband for inducing frisson. In a controlled environment, we evaluate detection (n=19) and triggering of frisson (n=15). Based on our findings, we conducted an in-the-wild music concert with 48 audience members using our system to share frisson. This paper summarizes a framework for accessing, triggering and sharing frisson. We report our research insights, lessons learned, and limitations of "Frisson Waves".

CCS Concepts: • **Human-centered computing → Interaction techniques**; **Interaction devices**; **Interactive systems and tools**; *Participatory design*; *Collaborative and social computing*.

Additional Key Words and Phrases: wearable computing, frisson, haptics, live performance, physiological sensing

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1 INTRODUCTION

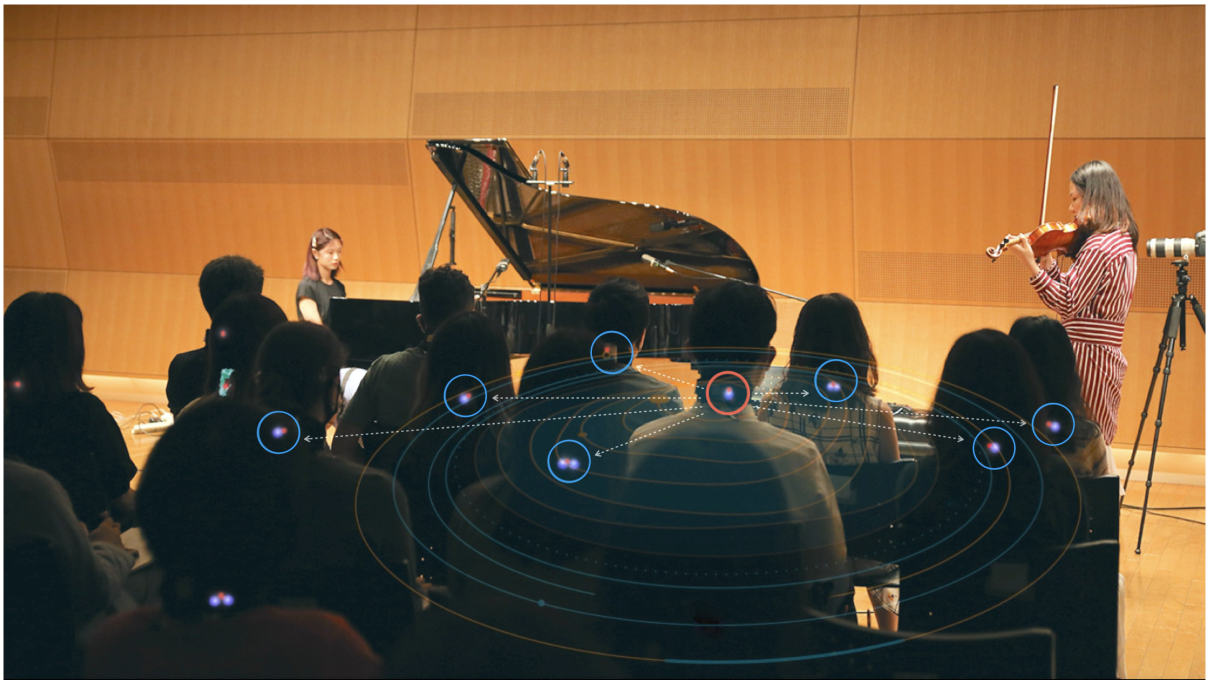

Fig. 1. Frisson Waves: Music performance with EDA/heart-rate base frisson detection and frisson sharing using a thermal neckband.

When music deeply resonates with us, many experience a sudden feeling of excitement and chills, otherwise known as frisson. Frisson is a psycho-physiological phenomenon commonly described as having goosebumps or feeling shivers down one's spine. This sensation can be evoked by intense emotions or it can be triggered via external stimuli [2, 46]. Previous research reported most people sometimes experience "the chills", which is oftentimes described as the feeling of goosebumps and shivers on the neck, scalp, and spine, when listening to music [35]. While some people may never experience this sensation. Studies link the experiencing of aesthetic chills to moments of peak pleasure and emotional responses [2, 3, 47]. Individuals who experience frisson tend to feel higher degrees of pleasure than those who do not experience frisson [16]. Based on these findings, we assume enhancing frisson sensations may increase the aesthetic experience, especially for those who never experience frisson naturally.

In our research, we present the first in-depth exploration of frisson from detection, over triggering to sharing this complex feeling. Frisson is an intimate personal experience, there are a lot of divergent descriptions of frisson as a feeling (e.g. chills down the spine, goosebumps on arms or neck) [2]. Only around 30% of people can actually experience it. However, it seems at least the timing of frisson in musical pieces can be more clearly defined. The feeling is usually very short: usually around 4–10 seconds. It can be described as pleasurable [28, 56]. Typical stimuli can be found in loud parts of music and parts that violate some expectation (introducing a pattern and then breaking with it, therefore violating some kind of muscial expectation of the listener) [8]. In a live performance such as music concerts, speeches, or movies, verbal communication is usually not encouraged. Therefore, the exciting moments of frisson are often difficult to communicate and share with each other. Previous works related to goosebumps, shiver sharing and transmission exist, such as by Neidlinger et al. [33] who explored externalizing the feeling of goosebumps in their work ”AWElectric”. Cooper et al. [14] found that people's temperature goes down if they see others shiver. However there is a gap in the literature about sharing frisson. To this end, we present "Frisson Waves".

We investigate if sharing frisson can lead to a deeper understanding of other people's aesthetic experience and further elicit an expressive appreciation of the musical piece. Thus far frisson has been relatively under-explored [16]. To start to address this, we explore the feasibility of sharing frisson through a combination of lab studies and in-the-wild concerts, and we investigate the potential influence of this on the audience's live experience through multi-modal evaluation methods. We aim to augment the aesthetic experience through enhancing the capability of feeling frisson which is usually affected by music appreciation and training [16], personality [50], openness [13], physiological and neural features [42]. While it may not be possible to change these individual characteristics directly, we aim to mediate frisson between people using a thermohaptic approach that allows neighboring people to perceive frisson beyond their conscious control [24]. For example, if a person who is sensitive to music and appreciates music feels frisson at a specific moment in a piece, a person who receives our actuation might also feel this frisson or at the very least have their attention drawn to how special that moment is. The concept is akin to the intuition that sometimes we gain appreciation for a piece of music only after reading favourable reviews. In essence, our system aims to provide feedback via a real-time physiological "review" during the concert.

Going to a concert is a collective experience. The physical presence is a predictor of connectedness between both artist and the audience [36]. Three primary perspectives can be identified for people who go to live performances rather than tuning in to records: concerts are defined as live events, they include communal, social components and they focus on a specific kind of music. Experiencing live events usually makes audience members more susceptible to spontaneous synchronization, and entrainment [53]. Previous research findings suggest that a higher synchrony of physiological signals among audience members in classical music concerts may have a positive influence on their aesthetic experience and social connectedness [36, 54]. Performers and audience members gathering in the same space and at the same time draw their attention on the music piece together. As a quintessential example of rhythmic join action, music can elicit synchronized reactions more than other scenarios [25], which provides researchers more opportunities to investigate psychological and physiological entrainment. By further sharing intimate feelings of frisson, the emotional contagion, connectedness, and even physiological synchrony between people might be further enhanced. We therefore hypothesize that increasing the synchrony of psycho-physiological phenomena with external stimuli between audience members may positively influence their aesthetic experience and social connectedness.

The wider aim of the Frisson Waves project is to positively influence the concert experience by increasing psycho-physiological synchrony through mediating frisson between audience members. In essence the work aims to turn aesthetic perception inward: to explore intimate reactions, enabling a sense of attention and an act of listening that is individually transformative as well as it is collective. It is envisioned as a communal assemblage of frisson experiences to evoke synchronization and connectedness among spectators and to provide a social component of implicit communication. Towards this we aim to mediate audience sensations and experiences by creating a new design space for bi-directional performer-audience interactions, which we evaluate during a live classical performance. In this paper, we summarize our exploration of sharing frisson sensation through a self-built system with the hope that this article will stimulate the interest of others in this hitherto unexplored field.

Frisson Waves is an exploratory work at the intersection of performance and science that consists of two parts: the development of an unobtrusive wearable system that can detect, trigger, and share frisson; and a series of experimental concerts that trial the deployment of the system. The main contributions of this paper are as follows:

- 1) We present and discuss the concept of detecting, triggering and potentially sharing frisson among audience members during real-world classical music concerts.
- 2) We describe an open integrated wearable system that consists of a wrist band, back-end processing, and output. Our proposed system enables the capturing and translating of physiological signals into thermal information to induce frisson. We evaluate the system for frisson recognition (n=19), and frisson triggering (n=15). We detail information about the design process, as well as how these sensing modalities can be used to detect frisson, with a special focus on sensing heart rate and electrodermal activity (EDA). The data and analysis is open-sourced and can be accessed publicly under https://osf.io/rzpn3/.
- 3) We conducted a proof-of-concept concert performance using our frisson sharing system. The concert was performed by five musicians in front of an audience of 48 people. Frisson was mediated between a subset of audience members and a live feed of psycho-physiological data from the audience was used to control various synthesizers. We discuss the outcomes and implications of sharing psycho-physiological data among audience members and demonstrate the opportunities of this new design space.

2 BACKGROUND

Recently, the HCI, UbiComp and other related communities have shown increased interest in the embodied interaction and emotion-elicitation fields. For example, experience sharing from exploring autonomous sensory meridian response (ASMR) to animating awe for embodiment and externalizing cues for communication [1, 27, 32, 33]. Niu et al. discussed design implications for social interactions based on embodied communication principles [34]. Our work is inspired by these research directions, focusing on aesthetics-induced frisson and exploring potential interpersonal interaction approaches using physiological sensing and interoceptive interactions. In the following, we will highlight some research on defining and measuring, as well as exploratory works on triggering and sharing frisson.

2.1 Embodied Aesthetic Chills: Frisson

Frisson is a feeling that describes the experience of body states like goosebumps, shivers, and skin tingling. Frisson is described as a sudden strong feeling of excitement often experienced together with so-called goosebumps [30]. Due to the numerous descriptive terms that have been associated with this experience (chills, thrills, goosebumps, shivers, and goosetingles), the succinct French term frisson makes it beneficial to provide continuity to this body of research [13, 51].

Frisson is known as aesthetic chills or musical chills which refer to a set of bodily sensations, such as shivers, or piloerection (goosebumps), transient paresthesia (skin tingling), sometimes along with mydriasis (pupil dilation). The embodied feeling of frisson induced body sensations is a physical feeling of shivers down your spine and tingling on the nape of your neck and the back of your arms [30, 46]. Having goosebumps is a physiological phenomenon where small bumps appear on the skin surface as the hairs stand up. Frisson can be caused by cold, fear or a strong emotional stimulus. Frisson or aesthetic chills is personal, with highly individual differences rather than a shareable experience among people [7]. However, while some people have a strong frisson response [35], not all people perceive these moments of frisson naturally.

From a psychology perspective of frisson definition, frisson is a set of body reactions such as goosebumps or shivers that can be induced by intense and discrete emotions [38]. Mori et al. [31] indicated that the peak emotional response, aesthetic chills could be characterised by mixed emotion rather than basic emotions or two emotional dimensions. Frisson has distinct varieties and is not equivalent to a single dimension in valence-arousal-power space. Instead, frisson is constructed, characterized by groupings in, and between, both bodily activity and emotional experience data based on the multiple correspondence analysis: warm chills (warmth, smiling, happiness, stimulated and relaxed), cold chills (coldness, frowning, sadness and anger), and moving chills (lump in the throat, tears, affection, tenderness, being moved and intensity) [2]. Frisson, as well as aesthetic chills, appear in the middle of multidimensional scaling space which shows a spectrum of responses ranging from visceral responses to cognitive responses, which reflects it has both visceral and abstract components [42].

Humans uniquely appreciate aesthetics, experiencing pleasurable responses to complex stimuli that confer no clear intrinsic value for survival [42]. Embodied aesthetics refers to embodied responses and resonance of aesthetic emotions and experiences. Aesthetic chills are related to aesthetic emotions [47], Perlovsky et al. [40] suggest that aesthetic emotions are emotions that we feel when we are in aesthetic activities such as dancing, painting and gymnastics, which has elements related to pure beauty or when we appreciate things. There are a lot of works focusing on the qualitative aspects of frisson, introducing different scales and surveys for recording and measurement [39, 43–45, 52].

2.2 Measuring of Frisson

There are many ways to detect and measure chills or goosebumps, such as physiological sensing, optical measurement, or self assessment. Through recording the spatial frequency changes in the visible domain, it is possible to accurately detect the onset of goosebumps. Research from Benedek et al. [6] combined the optical continuous measurement of piloerection and self-report method to record goosebumps which provided a reliable mapping of emotion and occurrences of visible piloerection. However, the manifestations of frisson do not necessarily cause piloerection and depending on the type of skin and device placement, optical measurement may not be suitable for our case. A lighter and simpler wearable device is preferable in live music performances. Kim et al. [26] previously explored measuring mechanical changes in the skin to detect goosebumps through a capacitive skin piloerection sensor. This is a consistent and convenient measurement though it's not applicable for large live performances due to the limited skin area and costs.

The work of Grewe et al. [20] revealed the relationships of physiological responses, emotions and chills. Reportedly, heart rate (HR) and electrodermal activity (EDA) features are related to chills and frisson. Heart rate variability (HRV), as the flucturation in the time intervals between adjacent heart beats, could reflect dynamic affective processes [48]. EDA is an authoritative indicator of emotional arousal associated with human behavior. It reflects the sympathetic nervous system responses related to emotion. Benedek et al. [5] also found the increase of phasic electrodermal activity and increased respiration depth are associated with piloerection. The data set from Zhang et al. [57] includes 457 people's simultaneous EDA responses to music emotion recognition. Grewe et al. [19] looked into EDA and chills stimulated through four different sensory domains (tactile, aural, visual, gustatory).

In summary, frisson can be assessed via a combined self-report and physiological (e.g. galvanic skin response) measurement. Detecting physiological signals such as EDA, respiratory rate and HRV combined with self-report are the most efficient and common ways that do not require bulky and complicated setups and can be deployed in large scale settings.

2.3 Triggering of Frisson

In live music performances, there are various factors that typically constitute frisson: cognitive factors such as personal attachment to the performing content, individual differences such as individual characters or openness toward things and experiences, social and environmental context, acoustic properties, as well as aesthetic emotions. Based on the natural factors that cause frisson, there are a lot of related works exploring triggering frisson from external stimulus. Interoception interaction provides the possibility to trigger frisson feelings through driving embodied reactions such as goosebumps and shivers. Grewe et al. [19] proved that among different sensory domains, tactile feedback is the most effective trigger. In "The Thermal Feedback Influencer" [23] project, sudden cold thermal feedback when listening to music also proved to be the obvious trigger of frisson and could enhance the music listening experience. The project "Frisson" [24] created a spine-attached thermal band as an aesthetic prosthesis to induce emotions from the body up through interoceptive technologies. Work from Fukushima et al. [17] and "MAGHair" [9] controlled and stimulated body hair to augment the feeling of surprise and awe. Colver et al. [13] found that aural stimuli such as aesthetic works of music or sound are also suitable for triggering frisson.

2.4 Sharing of Frisson

Since not everyone could feel frisson [35], and due to the lack of communication in typical music concerts, we believe sharing frisson and turning individual musical experiences into collective ones can create a new form of listening. Previous works have showed frisson sharing exists. Neidlinger et al. [33] have explored externalizing and sharing the feeling of goosebumps with color visualizations and inflatable textiles in the work ”AWElectric”. Cooper et al. [14] found that people's temperature goes down if they see others shiver. However, there was no evaluation as of yet on the user experience. So far, no attempts have been made to share frisson veritably and collectively during live performances to create cues for interpersonal implicit communication. To bridge this gap, we introduce an interactive system based on physiological sensing and frisson haptics that detects, induces, and shares frisson.

3 DESIGN PROCESS

The system evolved in an iterative co-design process with professional classical music performers, human factors/haptics researchers, and user experience designers. The system was developed iteratively over the course of four studies: an in-the-wild study piloting the design requirements for frisson feedback during a live performance, a lab study validating a method for automatic frisson detection, a lab study evaluating the frisson inducing device, and a final in-the-wild study evaluating the complete system during a live performance:

- **Exploring Frisson In-Situ Concert I.** This preliminary in-the-wild study, discussed in Section 3.1, aimed to understand the audience's expectations of feeling and sharing frisson. The study confirmed the positive feedback of feeling frisson and the spectator's tendency to share frisson, as well as piloted the system design requirements.
- **Physiological sensing wristband and frisson detection ML model** is introduced in 4.1 and 4.2. This lab study aims to detect frisson accurately by utilizing a physiological sensing wristband and developing an ML model. The physiological sensing wristband records and extracts EDA and HRV that can be used to detect when someone has frisson. The ML model processes the wirelessly streamed physiological data for real time classification of the data as frisson or non-frisson. The model with the best performance presented an average accuracy score of 85.78% with an average precision score of 81.75%
- **Frisson induction neckband** is introduced in 4.3. This lab study aims to trigger frisson efficiently by developing a neckband with Peltier thermoelectric cooler modules (TEC). This study confirms the neckband is able to trigger 93% of 15 participants to feel frisson, 73% of them felt intense frisson.

- **Frisson-sharing server and Frisson-Sharing Concert II.** is introduced in 4.4 and 5.1. The frisson sharing server controls the operation of all the devices and manages data processing and recording. The aim of the Concert II. study was to determine if frisson sharing can positively impact an audience's musical experience. This study found several spectators' decrease in enjoyment caused by the neckband, and the uncontrolled interpersonal relationships of the live study both meant it was difficult to draw a quantitative conclusion on enhanced frisson occurrences and enjoyment. However, higher physiological synchrony and relatively higher self-reported social connectedness are found in the audience who shared frisson compared with those who did not.

3.1 Field Study: Live Concert I. Exploring Frisson In-Situ

In order to better understand the impact of frisson and how performers and spectators think toward sharing frisson in a wild live performance, we held an experimental concert with 20 audience members (female=13; male=7) between 20 and 60 years of age (mean age=29.5, standard deviation=11.91). COVID-19 infection prevention measures were implemented in this concert by disinfecting all devices and keeping an appropriate distance. The experimental concert included a 40 minutes classical piano program, featuring “Chopin Prelude, Op.28 No.15”, “Chopin Ballade, No.1”, “Grieg: Piano Concerto in A minor, Op.16 Cadenza & Coda”, and “Rachmaninoff: Études-Tableaux, Op.39, No.1”. These works offer a wide range of textures, dynamics, tempos, and implied emotions which are regarded as aesthetic emotion-elicitation pieces and allowed us to observe the aesthetic responses of the audience in many different ways.

Each pieces' frisson occurrences, related embodied responses and qualitative comments of frisson were accessed with questionnaires. Based on subjective responses from 20 audience members, 69.72% have experienced frisson and regard it as a positive component of an enjoyable live music performance. Wishing to experience more frisson was reported by 83.33%. 85% of the spectators, who reported they usually communicate with their friends in concert contexts such as eye contact, holding hands, talking or whispering and so on. This suggests that people have the tendency to communicate with others in such scenarios. Through the interview of spectators who felt frisson, one of them reported "there is the deep touch of sublime that only happens when I am in this concert"; other user comments included "feeling deep breathing", "increasing temperature" ,"starting to sweat", "feeling goosebumps", "heartbeat goes faster and faster", "a lump in the throat", and "eyes getting wet, tears falling". Most of them reported they would like to share their visceral reactions and exciting moments such as frisson responses with other spectators without interfering with the performances, which shows the possibility of a silent implicit interaction approach that could facilitate meaningful interpersonal communication.

This pilot study was done to understand and confirm the audience's expectations of feeling, sharing frisson and social needs during a live performance. Based on our observations, we decided to design an unobtrusive frisson-sharing system which can be deployed at scale.

3.2 Design Concept

We designed two hardware devices for triggering and detecting frisson (see as Figure. 2). The first is a wristband measuring EDA and blood volume pulse (BVP) (see as Figure. 2.(2)). The second device is a neckband with haptic actuators and Peltier thermoelectric modules to induce frisson (see as Figure. 2.(1)). With this setup we can detect with a certain degree of precision the occurrences of frisson or onset of intense emotions using the physiological data. In the case of detection, frisson is spread or shared to the audience members sitting next to the one experiencing frisson. In the case of successful induction of frisson, we assume that it is detected and will continue spreading through the audience akin to ripples or waves in the water [21].

The flow of sharing frisson is as shown in Figure. 3. Firstly, physiological data recorded from the wristbands is streamed to the server in real time. Secondly, the server processes the received data, extracts certain features

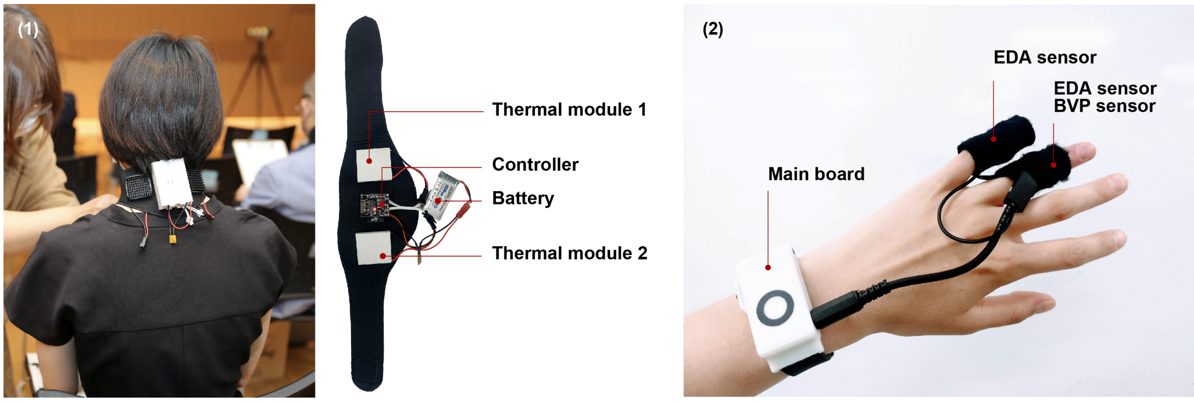

Fig. 2. Thermo-haptic Neckband and Wristband

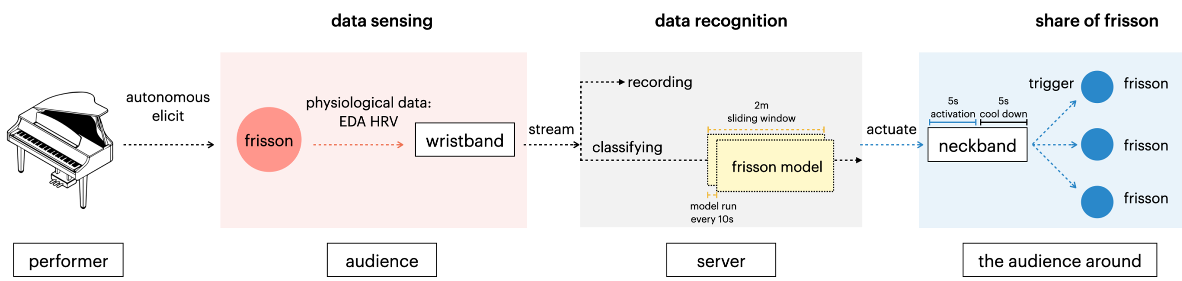

Fig. 3. System Development Framework

and detects frisson using the trained model every 10 seconds and operates within a 2 minute adjustable sliding window. Thirdly, the system activates the thermo-haptic neckbands around the detected audience members like a drop of water falling down to create the rippling wave pattern. Thereby, the system enables the transmission of frisson in a pattern like a rippling wave.

4 SYSTEM DEVELOPMENT AND EVALUATION

We developed a system with two devices, one for detecting and one for triggering frisson, and conducted a series of user studies to evaluate them. The final version of the complete system was used during a live concert (see Section 5.1) held on June, 25th, 2021.

4.1 Wristband: Frisson Self-report and Physiological Data

Automatic detection of frisson is performed using a smart physiological sensing wristband [12] (see as Figure. 2.(2)) that measures BVP and EDA. The devices utilize ESP32 modules and use WiFi to stream the recorded data. BVP is measured via a reflection-based optic plethysmograph with the sampling rate of 50Hz. EDA as the change of skin conductance is measured with a Wheatstone bridge, an instrumentation amplifier and ADC with 16-bit resolution in +-2V range, with basic low-pass RC filters on both. EDA sampling rate is 4.545 Hz, 12-bit resolution.

Readings are streamed to the server software where the heart rate variability (HRV) and EDA-related features are extracted to be fed into the frisson detection model since studies showed EDA and HRV physiological signals have the most obvious pattern changes regard to aesthetic chills [4, 19, 20]. The frisson detection model runs every 10 seconds for each participant and operates with an adjustable sliding window size around one minute. To ensure an adequate amount of data, the server sent data in a window larger than one minute (approximately 2 minutes) window each time. The full system description is shown in Figure. 3

4.2 A Machine Learning Model: Frisson Recognition

In order to train the model, we processed the recorded EDA and blood volume pulse (BVP) data as well as when the participants pressed the frisson-report button for data labeling.

Experiment Procedures The same Thermo-Haptic neckband and wristband were used with a counterbalanced order of 3 parts, including part A, part B, and part C. Part A is a five minute excerpt from Gustav Holst's "The Planets: Jupiter, the Bringer of Jollity", approximately 4:00-9:00. According to previous studies, this particular 5 minutes is the part most successful in provoking chills [4]. Part B is a three minute cold thermal feedback stimulus session through the neckband with no music stimulation. The cold feedback onset period is 8 seconds: 3 seconds cold feedback "on" and 5 seconds cold feedback "off". We will introduce more details on the thermal feedback in section 4.3. Part C is a 5 minute piano recording from Frédéric Chopin's "Prelude, Op. 28, No. 15". It was recorded from the first live concert we held and rated most likely to have frisson from the audience. In this study, we only turn on the Thermo-Haptic Neckband in one music part throughout three sessions: A and B or B and C.

We recruited 33 volunteers (female= 17; male = 16) from 7 countries aged 22-37 years old (mean = 26.09) for the 30 minutes study. Once the study began, participants filled out the demographic questionnaire followed by the explanation of frisson while the investigators helped them put on the wristband with a frisson-report button and the neckband with two thermal modules placed on the back of their neck. Then investigators then explained the definition of frisson and when to press the button.

Model Training We use a support vector machine classification (SVM) algorithm in our frisson detection referring to some previous works using physiological data to detect physical or mental phenomenon [41, 49]. Our model was trained using the features extracted from a sliding window of 1 minute moving every 1 second. (Note that during the real-time detection stage, to ensure sufficient data in the event of data loss, 2 minutes of data is sent, from which only 1 minute is ultimately classified at a rate of every 10 seconds.) The window was labeled as a frisson event if the button was pressed within the window. We removed the participant's data if the data was either too noisy to process or too few frisson events were reported, which left us 19 participants' data in total. Each participant's raw EDA data was passed through a 2^{nd} order Butterworth low-pass filter (0.5 Hz). And Each participant's raw BVP data was passed through a 4^{nd} order Butterworth low-pass filter (4 Hz). We extracted four EDA features and three HRV features using Neurokit2 [29] from the filtered signals.

According to the feature importance by a Random Forest Classifier, we selected the following features and normalized the values to remove individual differences:

- EDA-Tonic: EDA Tonic component value
- EDA-Phasic: EDA Phasic component value
- Tonic-diff-60: the change EDA Tonic component value in 60 seconds
- Tonic-diff-30: the change EDA Tonic component value in 30 seconds
- HRV-MeanNN: the average of normal sinus beats' interbeat intervals (NN)
- HRV-pNN50: the percentage of adjacent NN intervals that differ from each other by more than 50 ms
- HRV-pNN20: the percentage of adjacent NN intervals that differ from each other by more than 20 ms

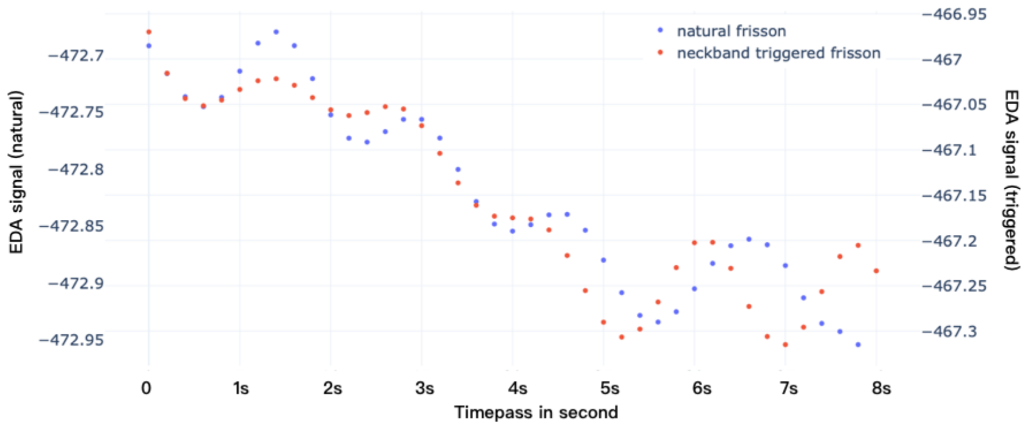

Fig. 4. One subject's EDA signal plots of natural and triggered frisson events lasting for around eight seconds. A similar trend of filtered EDA signal for natural and triggered frisson events could be visually inspected.

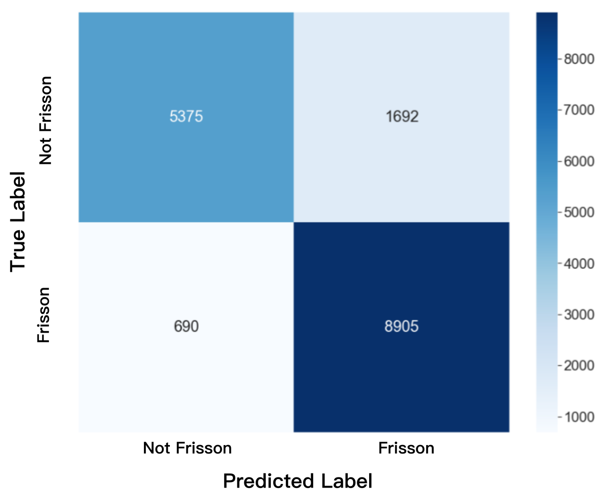

Fig. 5. Confusion matrix for the prediction model with LOPO-CV. A row represents an instance of the actual classes whereas a column represents an instance of the predicted classes.Each number represent the sample numbers falling into each quadrant.The overall sensitivity is 92.81% and the overall specificity is 76.06%.

Biosignals of both the original frisson and synthetically generated frisson events were analyzed and plotted. Firstly, we visually inspected the trend and change of biosignals and found the two types of events were similar enough to be both considered as frisson experiences. Figure. 4 shows one subject's example of frisson events (natural and triggered) and the trend of filtered EDA signal recorded. Moreover, we trained a trial model using the data from three subjects combined who reported frisson in both natural sessions and triggering sessions. The model was trained on the data in the natural session and tested on the triggering session with an accuracy of 80.42% as an initial result. Both of the results supported our concept.

We further developed our model using all the data from 19 participants and applied leave one participant out cross validation (LOPO-CV) to divide data into training and testing sets. The classifier with the best performance presented an average accuracy score of 85.78% (sd = 11.23%) with an average precision score of 81.75% (sd = 12.48%). Figure. 5 illustrates the overall performance of the model.

4.3 Thermo-haptic Neckband: Triggering Frisson

Our system uses a thermo-haptic neckband(see as Figure. 2.(1)) that includes two Peltier TECs fixed on a neckband. Each TEC has an exposed heatsink attached to the side opposite to the user's skin. The device is controlled by an ESP32 module and communicates with the system server using WiFi. It is powered from a 1000 mAh 3.7V battery which ensures several hours of constant usage. There was 3W of heat transfer between the sides of the peltier module, the exact temperatures depend on the thermal conductivity of the neck - Peltier element thermal joint. Since the skin heat conductance, temperature, and neck geometry are highly individual, we test and chosen that 3W of heat transfer is a generalizable estimate. In the event of activation each thermal module is turned on for 5 seconds with a consecutive 5 seconds of cool-down time, allowing the heatsink to dispose of the accumulated heat, which ensures constant performance of the thermal actuation. In total, each TEC consumes up to 1.2A of current at fully charged battery voltage of 4.2V. As the battery discharges, the current drops to 0.9-1A, which provides sufficiently stable cold sensations. For safety reasons the battery is protected with a 2.5A PPTC fuse.

Thermo-haptic Neckband Study In order to test whether the Thermo-Haptic Neckband [22] can trigger frisson at all we conducted a simple user test with 15 volunteers (female=7; male=8) aged 22-37 (mean =26.4). Participants were explained the concept of frisson while the investigators helped them put on the wristband with a frisson-report button. They were asked to press the button as long as they experienced frisson or any form of shivers. The two Peltier TEC modules of the neckband were placed on the back of their neck for one minute and provided pulses of cold thermal feedback to trigger frisson. Afterwards, the participants were asked to report if they experienced frisson-like feelings or not and were asked to rate the intensity of their frisson experience on a 7-point Likert scale (1= not at all; 7= very intense frisson feeling). The two TECs were pumping about 5-5.5W of heat and reached a surface temperature of 24°C.

Results We analyzed three sets self-report data: if the participants pressed the button during the test, if they reported had frisson and if they had higher than a level 4 intensity of frisson according to the interview. If yes, we marked the feedback data as 1, otherwise 0. Three one-tailed T-tests were performed. A total of 52 button presses were recorded from 11 out of the 15 participants ($M=.73$; $p=.034$). 14 out of 15 participants reported they experienced frisson-like feelings during the test ($M=.93$; $p<.001$). 11 participants consciously experienced higher than level 4 frisson during the test ($M= .73$; $p=.034$). This result suggested that the neckband could successfully trigger frisson.

4.4 Frisson Sharing Server

The server software controls each device via a TCP/IP network connection. The server records all the data from the wristbands and manages the data processing and recording. The server starts a python script for each device that extracts the EDA and HRV features necessary for the frisson classification model and runs the classifier every 10 seconds for each device. If an occurrence of frisson is detected, python script reports it back to the server. Then the server commands all the neckbands adjacent to the participant who had just experienced frisson to activate and apply cold feedback to their wearers.

The server side is developed in Qt C++ and is capable of handling hundreds of simultaneously active devices. It is capable of re-streaming the data of the selected participants to other computers for generation of real-time visuals or audio. During the final performance mentioned in 5.1, we streamed live heart rate data to an Ableton Max for Live patch to generate real-time soundscapes. Although the data has to be buffered on the wristband side, the server is gradually de-buffering it for the stream and produces a smooth stream at about 50 Hz. The delay caused by several transmission buffers averages at 400 ms.

5 LIVE CONCERT II. SHARING FRISSON

The purpose of the concert was both to test the system's viability at detecting and triggering frisson experiences in the wild, and to investigate and compare any differing effects on frisson-sharing and non-sharing groups. Specifically questions related to their frisson experience, their physiological synchrony and their sense of connectedness. We tested our complete system in an in-the-wild study where we organized a Frisson Waves Concert on June 25th, 2021 at Kawasaki Symphony Hall Assembly Room.

5.1 Concert Information

Five professional musicians, each with roughly 20 years of experience, curated and composed a musical program based on their artistic interpretations to evoke the audience members aesthetic responses. In the following, we describe the concert program.

The concert consisted of three sessions. Session 1 was a 20 minute interactive ambient music performance titled "Reflections on Chopin Prelude Op.28 No.15" was based around two electronic artists generating sounds with laptops and synthesizers from the audience's real-time heartbeats and frisson physiological signals using custom-built patchers in Max/MSP. These patchers function by receiving data from the server via OSC (open sound control) protocol, which is then distributed by the artists to several filters, triggers, and sound modifiers. One violinist and one pianist performed with the electronic artists together with audiences' physiological feedback loop, which transformed the performance from a more structured classical work into a semi-improvisational performance piece. We composed this piece to express the lost feeling in the gloomy periods and bring the audience implicitly together with us to complete this piece.

Session 2 was a 21 minute classical piano program of "Beethoven: Sonata No.30 Op.109". In the opinion of the pianist, this sonata, composed by Beethoven in 1820, is very compact both spiritually and technically. It has a wide variety of emotions, including melancholy, joy, and a feeling of grace. It sometimes portrays resentment and conflict as well. In particular, the third movement, which begins with a naive and romantic theme and consists of six variations and a coda, expresses various human emotions skillfully such as deep love and conflict hidden in Beethoven's innermost feelings.

Session 3 was an 18 minutes classical piano program of two pieces by Frederic Chopin. The first was "Nocturne Op.27 No.1". This nocturne, composed in 1835, was written in a deeply sorrowful tonality in C sharp minor. A theme consisting of a wide-range chord in the left hand and a simple melody that echoes above it in the right hand. Chopin's delicacy has changed from the mysterious grace to the dramatic appearance of Mazurka in the middle part and the sudden appearance of Mazurka comes as if to express the national feelings towards Chopin's home country Poland, with the piece then returning to the main theme quietly. It revealed his love of his homeland and the resentment and anxiety that dwelled somewhere in his heart. The second piece was "Preludes Op.28 No.18 24". These preludes, which were completed on Mallorca in 1838, were influenced by Bach's equal temperament and were composed with one song each, covering all 24 tonalities. The length and difficulty of each piece are different. Although there is no unity between the songs, the characters of each tonality are expressed in a delicate, graceful, and bold way. That is typical of Chopin's works, and the harmony of the songs before and after is well maintained. Each piece is a straightforward projection of Chopin's music and feels for life. It is a collection of preludes that skillfully expresses human emotions. Chopin composed these pieces to cover the travel expenses for his escape to Mallorca with George Sand.

5.2 Audience

48 audience members in total attended the concert (female=28; male=19, 1 other or preferred not to say) between 19 and 83 years (mean =38.53, sd=15.09). The audience registered voluntarily through a concert poster posted on social media with knowing the time, location, music programs of the concert. When they came to the concert, we prepared flyers to illustrate the concert and system implementation and delivered to each participant together with the consent forms about data usages and photography before they entered the hall. COVID-19 infection prevention measures were implemented in this concert such as regulating the distance between all participants as well as sanitizing all the wearable devices before and after usage. The participants could stop wearing the device or leave the hall anytime they want.

48 audience members were able to choose to sit in one of two groups with knowing the experience difference: sharing-frisson and non-sharing groups. The frisson-sharing group consisted of 24 audience members wearing our neckbands and wristbands (see as Figure. 1). The non-sharing group of 24 audience members wore only the wristbands.

We designed the questionnaire which included the audience's frequency of feeling musical frisson or aesthetic chills both in general and in this experimental live concert. These two questions were accessed with a 5-point Likert scale (1= Never, 3=Sometimes, 5=Very often). Intensity of frisson feeling in this concert were accessed with a 7-point Likert scale of the question "I have felt very intense frisson during this concert." (1= Disagree Strongly, 4= Neutral/Mixed, 7= Agree Strongly). Enjoyment and engagement of this concert are accessed with a 7-point Likert scale (1= disagree strongly, 4= Neutral/Mixed, 7= Agree Strongly). For audiences who are in the frisson-sharing group, "feeling frisson induced by the neckband more than other similar concerts" and "decline of enjoyment because of wearing neckband" was assessed using a 7-point Likert scale (1= Disagree Strongly, 4= Neutral/Mixed, 7= Agree Strongly). Besides measuring frisson occurrences, the study also measures connectedness, the experience of relatedness between people, which is a central concept in understanding and evaluating communication media, in particular awareness systems [55]. Referred to study [54], which explores physiological synchrony with connectedness in live concerts, we accessed connectedness score with a 7-point Likert scale (1= Disagree Strongly, 4= Neutral/Mixed, 7= Agree Strongly) through this question "I felt connected with people sitting around me". To eliminate the effect of interpersonal relationship, it's accessed with rating the number of acquaintances who are sitting adjacent to the user. Questionnaires are also accessible together with the dataset in our supplementary material (Appendix. A.1).

5.3 System Implementation

We implemented the system mentioned in section4 with the same setup, data streams from the physiological sensing wristbands in4.1 are managed by the server software in4.4, and the server records data and classifies frisson with the machine learning model in 4.2 every 10 seconds. If a frisson signal is detected of one participant, the server commands and activates all the neckbands mentioned in 4.3 adjacent to the participant.

6 CONCERT II. FEEDBACK AND DISCUSSION

This section presents and discusses the outcomes of implementing the Frisson Waves system in-the- wild. Overall, the audience evaluated the concert with the system positively with relatively high enjoyment levels (mean= 6.2, sd= 1.01) from both groups. Compared with their previous experiences in similar events, 62.5% of the audience reported that they enjoyed more in this concert. On the contrary, 14% of the audience reported they used to have a better experience without. We further investigated the possible reasons and found 7 of them found the neckbands uncomfortable, which may suggest the necessity of improving the neckband's user experience.

With the audience's immersion throughout the concert in mind, we did not include real-time self-reporting for frisson considering the risk of distraction and detriment of enjoyment. This resulted in a limited evaluation on

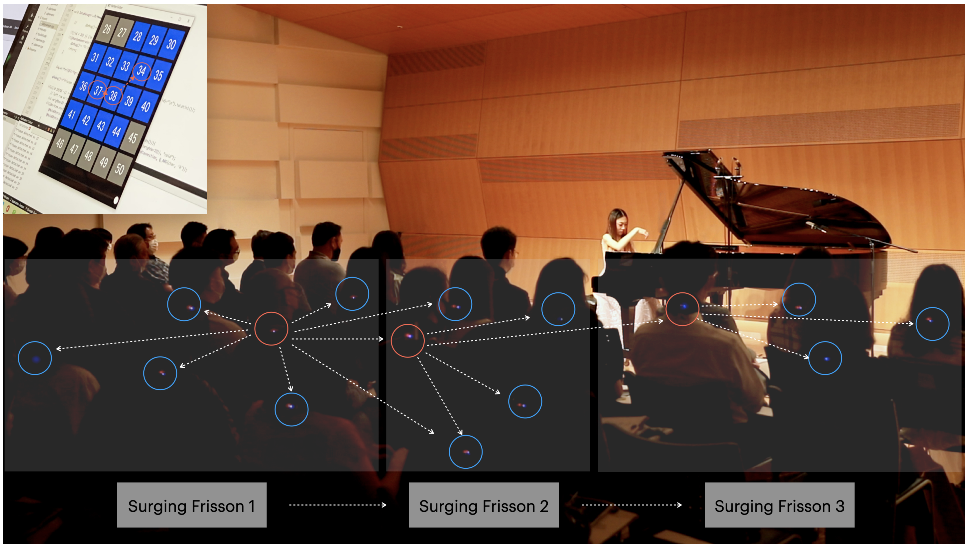

Fig. 6. Example of frisson transmission effect matched with seat number in Live Concert II.

the frisson prediction model's performance in-the-wild and distinguishing between natural frisson and synthetic frisson in a statistical way. However, researchers were monitoring the system during the whole concert to observe the feasibility of the system. Here, we mainly discuss the following aspects of the feedback from audience's subjective reported frisson feeling, connectedness and physiological states.

6.1 Enhanced Frisson Occurrences

We observed the artefact Frisson Waves effect as we designed for example in Figure. 6. The frisson signal was detected from subject 33, adjacent neckbands were activated and subject 34 successfully triggered frisson then shared to subject 38.

For all the 48 audience members, according to the questionnaire answers, 60% of them were familiar with the concept of frisson, 20% were familiar to a certain extent, and the remaining 20% audience members were not familiar with frisson. On a daily basis, about half of the audience reported feeling frisson between "sometimes" to "often", while the other half reported feeling frisson "rarely" to "never". However, the numbers of feeling frisson in relation to music are slightly different. 60% of the audience reported to feel frisson in relation to music, while 40% felt frisson in relation to music "rarely" to "never". In terms of frisson experiences in this concert, 40% of audience members reported that they felt more frisson during this concert than usual, while 8.3% felt less frisson. 6.25% reported feeling no frisson at all and the rest found it hard to answer. We found a strong correlation exists between the reported frequency of experiencing frisson normally and frisson during this concert ($R= .62$, $p< .001$).

For the frisson-sharing and non-sharing groups, there is a noticeable difference in the reported number of frisson occurrences during the concert. Although the non-sharing group had reported feeling frisson in relation to music more often than the other group, the non-sharing group did not experience more frisson during the concert than usual. 41.67% of the non-sharing group reported that they had more frisson than usual, 54% of frisson-sharing group reported that they had more frisson than usual, the frisson-sharing group had an 8.8% increase of frisson than usual, which suggests that the frisson-sharing mechanism does increase the number of frisson occurrences. This leads us to think that increasing frisson in a group which is originally less familiar with frisson is proof of the adequacy of the system. This result suggests our system worked as we expected for detecting and actuating neckbands to trigger frisson in a live concert scenario.

6.2 Enhanced Connectedness

In order to evaluate our hypothesis that the sense of connectedness in the frisson-sharing group would be higher than in the non-sharing group, we compared the subjective connectedness score between the two groups. However, these scores were found to correlate with the number of acquaintances sat adjacent to one another(R= .31, p= .03). Among the frisson-sharing group, the number of adjacent acquaintances (mean= 1.08, sd= 1.06) is 40% less (p = .017) than the non-sharing group (mean=1.8 ,sd=1.32). The connectedness score in the frisson-sharing group (mean= 3.54, sd=1.53) is 16% less (p = .11) than in the non-sharing group(mean=4.17, sd=1.85). We cannot state a significant difference (p = .11) of the sense of connectedness within the two comparison groups, though we assume that the score should have a much stronger decrease in the frisson-sharing group based on the significantly fewer (p = .017) acquaintances. Since it was an experiment in-the-wild study, the audience were allowed to pick their preferred seats, the groups were not balanced by the personal relationships, and the non-sharing group happened to know each other much better than the frisson-sharing group. This highlights the importance of taking personal relationships between participants into consideration when evaluating connectedness. To be able to evaluate how well the system enhances connectedness among audience members, further experiments will be needed under tighter conditions.

6.3 Enhanced Physiological Synchrony of EDA

Besides subjective feedback from audience members, we explored the physiological data collected and calculated the physiological synchrony (PS) of each group. PS occurs when the "physiological activity between two or more people" becomes associated or interdependent" [37]. Therefore, we consider PS as a feasible metric to quantify the experience of physiological connectedness. Following the prior work of Gashi et al. [18], we conducted the decomposition into EDA tonic and EDA phasic, normalized the two components to remove individual differences, and processed dynamic time warping (DTW) to calculate the accumulated distance between every two persons in each group [18]. After removing noisy and incomplete datasets, we have the EDA data from 9 audience (non-sharing: 4, sharing: 5) in the first session, 16 audience (non-sharing: 7, sharing: 9) in the second session, and 16 audience (non-sharing: 7, sharing: 9) in the third session. Figure. 9 shows one audience's EDA signal and Figure. 8 shows one audience's BVP signal as examples. Both of the data were collected during the first session. Figure. 9 and Figure. 8 can be found in the Appendix. A.3. Figure. 7. presents the distribution of accumulated distances normalized with the signal length between each pair within the group. According to the t-test results, we found the normalized accumulated distances of EDA tonic in the frisson-sharing group (mean = .19, sd = .11) was significantly larger than that in the non-sharing group (mean = .10, sd = .06),$t(56) = 3.51$, $p<.001$. However, the normalized accumulated distances of EDA phasic in the frisson-sharing group (the first session: mean = .003, sd = .002; the second session: mean = .003, sd = .002) was significantly smaller than that in the non-sharing group (the first session: mean = .008, sd = .002; the second session: mean = .005, sd = .002) for both the first session, $t(15) = -4.50$, $p < .001$, and the second session, $t(56) = -2.81$, $p < .05$.

The EDA tonic component indicates the slow change of skin conductance levels while the EDA phasic component reflects the quick and prompt change of skin conductance response [10, 11, 15]. Therefore, our findings may suggest wearing the neckband and sharing frisson could provide audience members more physiologically similar experiences in terms of short-term and sudden feelings of arousal compared with the long-term trend in certain concert sessions.

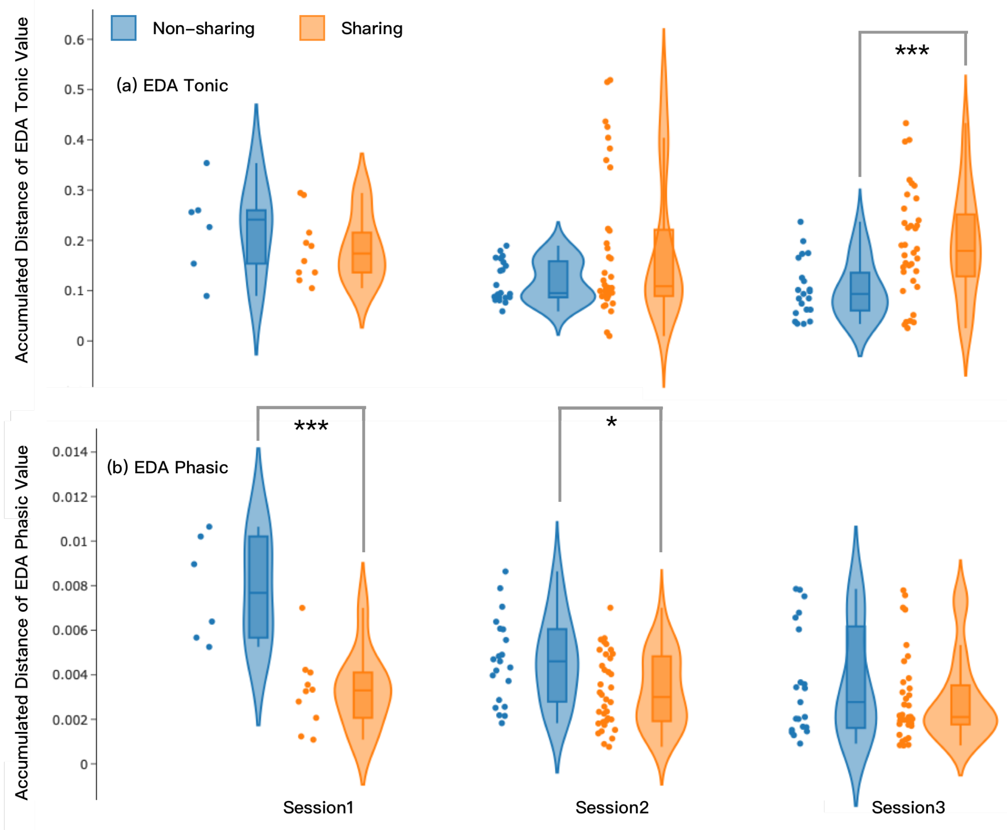

Fig. 7. Comparison of paired similarity of EDA tonic (a) and EDA phasic (b) between every two audience members in two groups. Each point represents the signal distance between one intragroup pair of audience members. The smaller the distance, the similar the pair of data. In the third session, the distances of EDA tonic in the frisson-sharing group was significantly larger than that in the non-sharing group. While, in the first two sessions, the distances of EDA phasic in the frisson-sharing group was significantly smaller than that in the non-sharing group. ($^{*}p$<.05, $^{**}p$<.005, $^{***}p$<.001)

7 DISCUSSION

We discuss the social impact of creating and sharing frisson, introspection from the exploratory process, as well as visionary possibilities which could augment human perception in musical experiences.

7.1 Qualitative Difference between Artificial Frisson and Natural Frisson

In order to better understand the qualitative experience of the artificial frisson induced by our technology, we interviewed three audience members in the frisson-sharing group after "Frisson Concert II." Subject 30 claimed to rarely experience natural frisson when listening to music, stating it would only happen once every few years. However, whenever they do experience natural frisson while listening to a piece of music, the listening experience would leave a profound and lasting impression on them. Subject 30 then goes on to explain that the synthetic frisson similarly increased their attention to the piece of music. However, the listening experience did not leave as deep of an impression on them after the concert was over. Subject 33 stated that the technology successfully induced synthetic frisson for them. However, they argue that naturally occurring frisson would typically be accompanied by a feeling of resonance with the music. This would be lacking for the synthetic frisson. Subject 27 reported that natural frisson would come from an emotional engagement with some particular parts of the music while cold synthetic frisson would just come from the cold. At the same time, synthetic frisson also made the concert more stimulating as a whole. Based on these interviews, we presume that there is a qualitative difference between the artificial frisson caused by our technology and the frisson that people naturally feel when listening to music. We believe that this qualitative difference between artificial and natural frisson opens up new creative opportunities, as it allows us to explore the complex interplay between music and cognition.

7.2 Sharing Frisson Constitutes a Collective Experience

Both subject 30 and 33 reported a sense of surprise when they noticed someone close to them experiencing frisson. This aroused their curiosity as to what kind of experience the other person was having in that moment and why they might resonate so strongly with that moment of music. Subject 27 claimed they started to notice other audience's presence through the clues of feeling others' frisson. Subject 30 also stated that they enjoyed being able to share how they resonated with the music with others. This suggests that sharing frisson between audience members can constitute a unique kind of collective empathetic experience.

7.3 Future Applications for Frisson Sharing

Beyond using the system in a music concert context, we believe that the system can be applied to wider scenarios related to live experience as well. For example, our system could potentially be used to mediate frisson between audience members at a movie screening in theaters, watching dance performances, visiting museums, listening to speeches, and other performing scenarios. Especially during a pandemic, when talking or direct contact are discouraged, implicit communication approaches are crucial for fulfilling human social needs. Beyond that, our system could possibly also be used to share bodily sensations across remote locations. One potential application for frisson sharing between remote locations might be online concerts, where the audience is watching from home. Being able to share bodily sensations across remote locations might help to facilitate the collective experience that concert goers typically long for. There's also a potential to develop user dependency of a similar system for sharing human emotions and feelings to create empathetic collective experiences. We could also imagine that through this design process and system platform, other emotions and feelings could also be accessed, shared, and communicated to others. Elevating the affordances of physiological data sensing to create a feedback loop between and beyond audience and performers, Potentially, Frisson Waves opens up new horizons for facilitating a new form of "cybernetic togetherness".

7.4 Neckband in a Ubiquitous Context

We demonstrated our system in a live classical music concert. Beyond this, we believe that the system can be applied to a variety of other ubiquitous contexts as well. Our current implementation comes in the form of a neckband. This form factor allows the device to be taken on and off quickly. For a more personalized experience, it would be possible to integrate our system into clothes, for example a shirt or a turtleneck sweatshirt that is worn directly on the body. Locations other than the neck may be suitable for triggering frisson as well, and will be explored in future studies.

7.5 Frisson Sharing Design Guideline

Besides the concept, framework, and system which we demonstrated, we would also like to discuss the lessons we learned which other designers might consider when developing similar systems. Designing a data sensing tracking protocol would help recording and streaming valid data in less controllable in-the-wild studies. As with reporting problematic data source from the server, researchers could help participants wear the devices with a stabler connection in time. Testing the frisson model in a controlled environment before in-the-wild studies would provide a convincing baseline to evaluate the model's performance and distinguish artificial frisson and natural frisson. A user-friendly re-design of the neckbands would help to reduce the constrained impact on the user experience. A larger user group or a more socially controlled method would be more accessible for evaluating the impact on connectedness and togetherness. We hope Frisson Waves can give insights for those whom would like to design similar systems through providing a formidable starting point for developing frisson sharing systems.

8 LIMITATIONS

There are still some limitations with our in the wild field study. Firstly, to avoid the risk of distraction we did not include real-time self-reporting for frisson in our field study. This may limit our evaluation of the frisson prediction model's performance in the wild, making it difficult to distinguish between natural and synthetic frisson. Moreover, not all recorded data from the in the wild study was successfully saved. Therefore, we were not able to explore every audience member's data and compare between groups. Thus, we may have missed some insightful differences between frisson-sharing and non-sharing groups. Furthermore, a re-design of the neckband is warranted as to reduce its impact on the user experience. To give a more direct and tangible understanding of how much temperature has to change to elicit a feeling of frisson, we will add a thermal sensor to the surface of each Peltier of the neckband to measure the temperature presented to the participants for future experiments. To have a more accurate understanding of how long the thermal feedback activation timing is more efficient to the trigger frisson, We will conduct a more detailed control group experiment in the future. For evaluating the impact on connectnedness and togetherness, a more controlled method and or a larger sample size is required.

Frisson Waves explores a new form of "cybernetic togetherness" by allowing one person to perceive another person's response to and appreciation of live music. We hypothesize that sharing embodied sensations such as frisson during a live concert can lead to a new way of appreciating the music. However, our approach might potentially interrupt the natural music appreciation process. For example, person A may feel frisson at similar moment as person B, albeit a few seconds later. In this scenario, person A's natural frisson response would overlap with the synthetic frisson that has been triggered by person B's sensation. What happens at this overlap of natural and synthetically induced frisson has not been explored as part of this study. Person A's natural experience may be augmented as a result of this overlap, however it might also be interrupted. Possibly, an entirely new sensation will emerge from this overlap in stimulation. This possible occurrence has not been mentioned by the participants or investigated by the study. For a conclusive answer, further investigation of this occurrence is warranted.

This exploratory work raises questions: As we are headed towards a future of interconnectedness, the potential of artificial interruption leads us to reconsider affective augmentation and manipulation. In an increasingly interconnected world where technology mediates how and when we feel, we need to have more responsibility to design such technology. Frisson Waves opens up a much-needed dialog about these questions. While the experience of sharing your intimate feelings can be empowering, it can also be dangerous. Where to draw the line? Do we need to draw a line?

9 CONCLUSION

This work introduces Frisson Waves, a system that detects and triggers frisson and can be used to create a shared frisson effect among audiences during musical performances. The system works by translating physiological signals into thermal information, enabling us to automatically detect frisson through a smart wristband with a trained real-time frisson classifier, trigger frisson through a smart neckband with two Peltier thermal modules, and share frisson through our open integrated server.

We devised and piloted the concept during an initial live performance, we conducted several studies to evaluate the system, and we tested the final system during a 90 minute concert for 48 spectators. We demonstrated that a simple wearable device with embedded Peltier TECs can induce clearly reported frisson in 93% of participants (N=15) . We demonstrated a classifier trained on 19 participants with 85% accuracy and were able to process data from the other 48 audience members in real time and in the wild. The feedback from the concert suggests that frisson is shareable using our system. The system is shown to enhance the frisson feeling for people who are not familiar with frisson, and to enhance the feeling of connectedness between audiences.

Besides deepening our understanding of frisson and how to share this phenomenon, this research also looks into the implication of a frisson-sharing system. We hope that the questions raised in this work around artificial and natural experience, individual and collective experience, along with the technical contributions of Frisson Waves, will provide some help and inspiration to those seeking to design similar systems or experiences.

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A SUPPLEMENTARY MATERIALS

A.1 Dataset

The 33 sets of physiological data recording in the frisson detection ML model study consisted of audience EDA, BVP signals, and self-report frisson labels. We have 33 recordings in total (male = 16; female = 17). By eliminating incomplete or noisy data records, the sets of data from the recruited participants were 19 recordings.

The 48 sets of physiological data recording in Concert II. three sessions consisted of audience EDA and BVP signals over three sessions in Concert II. We have 48 recordings in total (male = 19; female = 28, prefer not to say=1). By eliminating incomplete or noisy data records, the breakdown sets of data from the recruited participants for each session was: 1st, 9 (male= 3; female=6), 2nd, 16 (male=6; female=10), and the 3rd, 16 (male= 5; female=9).

We uploaded the dataset together with the questionnaires used in the two concerts (Exploring Frisson in In-Situ Concert I. and Sharing Frisson Concert II.) to the following link: https://osf.io/rzpn3/.

A.2 Descriptive Statistic

Table 1. Comparisons of Mean and Standard Deviation Values of Concert II. Subjective Feedback and EDA Features between Frisson-sharing Group and Non-sharing Group. ***p<.001)

Dependent Variables		Frisson-sharing Mean(SD)	Non-sharing Mean(SD)	Statistics t
Enjoyment (1-7 Likert Scale)		6.13(0.99)	6.29(1.04)	-0.59
Engagement (1-7 Likert Scale)		4.86(1.73)	5.21(1.28)	-0.76
Frisson Frequency (1-5 Likert Scale)		2.83(1.05)	2.67(1.00)	1.03
Frisson Intensity (1-7 Likert Scale)		4.08(1.74)	4.33(1.81)	-0.49
Frisson Frequency Induced by Neckband (1-7 Likert Scale)		4.33(1.74)	/	/
Connectedness Score (1-7 Likert Scale)		3.54(1.53)	4.17(1.85)	-0.76
Number of Acquaintance Sitting Around		1.08(1.06)	1.99(1.30)	-2.32*
Normalized Accumulated Distances of EDA Tonic	Session 1	0.184(0.067)	0.223(0.092)	-0.989
	Session 2	0.181(0.142)	0.119(0.041)	1.936
	Session 3	0.192(0.107)	0.103(0.058)	3.515***
Normalized Accumulated Distances of EDA Phasic	Session 1	0.003(0.002)	0.008(0.002)	-4.505***
	Session 2	0.003(0.001)	0.005(0.002)	-2.809***
	Session 3	0.002(0.002)	0.004(0.002)	-1.197

A.3 Plot Examples

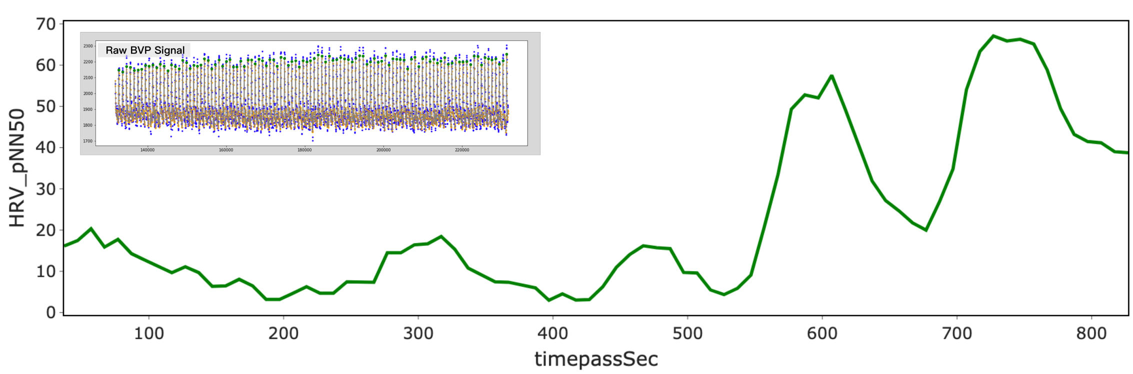

Fig. 8. BVP signal example collected from one audience member during the first interactive session of the concert. The left-top plot presents a period of BVP raw signal. The green line chart shows one of the HRV feature used in the model training.

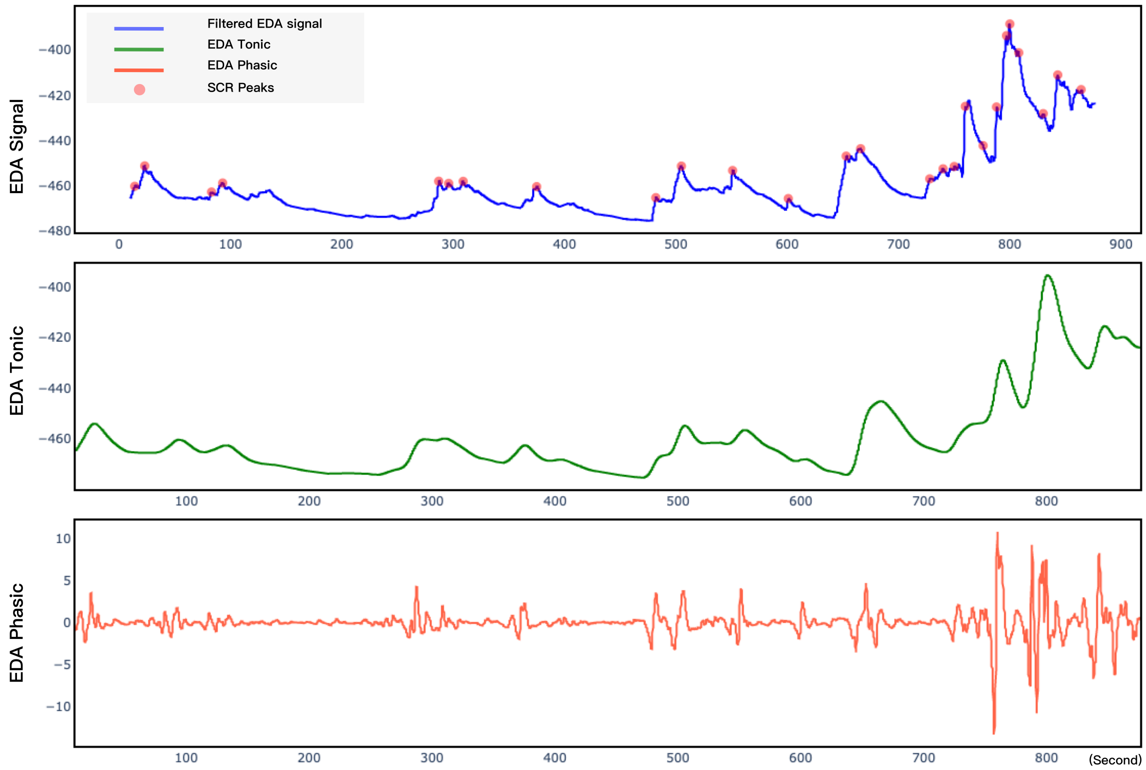

Fig. 9. EDA signal example collected from one audience member during the first interactive session of the concert. The upper plot presents the EDA signal after a low-pass filter. The orange markers highlight peaks in skin conductance response (SCR Peaks) which is related to sudden change of EDA. The middle and the bottom plots present Tonic and Phasic components extracted from EDA signal [15] which are key features in the prediction model.