"Please Share": Promoting Embodied Forms of Interpersonal Stress Sharing Through Real-Time Neurofeedback

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Abstract

Sharing with others can play a vital role in helping to cope with stress and emotional burdens. Biofeedback systems have been growing in HCI as supportive of individual stress management; however, the potential of leveraging neurofeedback systems for embodied forms of interpersonal stress sharing remains unexplored. We present *Minus×Minus=Plus*, an interactive system that externalizes collective neural activity to create a shared affective space. The system allows two participants to visualize their stress in real time via Electroencephalography (EEG) and to jointly transform it through two forms of haptic interaction. The system was tested with 110 participants (55 pairs), and their experience of embodied stress sharing was evaluated. Results show that our system significantly promoted the sharing process, underscoring the central role of visual and haptic modalities. This work contributes empirical evidence and design insights for developing neurofeedback systems that foster interpersonal stress sharing and support mental health.

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**.

Keywords

Stress Sharing, Neurofeedback, Physiological Data Visualization, Haptic Interaction, Interpersonal Touch

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1 Introduction

Stress is a psychophysiological state that arises when environmental demands exceed an individual's coping resources [59]. Stress has become a major health concern in society, and it is linked to a wide range of physiological and psychological disorders, including anxiety, sleep disturbances, and cardiovascular disease [91]. Therefore, stress management is an essential focus of public health efforts.

In Human–Computer Interaction (HCI), biofeedback technologies are increasingly used for stress management. Biofeedback converts physiological signals, such as Heart Rate Variability (HRV), Electrodermal Activity (EDA), and Electroencephalography (EEG), into visual or auditory information in real-time. This process improves awareness of stress responses and strengthens self-regulation [25, 62, 79]. Research increasingly shows that biofeedback effectively supports stress management, making it a valuable tool for individuals who are coping with stress [92, 108].

However, stress is not merely an individual phenomenon. Especially in workplaces, schools, and relationships, stress embodies a social character. Its emergence and regulation are shaped by interpersonal interactions and social support [10]. The sharing of stress suggests that stress experiences and physiological responses can be distributed and correlated between people, helping them to reduce their stress [81, 103]. Some studies have explored integrating biofeedback into social interaction [49]. However, little is known about designing neurofeedback systems for stress sharing.

While traditionally limited to professional psychological and clinical research, EEG has recently seen broader applications in stress management due to the advent of low-cost devices [57, 67]. Compared with signals such as HRV and EDA, EEG offers higher temporal resolution [11], enabling finer-grained tracking of rapid physiological changes and enhancing responsiveness in interactive tasks. In interpersonal stress regulation, such high-resolution feedback is important for revealing dynamic physiological interactions and guiding timely emotional and behavioral adjustments [96]. Therefore, EEG-based neurofeedback is well-suited for social stress management.

We argue that neurofeedback-based stress sharing involves more than the shared externalization of brain signals. It should be understood as a dynamic, interactive process. From an embodied perspective, stress and affect are shaped not only by the brain but also through bodily engagement and interpersonal exchange [35, 109]. This indicates that haptic modalities can deepen our understanding of affective experiences in stress sharing. Research on mediated touch shows its potential to foster empathy, intimacy, and connectedness [18, 40, 73]. However, in HCI, few studies have examined how haptic interaction influences neurofeedback-based stress sharing.

To explore this synthesis of social, embodied, and neuro-technological opportunities, we present *Minus×Minus=Plus*, an interactive system for shared stress experiences. The system integrates collective EEG

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visualization with two distinct haptic modalities: object-mediated interaction and interpersonal touch. Through the design and evaluation of this system, we seek to investigate:

1) Can this system facilitate stress sharing?

2) How can stress sharing, as an interactive process with multiple facets, be briefly measured in our neurofeedback setting?

3) How do participants perceive the roles of different interaction modes (visual, object-mediated, and interpersonal touch) in enabling stress sharing within this neurofeedback experience?

We deployed the system as an interactive installation at a public art exhibition. This in-the-wild study served two purposes. First, it functioned as a cultural probe to elicit conversation and reflection on sharing stress. Second, it provided a setting for an empirical study in which we evaluated its effects using a mixed-methods approach. To capture participants' experiences, we developed the Stress Sharing Experience Questionnaire (SSEQ) and conducted semi-structured interviews after each session.

The key contributions of this work are as follows:

1) We develop *Minus×Minus=Plus*, a multimodal EEG neurofeedback system that integrates real-time collective visualization, joint object-mediated interaction, and interpersonal touch to scaffold shared stress experiences, significantly facilitating participants' stress sharing.

2) We advance the conceptual understanding of stress sharing by articulating a process-oriented framework with theoretically grounded facets, and we introduce a preliminary, brief questionnaire to capture this process in interactive settings.

3) We provide empirical insights into how different modalities (visual feedback, object-mediated interaction, and interpersonal touch) jointly enhance stress sharing, yielding design implications for collaborative biofeedback.

2 Background and Related Work

2.1 Stress and Stress Sharing

Stress is increasingly prevalent in contemporary life and is commonly described as feelings of anxiety, tension, or being overwhelmed. Beyond subjective experience, stress is understood as a complex psychophysiological process. It occurs when individuals perceive environmental demands as exceeding their coping resources, triggering coordinated emotional, cognitive, behavioral, and physiological responses [16, 59]. A defining feature is physiological arousal, which refers to the body's automatic mobilization to meet challenges, often manifested in elevated heart rate, altered respiration, increased perspiration, or muscle tension. While moderate stress may be adaptive (eustress), prolonged or excessive activation (distress) can undermine both physical and mental health [88]. Supporting stress regulation has become an important area of inquiry in HCI, with increasing attention to health, well-being, and quality of life [26].

Traditional stress management interventions often emphasize self-regulation strategies, including mindfulness, relaxation, time management, and cognitive-behavioral methods [80]. Although valuable, these approaches adopt an individualistic perspective. They overlook stress as both a personal burden and a relational process that often arises and is managed within social relationships [5, 89]. To address these limits, research has shifted toward social approaches to regulation. Mindfulness-based group interventions, for example, have been shown to reduce perceived stress and improve emotional regulation and self-care behaviors in clinical populations [84]. Work on peers' co-regulation in small-group learning likewise demonstrates how students monitor and respond to one another's emotions and coping during collaborative tasks, distributing regulatory work across the group rather than locating it solely within the individual [68]. Together, these accounts frame stress as a phenomenon that is negotiated and regulated within ongoing relationships.

Building on these perspectives, we use the term stress sharing to refer to an interpersonal approach to managing stress through communication and mutual engagement with others. We draw on three complementary accounts to articulate four mechanisms of this process. The social sharing of emotion theory highlights expressive disclosure as a core interpersonal act [81]. The interpersonal emotion regulation framework emphasizes how people perceive others' affective states and respond with regulatory behaviors [109]. The dyadic coping model situates these exchanges within a relational system, beginning with awareness of one's own stress and culminating in coordinated supportive responses [5]. Together, these perspectives motivate a four-part view of stress sharing: becoming aware of one's stress, expressing it, perceiving and interpreting the partner's state, and responding through co-regulation. Social support and stress-buffering theories further suggest that such exchanges can increase perceived support and relational closeness, which in turn can help mitigate the impact of stress [20, 58].

Guided by this structure, we capture stress sharing through subjective appraisals that correspond to these mechanisms and their immediate relational consequences. We therefore include self-perception as an intrapersonal precursor, expressiveness and social perception as interpersonal processes of disclosure and understanding, co-regulation efficacy as an appraisal of shared regulatory capacity, and connectedness as an immediate relational outcome. Below, we describe the five facets and their theoretical grounding.

- `Self-perception`: Self-perception refers to awareness of one's own emotional state, which may serve as a prerequisite for sharing stress. According to the Self-Perception Theory [4], individuals infer their feelings by attending to their own bodily cues. Higher levels of bodily awareness have been linked to more accurate recognition of stress responses and a greater likelihood of seeking support [69].
- `Expressiveness`: Expressiveness describes how individuals communicate their stress to others. It includes both verbal disclosure and nonverbal cues that signal stress [54]. Research indicates that emotional expression supports regulation and relational closeness [75]. Expressiveness has also been identified as a core component of dyadic coping with stress, highlighting its role in initiating and sustaining interpersonal support processes [5].
- `Social perception`: Social perception involves recognizing and interpreting another's emotions through verbal and nonverbal signals [109]. Stress sharing is not a one-way disclosure but a reciprocal exchange. Accurate perception of a partner's emotional state is essential for establishing shared awareness and informing responses [81].

- `Connectedness`: Connectedness is a perceived sense of closeness that can emerge even in short-term interactions. It can provide the relational foundation for stress sharing [58]. Social Baseline Theory posits that close relationships reduce perceived threat and stress burden [17]. Social connectedness also strongly predicts well-being and self-regulation [60]. These perspectives indicate that connectedness enhances the effectiveness of stress sharing.
- `Co-regulation efficacy`: Co-regulation efficacy refers to participants' belief in their shared ability to manage stress [5, 109]. This facet reflects both the outcome and the core value of stress sharing. It indicates how much interpersonal interaction is perceived to reduce stress.

Together, these five facets provide a practical lens for examining how an interactive system may support stress sharing in situ. To empirically examine this theoretical structure, we conducted an Exploratory Factor Analysis (EFA) to determine whether these facets converge into a single construct.

2.2 Biofeedback Systems for Stress Management

Stress management research has increasingly investigated the detection and measurement of stress through physiological signals such as Photoplethysmography (PPG), Electrodermal Activity (EDA), and Electroencephalography (EEG) [94]. Biofeedback systems use these signals to deliver real-time information about internal states, creating a closed loop that enhances self-awareness and voluntary control [53, 102]. EEG-based neurofeedback provides distinct advantages by directly measuring neural oscillations across frequency bands (e.g., Alpha, Beta, Theta) with high temporal resolution [93]. Compared to peripheral measures such as HRV or EDA, EEG yields more detailed data, making it a valuable tool for investigating stress regulation. Although EEG neurofeedback is established in clinical contexts, its everyday use in non-clinical settings remains underexplored. Recent advances, such as consumer-grade EEG devices and stress-detection algorithms, highlight the potential to expand neurofeedback into broader applications [85]. Neural correlates link stress to reduced alpha power (8–12 Hz), associated with calm states, and increased beta power (13–30 Hz), associated with active concentration and anxiety [39, 52]. Building on these findings, neurofeedback training enables individuals to voluntarily regulate brainwave patterns to change habitual stress responses [93]. Our work takes up this potential by applying EEG-based neurofeedback in everyday contexts to explore its role in stress sharing.

Many biofeedback systems for stress regulation are based on relaxation and mindfulness training. For example, [12, 14, 100] explored guided breathing to regulate stress-related signals such as HRV and EDA through gamified experiences and immersive environments. [24, 63] integrated mindfulness practices with EEG neurofeedback to encourage present-moment awareness and calm states. There are also studies in personal informatics systems that visualize biodata to help individuals identify stress triggers and coping patterns in daily life [51, 87]. While these systems effectively support individual awareness and regulation, they give less attention to the social potential of biosignals as resources for both information and connection [97]. Our study focuses on social neurofeedback, using shared brainwave data as a medium for stress sharing between participants.

Recent research has begun to explore social biofeedback. For instance, *StressDiffuser* is an HRV-based system that conveys a child's stress state to a parent during homework sessions to support supervision [63]. This asymmetric design increases parental awareness but risks creating monitoring pressure that may heighten stress. In contrast, symmetric systems such as *AffectiveWall* and *BallBounce* visualize collective stress through HRV or GSR data in workplace contexts to support group reflection and stress reduction [72, 106]. These designs often use anonymity and aggregation to reduce discomfort, but such strategies limit opportunities for deeper interpersonal connection and sharing. More expressive approaches, such as *IntimaSea*, a mobile application enabling couples to exchange affective signals, emphasized intimacy and communication but remained primarily remote and display-based [50]. Sharing physiological data in such systems also raises ethical concerns. Akiri et al. present a web-based Stress Reflection system that links EDA with synchronized video from high-stress simulation training and find that trainees are enthusiastic about sharing their stress data while articulating a few concrete risks. They therefore propose guardrails that emphasize autonomy and consent, transparency about who can access which data and for what purposes, and careful control over when and how data are reviewed [1]. Overall, existing systems externalize stress mainly through visual feedback and aggregated displays, with limited exploration of embodied or affective modalities. Our work extends this trajectory by incorporating embodied and haptic interaction alongside visual neurofeedback. In addition, we situate the system in a public, co-present setting, allowing us to probe both its experiential possibilities and the ethical concerns that arise when physiological stress is made mutually visible in daily life.

2.3 Interaction Modalities for Stress Sharing

Our stance on mediated stress sharing is informed by an interactional view of emotion and somaesthetic design. Boehner et al. [6] challenged the cognitivist framing of emotions as discrete information units to be detected and managed, emphasizing their co-constructed and co-interpreted nature as complex social and cultural products instead. From this perspective, design should not aim to decode emotions from bio-signals, but to create contexts in which people can reflect on and experience their emotions. Complementing this view, Höök and colleagues [45] emphasized the embodied dimension of affect, proposing the affective loop as an iterative cycle where bodily expressions and system responses continuously shape one another. Somaesthetic design extends this approach by foregrounding bodily and physical experience as central to emotional interaction, encouraging designs that invite felt, experiential, and aesthetic engagement [43].

From Höök's broader somaesthetic design principles, we adopt three as most relevant for mediated stress sharing: **(1) expressive interaction**, where biosignals are shaped into aesthetic forms that evoke emotion and invite interpretation; **(2) body involvement**, recognizing that emotion is lived and communicated through the body, which motivates our integration of touch as a medium of immediacy, intimacy, and connection; and **(3) balanced ambiguity**, where design responses are intentionally open enough to support personal meaning-making while structured enough to sustain shared experience. Guided by these principles, our system brings together visual feedback, object-mediated interaction, and interpersonal touch, each contributing in distinct ways to the experience of shared neurofeedback.

2.3.1 Visual Feedback. Visualization has long been the dominant modality in biofeedback systems. Early approaches relied on "cold" representations such as line charts, bar graphs, or numerical indicators of HRV or EEG. These formats prioritize precision but flatten the experiential qualities of affect. Inspired by somaesthetic design, more recent work has treated biosignals as expressive and aesthetic material, shaping them into metaphors such as particle systems, ambient light displays, or fluid animations. These artistic approaches engage participants emotionally and invite interpretation, extending biofeedback beyond monitoring toward experiential engagement.

In shared biofeedback, visualization is widely employed to externalize collective states. *ClockViz* [105] projected three distinct patterns on a clock face to represent group stress: static forms indicated calmer states, while increasingly dynamic forms suggested greater group stress. Participants not only read these patterns as indicators but also reported that static visuals made them feel more peaceful, whereas dynamic ones heightened their own sense of stress. *AffectiveWall* [106] displayed workers' stress levels as mint-green rings projected together on a wall, enabling individuals to situate their own state within the larger team and develop a sense of group awareness. Such collective visualizations foster relational understanding but often depend on anonymity and aggregation to avoid discomfort, which can dilute opportunities for interpersonal connection. By contrast, *IntimaSea* [50] represented users as marine animals whose depth signaled stress levels, with message bubbles serving as playful channels of intimacy and communication. This design illustrated visualization's potential to move beyond awareness and comparison toward cultivating connection. Taken together, these examples show that shared visualization in biofeedback can serve four functions: representing internal states, influencing participants' states, enabling relational awareness, and supporting connection.

2.3.2 Object-mediated Interaction. Object-mediated interaction uses physical objects as interactive elements to represent or manipulate data [66]. We use the term object-mediation instead of tangible interaction to distinguish it from interpersonal touch. In biofeedback, this often appears as squeezable devices, sliders, or object-based games that respond to biosignals such as HRV or GSR, providing a more embodied alternative to purely visual displays. These objects may change color, vibrate, or shift shape in response to physiological signals, allowing users to literally "grasp" their internal states [33]. In shared biofeedback, physical manipulation plays a distinct role: it grounds interaction in embodied engagement, where movement and touch deepen emotional connection and make stress more tangible as a shared phenomenon. Beyond representing stress, collaboratively manipulating objects fosters mutual awareness, synchrony, and a sense of joint agency, transforming biofeedback into a co-created rather than observed activity. Prior work has mainly focused on representational mappings where objects passively mirror biosignals. Future opportunities lie in designing artifacts that support expressive, co-experienced manipulation, amplifying stress sharing as a relational and embodied practice.

2.3.3 Interpersonal Touch. Interpersonal touch is a fundamental relational cue that conveys empathy, trust, and care while influencing both psychological states and physiological responses [97, 99]. Everyday gestures such as hand-holding, supportive pats, or embraces can reduce anxiety, lower heart rate, and foster closeness [30]. In mediated systems, touch has often been used instrumentally, for example, as a trigger to activate feedback or as a channel for transmitting signals, such as haptic devices that share heartbeat rhythms between partners [82]. Although these examples show the feasibility of touch in biofeedback, they often reduce its richness to simple cues. In stress sharing, touch offers a deeper opportunity: it provides a direct, embodied channel for co-regulation, enabling participants to physically communicate support and experience stress together in real time. Moving beyond touch as input, shared neurofeedback system can harness its expressive and relational qualities, complementing visual and object-mediated modalities to amplify immediacy, intimacy, and embodied connection.

3 Minus × Minus = Plus: Design and Implementation

We developed *Minus×Minus=Plus* as a prototype to explore how neurofeedback systems can foster stress sharing through visual and haptic interaction. The interactive system is grounded in the metaphor that two negative emotions, when shared, can transform into a positive outcome. The system translates participants' EEG signals into expressive visualizations, which are coupled with collaborative touch-based actions to enable joint transformation of the visuals. The system serves a dual purpose. As an artistic cultural probe, it communicates stress sharing as a collective approach to coping and invites a broad audience to reflect on mediated affective experience. As an empirical research tool, it provides a structured context for examining how people perceive, express, and connect around stress in short-term interactions.

3.1 System Overview

The interactive experience consists of a large projection screen and two stands, each equipped with a touch ball and a TGAM EEG headset. Participants stand side by side, facing the projection, while their stress signals are continuously captured and visualized. The experience lasts approximately six minutes and is structured into three stages of about two minutes each (Figure 1). A facilitator guides the process, while participants are free to communicate, ask questions, and behave naturally throughout.

- `Visualization Stage`: Once participants have correctly worn their EEG headsets and activated the touch balls, their stress signals are projected as two cube clusters, each rendered in a distinct color corresponding to one participant. The clusters appear side by side, aligned with the participants' positions, allowing each individual to clearly recognize their own visualization. Small cubes dynamically assemble into larger structures, with the number of cubes varying in real time according to the detected stress index. Higher stress values produce denser clusters.

- `Merging Stage`: In the second stage, participants are instructed to press their touch balls simultaneously. This action causes the cube clusters to move toward the center of the screen, with speed proportional to the force applied by each participant. If one participant stops pressing, the clusters return to their original positions. Sustained pressure by both participants enables the clusters to meet and intertwine, producing a dynamic fusion of their stress visualizations. This stage emphasizes synchronized collaboration and mutual effort.
- `Explosion Stage`: In the final stage, participants maintain pressure on their own touch ball with one hand while holding each other's free hand. This interpersonal touch triggers the merged clusters to condense into a shared sphere, which then bursts outward. The intensity of the explosion reflects the force applied to the balls, and sustained hand holding causes the sphere to explode completely and disappear, symbolizing the release of shared stress.

3.2 Modality Design

The interaction design of *Minus×Minus=Plus* was guided by three principles: expressive interaction, body involvement, and balanced ambiguity. These principles shaped how stress signals were transformed into visual forms, how touch was integrated as a medium of collaboration and intimacy, and how the system created space for interpretation while guiding participants through a shared experience.

3.2.1 Visual Feedback. Stress was externalized through clusters of animated cubes, translating intangible internal states into tangible, physicalized forms. The use of cubes conveyed rigidity and weight, qualities often associated with stress, while their dynamic assembly and disassembly introduced liveliness and potential for transformation. The number of cubes scaled with each participant's stress index, while brightness and density increased with higher stress levels, offering a nuanced indication of change without reducing affect to a binary "stressed or not." Distinct colors (red and green) differentiated the two participants, ensuring legibility even when visualizations merged. Across the three stages, the clusters underwent deliberate shape transformations that structured the shared experience. In the Visualization stage, cubes appeared as separate, box-like formations on opposite sides of the projection, reinforcing individuality and separation. In the Merging stage, the clusters spiraled toward the center, intertwining into a joint formation that symbolized togetherness and active collaboration. In the Explosion stage, the merged clusters condensed into a sphere that burst outward, dispersing dynamically across the screen. This trajectory—from rigid separation to intertwined fluidity to explosive release—embodied a metaphorical journey of stress sharing. In this way, the visual design functioned on two levels: first, as an externalization of stress, making participants' internal states visible, manipulable, and responsive to joint action; and second, as an embodied metaphor, guiding participants through a narrative arc of stress sharing that progressed from separateness to connectedness, and ultimately to cathartic relief.

3.2.2 Object-mediated Interaction. Object-mediated interaction in *Minus×Minus=Plus* centered on the use of touch balls as collaborative controls, requiring participants to coordinate their actions to shape the shared visualization. Pressing the balls simultaneously caused their individual cube clusters to move toward the center of the screen, with the applied force modulating the speed of convergence. This mechanism foregrounded interdependence: if one participant stopped pressing, the clusters retreated, making progress contingent on joint effort. Such collaborative manipulation emphasized both physical engagement and relational dynamics, transforming stress sharing into an embodied negotiation rather than a passive display. Beyond functional input, the design aimed to foster intimacy, co-presence, and a sense of joint agency, with the act of sustaining pressure together serving as a metaphor for mutual support in managing stress. In this way, object-mediated interaction functioned both as a control mechanism and as a channel for cultivating connection through embodied collaboration.

3.2.3 Interpersonal Touch. Interpersonal touch was incorporated as the final and most intimate layer of interaction, emphasizing physical co-presence and affective connection. In the Explosion stage, participants were instructed to hold each other's free hand while maintaining pressure on their own touch balls. This interpersonal contact functioned not only as a trigger for the visualization but also as a symbolic act of mutual support. The system responded by transforming the merged cube clusters into a unified sphere that burst outward, with the explosion's intensity modulated by the average pressure applied to the balls. This coupling of visual transformation with bodily touch highlighted stress sharing as both a sensory and relational experience. By requiring physical connection to initiate release, the design underscored the role of intimacy and trust in co-regulation, framing touch as a direct, embodied channel for externalizing stress together.

3.3 Technical Implementation

3.3.1 EEG Stress Index. To ensure ecological validity and maximize visitor throughput in the public museum setting, a deliberate choice was made to utilize dry-electrode sensors over clinical wet-electrode systems. Clinical devices typically require lengthy skin preparation and conductive gel, which hinders the spontaneous, low-preparation experience essential for public installations. Furthermore, unlike many commercial consumer headsets that restrict data access or rely on high-latency APIs, the TGAM module offers direct, real-time access to the data stream via standard serial communication. This ensures the low-latency responsiveness required for synchronized visual feedback.

Therefore, the system employed two NeuroSky TGAM sensors, each embedded in a TGAM headset and paired with an HC-05 Bluetooth module for wireless transmission. The TGAM is a single-channel EEG acquisition chip with a dry electrode placed at the left prefrontal lobe (Fp1) and a reference electrode on the earlobe. To improve signal quality in this unshielded environment, the TGAM implements hardware-level preprocessing, including a nominal 3–100 Hz band-pass characteristic and a mains-frequency notch filter (configured to 50 Hz in our installation) that together attenuate very slow baseline drift, suppress power-line interference, and

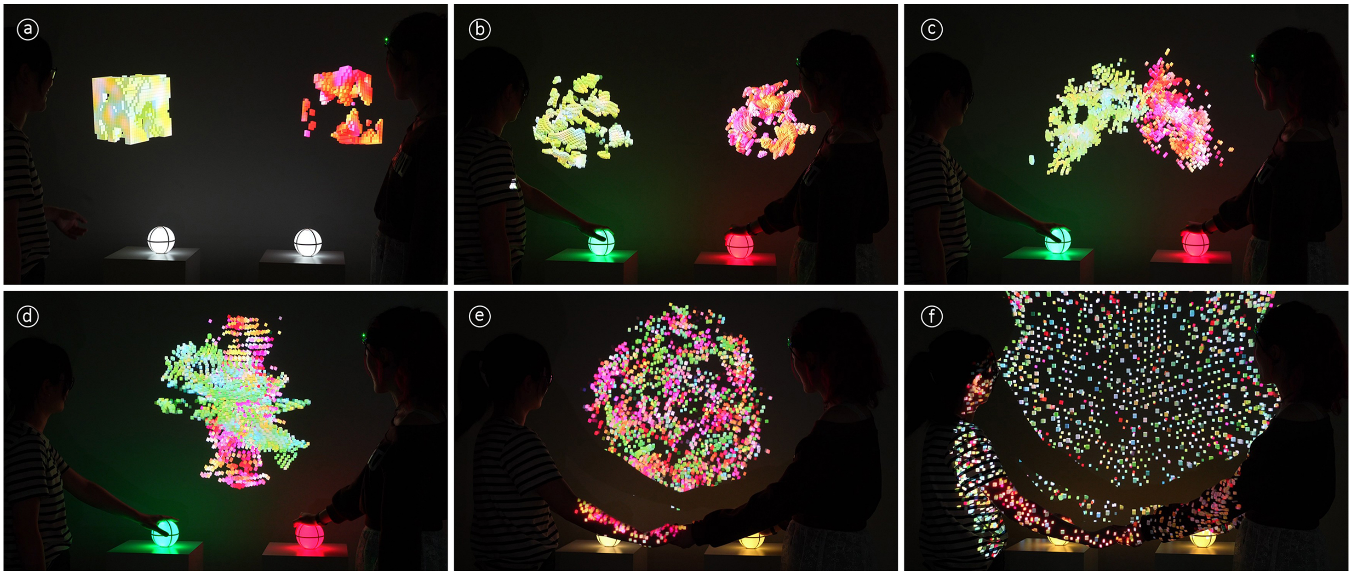


Figure 1: Stages of the stress sharing experience: (a) Visualization stage, (b–d) Merging stage, and (e–f) Explosion stage.

reduce the lowest-frequency components of ocular and motion-related artifacts, while preserving the alpha and beta bands that are critical for our stress metric.

The device samples raw EEG data at 512 Hz to derive precise frequency band power values across Delta, Theta, Alpha, Beta, and Gamma ranges, together with a signal quality flag. A custom C# program was developed to parse these byte streams, extract frequency band powers, and calculate a stress index for each participant. The stress index was defined as the normalized ratio of Beta (13–30 Hz) to Alpha (8–12 Hz) power, a widely adopted metric: elevated Beta activity is associated with cognitive arousal and anxiety, while Alpha power is linked to calm and relaxed states. To reduce noise and transient fluctuations, values were smoothed using a sliding five-second moving average. After processing, four distinct signals were output from the C# program and transmitted to TouchDesigner via TCP sockets: stressIndex1 and stressIndex2, representing the continuously updated stress indices for each participant; and eeg1Connect and eeg2Connect, Boolean values indicating whether each headset was properly connected and transmitting valid data. These four streams directly drove the real-time visuals in TouchDesigner: the stress indices controlled brightness, density, and cube count, while the connectivity signals enabled monitoring of device status and supported recovery from temporary disconnections.

3.3.2 Physical Prototyping. The system employed two handheld touch balls, each sized to fit comfortably in the palm. The shells were 3D-printed in semi-transparent white filament, diffusing the internal LEDs while concealing the electronics for a clean, minimal appearance. As the material is nonconductive, thin silver conductive fabric straps were embedded across the surface along the X, Y, and Z axes, serving as contact points for detecting interpersonal touch while preserving an unobtrusive aesthetic. Each ball combined pressure sensing and touch detection. Pressure was measured using FSR402 thin-film resistors mounted at the base, with an Arduino Pro Micro sampling the analog signals. Pressure readings from the FSR402 were translated into a 0–5 scale, where higher values indicated stronger presses. These values drove the LED feedback inside the ball while also being streamed to TouchDesigner. At rest, the balls glowed dim white; as pressure increased, the LEDs shifted to red or green, corresponding to each participant's cube cluster. Interpersonal touch was detected when participants held their respective balls and touched each other's skin, closing the conductive circuit and producing a measurable voltage change. This signal was interpreted by the Arduino as a binary event, synchronizing the LED color across both balls and sending a touchFlag to TouchDesigner. Communication between Arduino and TouchDesigner was handled via USB serial connection, with three data types continuously transmitted: ball1Pressure, ball2Pressure, and touchFlag. These signals drove the corresponding dynamics of the projected cube visualizations.

3.3.3 TouchDesigner Pipeline. The real-time visualization was developed in TouchDesigner, a node-based environment for interactive media. Input signals arrived through two channels: EEG data (stressIndex1, stressIndex2, and connectivity flags) streamed from the C# program via TCP, and Arduino outputs (ball1Pressure, ball2Pressure, touchFlag) sent over USB serial. These signals were mapped to parameters driving Geometry Instancing, which rendered cube clusters representing each participant's stress state. Scaling was modulated using a Noise CHOP (offset by the stress index and normalized with a Math CHOP) combined with a Ramp TOP, producing clusters that expanded, contracted, and shifted dynamically. Colors were defined within the instancing parameters: one cluster derived from R+G values (red-feel), the other from G+B values (green-feel). Stage transitions were implemented with a Sequence Blend SOP, interpolating between separated clusters, a spiraling merge, and an expanding sphere with explosion. The blend factor was modulated by pressure values, while the binary touchFlag triggered the final dispersal. After the explosion, the system paused for 10 seconds before automatically resetting to the initial state, forming a continuous loop. The final composition was rendered and projected at room scale, immersing participants in a shared, embodied visualization of their stress states. Figure 2 illustrates the data processing and visualization mapping workflow.

4 Field Study

The system was exhibited at Sea World Culture and Arts Center (SWCAC) in Shenzhen from June 28 to July 24, 2025, as part of the larger exhibition INVISIBLES. We treat this deployment as an in-the-wild, design-exploratory study rather than a tightly controlled laboratory trial. This approach is consistent with much prior social biofeedback and affective installation work, which focuses on experiential and relational outcomes and does not always introduce separate no-feedback or sham-feedback control conditions [46, 50, 64]. We conducted a field study over eight days during this period to examine whether the system could foster stress sharing and to explore participants' experiences. A total of 55 pairs (110 participants) engaged with the system.

4.1 Setup

The study took place in the L1 Coastal Gallery, a space measuring approximately 10 × 8 × 5 meters. Two projectors were mounted on the floor and edge-blended to create a seamless high-resolution display across a 10-meter-wide by 5-meter-high wall. Ambient lighting was dimmed to enhance projection visibility. Two stands equipped with touch balls and EEG headsets were placed about 6 meters from the projection wall, while a workstation in the corner managed the system. The ball electronics were connected to the computer via extended USB cables, secured to prevent tripping or slippage (Figure 3).

During study days, participants were recruited onsite. Two researchers coordinated the sessions: one managed recruitment, consent, scheduling, and crowd interactions, including answering questions from passersby; the other operated the system, guided participants through the experience, and conducted interviews.

4.2 Participants

We recruited 55 pairs (110 participants) onsite during the exhibition. Four participants did not complete the post-questionnaire and were therefore excluded from the quantitative analyses, resulting in a final quantitative sample of 106 participants (53 pairs; 37 males and 69 females). All 110 participants were included in the qualitative analyses. Participants had no known neurological or psychological conditions and the demographic information is presented in Table 1. All participants took part voluntarily and agreed to participate in pairs, either with someone they arrived with or someone they were matched with at the venue. Before beginning the experience, each participant was informed of the procedure, and signed a written consent form. Ethical approval for the study was obtained from the Institutional Review Board of the corresponding institution.

4.3 Questionnaire Design

The primary measurement was the five-item Stress Sharing Experience Questionnaire (SSEQ). To align the questionnaire with the five-facet process model conceptualized in our Related Work (Section 2.1), we constructed one item for each theoretical facet, aiming to capture the full lifecycle of the stress sharing process: 1) Self-Perception: "I intentionally attend to my bodily state to understand my stress." 2) Social Perception: "I am able to sense or detect the other participant's emotion or stress." 3) Expressiveness: "I am willing to share my stress or emotions with the other participant." 4) Co-regulation Efficacy: "I believe engaging in stress sharing and co-regulation is an effective way to reduce stress." 5) Connectedness: "Please select the image below that best represents your current relationship or closeness with the other participant" (adapted from the Inclusion of Other in Self scale). Given the in-the-wild museum setting, we prioritized ecological feasibility by selecting a single representative item for each of the five theoretical facets. This pragmatic approach balanced the need for broad content validity with the constraint of minimizing visitor burden. As detailed in the Results, we subsequently assessed the psychometric structure of these items and refined the scale to a robust composite indicator based on statistical validity.

Table 1: Participant demographics (n = 106)

Variable	Category	n
Age	18–25 years	55
	26–40 years	32
	≥41 years	19
Relationship	Family	20
	Friend	53
	Romantic partner	19
	Acquaintance	4
	Stranger	8
	Others: Colleague	2

In addition, we administered the short-form State–Trait Anxiety Inventory (STAI-6), a six-item instrument commonly used to assess momentary stress and anxiety in prior research [37, 107]. It consists of six items rated on a Likert scale. After appropriate reverse scoring, higher mean scores indicate greater levels of momentary stress.

4.4 Procedures

Each study session followed a structured process (Figure 4): 1) Introduction and Consent: a facilitator introduced the study, explained the procedures, and obtained written informed consent. 2) Pre-questionnaire: participants completed an online survey capturing demographic information and two pre-measures, SSEQ and STAI-6. 3) Interaction: participants wore EEG headsets with assistance. Once signals were verified, they were guided through the three stages of the installation (Visualization, Merging, and Explosion), each lasting about two minutes (total approximately 6 minutes). Participants were encouraged to talk and behave naturally during the interaction. 4) Post-questionnaire: participants completed the SSEQ and STAI-6 again, along with a multiple-choice question identifying which modality (visual feedback, object-mediated interaction, interpersonal touch, communication) contributed to their sense of stress sharing. 5) Interview: a semi-structured interview was conducted immediately afterward with each pair of

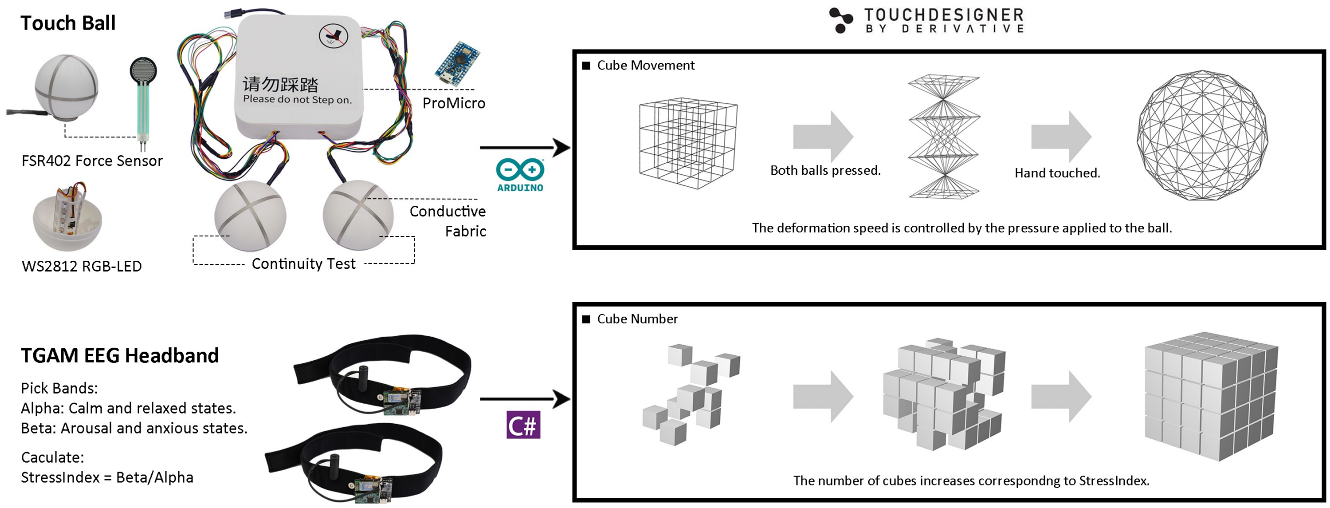


Figure 2: System hardware and data flow, showing how EEG and touch balls drive real-time cube visualizations.

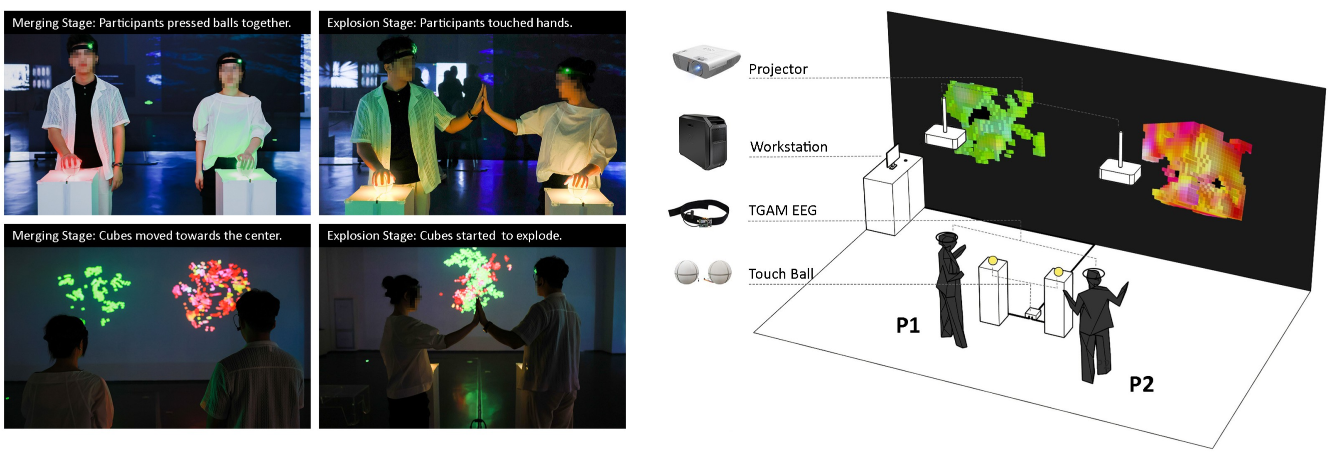


Figure 3: Left: A pair of participants during the experience. Right: Layout of the installation.

participants (1-on-2), focusing on their feedback and suggestions regarding the installation and their views on potential applications of social neurofeedback. The entire interaction and interview were audio-recorded with permission.

4.5 Data Collection and Analysis

Our dataset consisted of pre- and post-questionnaires, alongside audio recordings of the experience and interviews. Before statistical analysis, we tested for normal distribution and homogeneity of variance when assumptions were relevant. Exploratory factor analysis was conducted to examine the construct validity of the SSEQ. Paired-sample t-tests were applied to compare pre- and post-scores across dimensions, and Cochran's Q test with McNemar's post-hoc tests was used to analyze responses to the multiple-choice modality question.

Interviews were conducted in Mandarin with each pair of participants together and were audio-recorded, transcribed, and translated into English for reporting. We adopted this dyadic format to fit the time and logistical constraints of the field setting and to allow partners to reflect on the experience together. We believe this format encouraged participants to elaborate on each other's perspectives, but it may also have shaped what they felt comfortable sharing, especially more personal or critical views. We analyzed the transcripts through Reflexive Thematic Analysis [7, 8]. One lead researcher performed primary coding and theme development, while an independent peer engaged in structured debriefings at critical points to interrogate assumptions and refine thematic maps. This process ensured both depth of engagement with the material and rigor in interpretation.

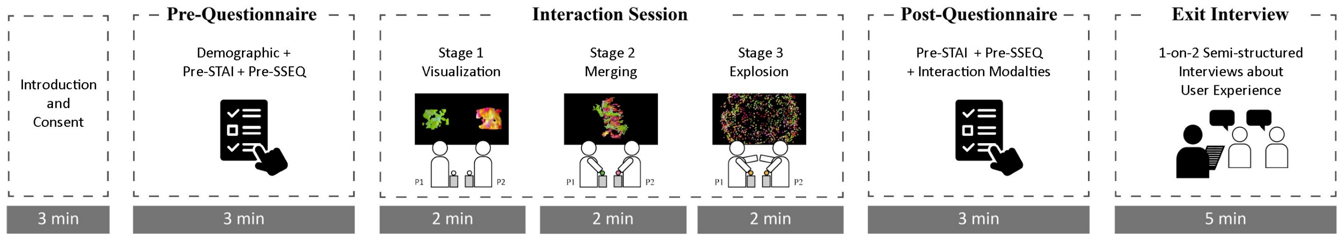


Figure 4: Field study procedures.

5 Quantitative Results

5.1 Reliability and Validity Analysis

We performed multiple analyses to assess the reliability and validity of the questionnaire. Our primary aim in this analysis was to examine whether the items representing the five theoretically derived facets could be reasonably represented by a single underlying construct of perceived stress sharing. We first conducted an Exploratory Factor Analysis (EFA) using Principal Axis Factoring (PAF) on the Pearson correlation matrix to examine the structure of the baseline (pre-intervention) SSEQ scores collected at the beginning of the field deployment (N = 106) [22, 32]. We retained a single factor, as only the first factor had an eigenvalue greater than 1. The results confirmed that the data were suitable for factor analysis (KMO = 0.675; Bartlett's Test: $p < 0.001$). A single factor emerged, explaining 34.038% of the total variance. Within this initial structure, two items, "Connectedness" (loading = 0.232) and "Self-perception" (loading = 0.229), exhibited factor loadings substantially below the acceptable threshold, indicating they were weak indicators of the underlying construct.

To enhance the scale, we removed these two items and repeated the EFA using the same extraction method and criteria. Sampling adequacy remained acceptable (KMO = 0.649; Bartlett's Test: $p < 0.001$). The revised three-item model showed stronger construct validity, accounting for 54.383% of the variance (Table 2). Internal consistency was satisfactory: Cronbach's Alpha was 0.762, and all items had Corrected Item-Total Correlations above 0.50. Removing any item did not increase reliability, confirming that the three items formed a coherent measure.

In conclusion, removing two problematic items produced a three-item questionnaire for measuring stress sharing. This revision was made to obtain a stronger composite indicator of overall perceived stress sharing, grounded in our five-facet conceptual framework. It is more parsimonious in structure and shows enhanced validity and strong reliability, with factor loadings ranging from 0.572 to 0.906. We therefore use the mean of these three items as the SSEQ score in subsequent analyses, while acknowledging that the reduced scale captures only a subset of the originally proposed facets and that further developing and validating the SSEQ as a more comprehensive scale for stress sharing is an important direction for future HCI and health-related research.

5.2 Effect of the Interactive Installation on Stress Sharing

We next examined the effectiveness of the interactive system in promoting individuals' stress sharing. Using paired-samples t-tests, we analyzed score differences before and after the experience across three single-item indicators representing the facets of social perception, expressiveness, and co-regulation efficacy. The results (Table 3) showed that scores for all three items increased after the experience. However, only the increase in expressiveness was statistically significant ($t(105) = 3.788$, $p < 0.001$).

Building on this, we calculated a composite "stress sharing experience" score using the three validated items. A paired-samples t-test was conducted to analyze differences between pre- and post-interaction scores (Figure 5). The analysis showed that post-interaction scores were significantly higher than pre-interaction scores ($t(105) = 4.785$, $p < 0.001$). This indicates the system was effective in enhancing stress sharing experience among users.

Finally, we conducted exploratory analyses on the two items excluded from the validated composite scale. Interestingly, the system also had positive effects: participants reported higher self-perception ($t(105) = 2.381$, $p < 0.05$) and stronger connectedness ($t(105) = 3.361$, $p < 0.001$). Although these items were not part of the core SSEQ score, they suggest that the system may provide broader psychosocial benefits beyond its primary design goals.

To explore potential variations across relationship types, we conducted descriptive analysis (visualized in Figure 6), noting that formal moderation testing was precluded by uneven sample sizes (e.g., $N = 2$ for Colleagues). While the 'Colleague' group exhibited the largest fluctuations, these results should be interpreted with caution due to the limited data. Notably, Stress Sharing scores improved for all groups except Strangers, who showed a decrease. Connectedness scores were consistently lower for Strangers and Acquaintances compared to intimate pairs. Regarding Self-Perception, scores increased across most relationship types, with the exception of Romantic Partners, whose scores remained stable between pre- and post-experience.

5.3 Analysis of Differences in STAI-6

To test whether participants experienced reduced stress through stress sharing, we conducted a paired-samples t-test comparing mean STAI-6 scores before and after the experience. The results showed no significant reduction in stress after the installation ($t(105) = 0.169$, $p > 0.05$), despite an improved experience of stress sharing.

Table 2: Comparison of Psychometric Properties Before and After Scale Revision

Item	Initial Model Factor Loading	Revised Model Factor Loading
Expressiveness	0.847	0.906
Social Perception	0.704	0.695
Co-regulation Efficacy	0.619	0.572
Connectedness	0.232	
Self-perception	0.229	
Overall Model Fit and Reliability Indices		
KMO measure of sampling adequacy	0.675	0.649
Total Variance Explained	34.038%	54.383%
Eigenvalue	1.702	1.631
Cronbach's Alpha Reliability		0.762

Note. The initial model included 5 items. The revised 3-item model, developed after removing two items with low factor loadings, demonstrated good internal consistency.

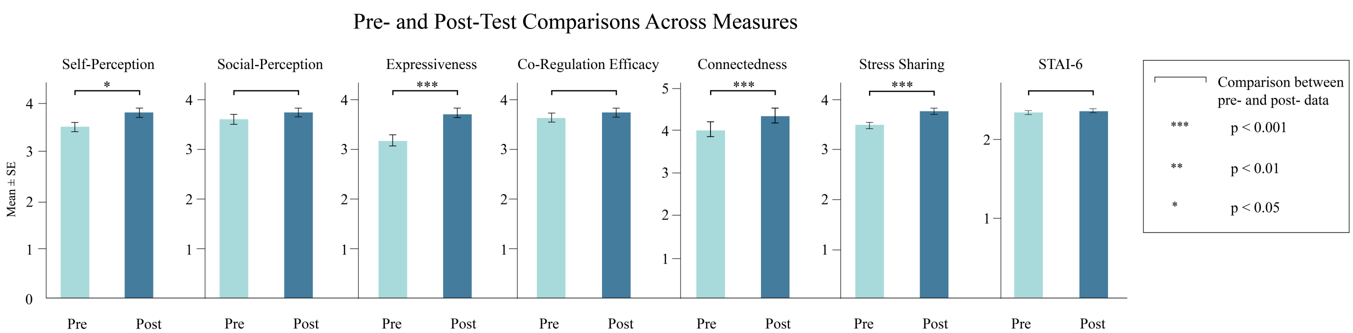


Figure 5: Pre- and post-test comparisons across measures. Bars represent mean ± SE. Asterisks indicate significant differences between pre- and post-test scores ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$).

Table 3: Results of Paired *t*-tests

Variable	Pre-interaction Mean (SD)	Post-interaction Mean (SD)	$t(105)$	p
Expressiveness	3.11 (1.12)	3.65 (1.01)	3.79	< 0.001
Social Perception	3.58 (1.03)	3.73 (0.90)	1.16	> 0.05
Co-regulation Efficacy	3.68 (0.95)	3.78 (0.95)	0.89	> 0.05
Stress Sharing	3.46 (0.69)	3.72 (0.64)	4.79	< 0.001
Self-perception	3.50 (0.99)	3.79 (0.95)	2.38	< 0.05
Connectedness	4.02 (1.83)	4.34 (1.83)	3.36	< 0.001
STAI-6	2.323 (0.27)	2.33 (0.41)	0.169	> 0.05

Note. M = Mean; SD = Standard Deviation.

5.4 Analysis of Differences in Perceived Stress Sharing

We also examined which modality participants perceived as most indicative of stress sharing. Participants responded to a multiple-choice question, and their answers are summarized in Table 4. We analyzed the data with Cochran's Q test, followed by pairwise McNemar's tests with Bonferroni corrections.

The results revealed a statistically significant difference in perceived stress sharing across the four modalities: visual feedback, interpersonal touch, object-mediated interaction, and communication ($Q(3) = 69.130$, $p < 0.001$). Specifically, perceived stress sharing in the visual feedback was significantly higher than in the interpersonal touch ($p < 0.01$), object-mediated interaction ($p < 0.001$), and communication ($p < 0.001$) conditions. Furthermore, both interpersonal touch ($p < 0.001$) and object-mediated interaction ($p < 0.01$)

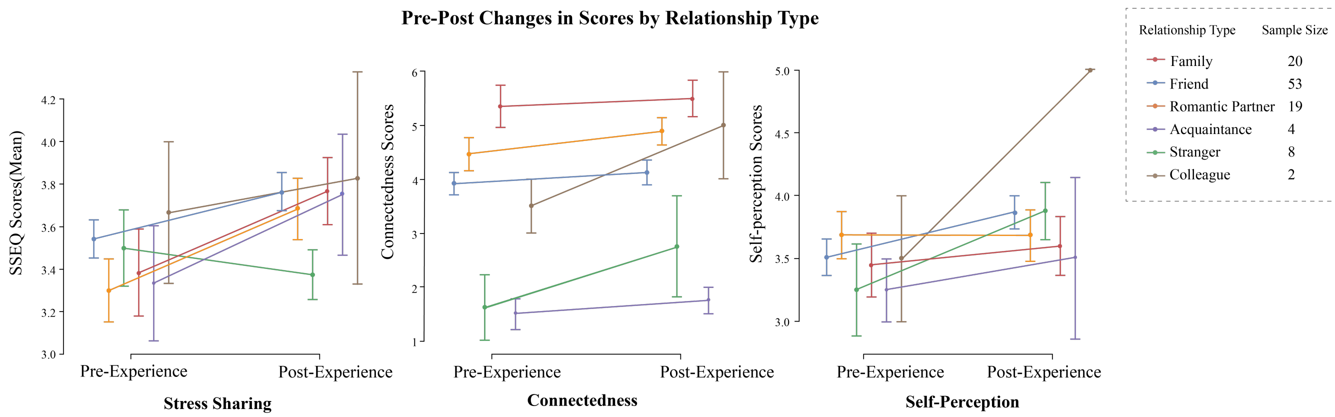


Figure 6: Pre-post changes in mean scores for Stress Sharing, Connectedness, and Self-Perception across relationship types. Error bars represent Standard Error (SE).

were perceived as involving significantly more stress sharing than communication.

Overall, these findings highlight the central role of visual feedback in conveying stress sharing, while communication alone was perceived as the least effective channel.

6 Qualitative Results

We analyzed audio recordings from the interaction sessions and the follow-up interviews. The conversations indicated that the system encouraged participants to discuss stress, while the interviews revealed striking or confusing moments and suggestions for future use. From these data, we identified three themes that structure our findings. In total, we collected 55 recordings from 110 participants, cited anonymously by IDs (e.g., G1P1).

6.1 Expressive Processes in Stress Sharing

This theme illustrates the social process in which participants verbally share and manage stress mediated by the system.

6.1.1 Expressing Stress Perception. Participants first acknowledged that observing the visuals increased their awareness of their own stress state. The visualization prompted them to ask about magnitude and fluctuation, linking what they saw on the screen to their internal experience. As G24P1 asked: "Is my stress showing as large or not?" and G44P1 wondered: "This image is dynamically changing. Is my stress really fluctuating like this?" These moments indicate that by externalizing stress as dynamic imagery, the system invited participants to observe and question their own stress experience.

At the same time, the visuals promoted social perception by making partners' stress visible and comparable. G56P2 expressed surprise: "Wow, your stress is full." G58P1 contrasted his partner's display: "She has almost no stress. Just one layer." Others also compared stress levels. G49P2 observed: "Look, his stress is decreasing while mine is increasing." These disclosures suggest that stress perception quickly extended beyond the self, fostering shared awareness of relative states.

In the Merging stage, participants' expressions became more socially oriented and metaphorical. Rather than merely noting levels, participants dramatized what they observed. G45P1 remarked, "I feel surrounded by your troubles." G49P2 described the interaction playfully: "It's like Snake, I'm eating your stress." G39P1 turned it into a contest: "Now it's about winning and losing." These figurative expressions transformed perception into a social performance, presenting stress as negotiable and shared rather than as a static value.

Finally, expressive talk about perception often opened the door to inquiry about underlying states. For example, G42P1 asked directly: "Why is your stress so high. What are you doing, what are you thinking?" Such exchanges show that expression of perception was not merely descriptive. It created openings to probe deeper into the causes and experiences of stress.

6.1.2 Expressing Stress Causes. After noticing fluctuations, participants sought to interpret why stress appeared as it did. These interpretations were rarely private. They emerged in social dialogue, as participants voiced explanations, speculated about causes, and asked each other questions.

Some participants linked changes in the visuals to immediate behavior or feelings. G48P1 reflected, "It feels like when I feel like talking, it increases." Interpretations also drew from everyday life. G58P1 compared their situations: "You're under a lot of work pressure, but I just finished my exam, so I'm more relaxed." Similarly, G48P2 wondered: "Could it be because I didn't sleep well, leading to this situation?" These comments show how participants mapped the abstract stress visuals onto concrete personal contexts. The visual feedback also encouraged participants to surface broader sources of stress in conversation. G51P2 disclosed, "My stress is about marriage. When am I ever going to get married?" G22P1 turned to their partner with questions: "Did you pass the nursing exam? What comes next?" By making stress visible, the system invited participants to search for explanations, connect the signals to life circumstances, and initiate dialogue about ongoing pressures and concerns.

6.1.3 Expressing Regulation Strategies. Participants experimented with different ways to regulate their stress visuals. These attempts were not always aimed at calming down. Some amplified their

Table 4: Frequencies and Percentages of Selections of multiple-choice questions

Interaction	Frequency of Selection (N)	Percentage of Cases (%)
Visuals	89	84.0%
Interpersonal Touch	64	60.4%
Ball Manipulation	53	50.0%
Communication	29	27.4%

signals or even provoked stress in their partner, treating regulation as playful experimentation. Breathing was a common approach. G33P2 noted: "My stress got smaller because I was adjusting my breathing." G45P1 reassured their partner: "Don't worry, just take a deep breath." Others used mental strategies. G33P2 said: "Imagine the situations when you're stressed, because right now I don't feel pressure." Participants also drew on everyday habits. G46P1 said: "If I check my work chat on my phone, I'll instantly feel stressed." G33P2 added: "I will scroll short videos. That's how I usually relax."

In the Merging stage, regulation sometimes took a physical form. G10P2 commented: "When I press harder, it decreases. It feels like a way to release." In the Explosion stage, the dramatic bursting visuals were experienced as relief, with several participants noting they felt their stress had been discharged.

These expressions show that regulation was both individual and social. By sharing strategies aloud, participants experimented with their own regulation and also learned about their partners' stress responses.

6.2 Roles of Interaction Modalities

This section examines how each of the three interaction modalities shaped participants' experiences of stress sharing. For each modality, we highlight what it enabled and the moments of confusion or difficulty that suggest design opportunities.

6.2.1 Visual Feedback. Visual feedback was both the most celebrated and the most challenging modality in the system. Participants emphasized its novelty and value but also noted confusion about what the visuals represented and how they could be controlled.

Participants described how the visuals made invisible stress tangible and measurable. G21P1 said, "I rarely pay attention to changes in my stress. This is very new to me. I could watch it for a whole day." G34P1 valued its scientific framing: "This feels scientific and rational. Many people are emotional and use horoscopes or fortune-telling to explain their state." The visuals also prompted reflection and regulation attempts. G27P2 said: "When the small blocks suddenly increased, I started to feel my stress. It really seemed to get bigger." Others experimented with control. G41P1 explained: "I tried using one thought or another to control it. It was fun."

Beyond self-awareness, participants emphasized that visuals gave them access to their partner's stress. G39P1 remarked: "Because she is my child, this helps me better understand her state and see if she needs help." The merged displays were also described as moments of connection. G19P2 explained: "I liked the moment of blending. It felt like we were together, our emotions influencing each other." These accounts demonstrate that visualizations not only communicate stress levels but also foster empathy and interpersonal connection.

The visuals also shaped participants emotionally, sometimes negatively and sometimes positively. For some, dense clusters of blocks created tension: "Looking at this wall makes me feel a bit nervous" (G22P2). For others, the final explosion was cathartic: "I liked the explosion at the end. It felt like a release of pressure" (G33P1).

Despite these affordances, participants often struggled with interpretation. Some questioned whether the visuals reflected psychological or physiological stress. G20P2 asked: "Does this represent psychological stress?" while G18P1 wondered: "Is this showing everyday stress?" Others noted mismatches between the display and their feelings. G46P1 said: "I don't feel very stressed, but why do I have so many blocks?" Comparisons with partners made this even more salient. G25P1 explained: "I usually have more stress than him, but it didn't show up here."

Participants also described difficulty controlling the visuals. G40P1 shared: "I tried deep breathing, which normally relieves stress. There, it showed my stress getting bigger. I didn't understand why." Some found improvement with practice: "At first breathing didn't help much, but later it worked. Maybe I got more skilled at it" (G19P1). Others were puzzled by the absence of a clear scale. G28P2 asked: "I couldn't clearly see how big my stress really was. Is there an average? Am I above or below it?"

Overall, visual feedback promoted self-perception, reflection, and regulation, while enabling new ways of knowing and connecting with others. At the same time, it posed challenges of interpretation, control, and clarity of measurement.

6.2.2 Object-mediated Interaction. Ball pressing was often discussed alongside merging visuals, but retained distinct functions. Some participants described it as a form of release: "Pressing the ball with my hand felt like transferring the pressure in my brain to the outside" (G10P2). For others, the ball was easier to understand than the neurofeedback-driven visuals. G41P1 noted: "The moment when the ball changed color left a deep impression. It made me feel that this was not a pre-set animation but something I was controlling in real time." This sense of direct, tangible control distinguished the ball from the more abstract visualizations.

Participants also suggested improvements. G19P1 imagined: "The form and material of the ball could change. If it were softer, like a stress ball you can squeeze, it would be more relieving." This highlights the potential of materiality and haptic qualities to strengthen the role of physical objects in stress regulation.

6.2.3 Interpersonal Touch. Touch was often mentioned alongside the explosion visuals and described as a positive social cue for relief.

G27P2 explained: "When the visuals exploded after we touched, it gave me a positive psychological signal, as if the stress was released." Participants also assigned touch its own meanings. For some, it created presence and closeness: "Touching hands made me feel there really was another person by my side. If I have stress, I can share it with them" (G33P2). For others, especially in close relationships, it was inherently regulating. As G45P1 reflected: "Physical contact is definitely necessary, especially because we are mother and daughter."

Not all participants were convinced of its impact. G44P1 asked: "Does this really make stress smaller?" G36P1 argued: "Sharing stress is not just about touching hands. It also needs a deeper resonance at the psychological level." The effect also varied with relationships. G22P2 noted: "Because we just met, the feeling was not very strong. I wonder what it would be like for people who are closer."

Taken together, these reflections suggest that touch can provide a tangible sense of presence and connection, opening the door to sharing and regulation. Yet meaningful stress sharing still depends on deeper communication and resonance between people.

6.3 Potential and Challenges of Social Neurofeedback System

Participants recognized strong potential for extending social neurofeedback beyond the installation. Stress was described as a universal issue, especially in high-pressure contexts like Shenzhen. As G12P1 noted: "So many people live under long-term pressure. Their brains are already overloaded, but they don't realize it." Many suggested applications in medical, psychological, and therapeutic domains.

Participants also mentioned applications in both close relationships and with strangers. In family settings, G37P1 explained, "I want to use this with my family. Kids are under great pressure now, and if we only notice problems later, it will be too late." In everyday interactions, they saw potential to defuse tension: "If I see someone is not in a good mood, I can avoid conflict" (G37P1). By contrast, others saw value in strangers. As G25P2 reflected: "In families it might feel frightening, but among strangers it could be interesting for making friends." Some also envisioned playful uses, such as integrating stress feedback into games.

At the same time, participants raised key challenges. Accuracy was a recurring concern: "If the measurement were more precise, it would have greater potential" (G41P2). Some worried the system itself could create anxiety: "It depends on the person. This could create more stress" (G29P1). Others questioned hardware accessibility, noting that similar sensing already exists in smartwatches and asking how this system would compare. The most frequent concern was privacy. As G30P1 emphasized: "People should have the choice to join, to share, or not. And how the data is used, and by whom, must be clear."

7 Discussion

7.1 Interactional Facets of Stress Sharing: Social Perception, Expressiveness, and Co-regulation Efficacy

In our study, social perception, expressiveness, and co-regulation efficacy emerged as the central interactional facets of the stress sharing experience as captured by the SSEQ. This suggests that stress sharing, as an interpersonal construct in this neurofeedback context, is primarily characterized by the ability to sense others' states, willingness to express stress, and belief in the efficacy of shared regulation.

In contrast, self-perception and connectedness exhibited weak factor loadings and were removed from the scale. One possible explanation is that self-perception primarily reflects self-awareness of stress, which may serve as a prerequisite but does not directly capture the experience of stress sharing [65]. Similarly, connectedness may function more as a contextual foundation that enables sharing, rather than an active experience [19, 98]. This aligns with prior research showing that interpersonal processes of emotion sharing rely strongly on social perception and expressiveness, whereas broader relational connectedness operates as a background condition [81]. These interpretations should be considered in light of the streamlined nature of our measure. Consequently, the multifaceted nuances of self-perception and connectedness may not be fully represented in this specific context.

7.2 System-Mediated Shifts in Stress Sharing

The system significantly enhanced participants' stress sharing experience. To capture this, the scores of social perception, expressiveness, and co-regulation efficacy were averaged, which together reflect the stress sharing experience. The results of paired-samples t-tests showed that participants' stress sharing scores were significantly higher after the system experience, indicating that the interactive system effectively facilitated the process of stress sharing between participants.

To examine which facet contributed most to this process, paired-samples t-tests were conducted separately for each item. Although post-scores were higher than pre-scores across all items, only expressiveness showed a statistically significant increase. This suggests that the system may be particularly effective in encouraging participants to articulate, thereby supporting stress sharing primarily from the perspective of expressiveness. This finding is aligned with recent research showing that interactive and feedback-based systems can reduce barriers to self-disclosure and promote emotional communication [74, 86].

Exploratory analyses were also conducted on the two excluded items, self-perception and connectedness. Both items showed higher scores after the system experience. The increase in self-perception may reflect participants' heightened curiosity about the relationship between their internal bodily states and experienced stress [95]. Similarly, increased connectedness scores suggest that engaging in a shared interactive activity fostered a stronger sense of relational closeness between participants. These findings indicate potential broader psychosocial benefits beyond the core construct of stress sharing, in line with studies showing that neurofeedback and shared physiological visualization can foster both self-perception and interpersonal connectedness [49, 70].

Analysis of variation in scores across relationship types revealed that self-perception scores generally improved, while stress sharing scores declined for strangers compared to intimate pairs. This divergence aligns with the Social Baseline Theory [18]. The theory proposes that proximity to strangers requires increased cognitive vigilance, which can overshadow the interaction's supportive potential. Intimate partners can facilitate emotion regulation through established trust [3]. In contrast, unacquainted dyads likely perceived the combination of haptics and physiological disclosure as a social burden. Consequently, these results indicate that biofeedback is an effective reflective tool for individual awareness. However, its capacity to support meaningful interpersonal sharing depends strongly on pre-existing social safety.

We further examined whether stress sharing translated into reduced stress levels, as measured by the STAI-6. No significant difference was found between pre- and post-scores. This outcome can be explained by the specific context of the study: participants took part in an exhibition setting where they were already in a positive mood, and unlike traditional stress-induction paradigms, our design did not introduce external stressors.

Complementing the quantitative findings, qualitative data illuminated how the system facilitated stress sharing at the experiential and interactional level. Specifically, participants' comments reflected changes in self-perception, social perception, connectedness, and expressiveness. First, the visual feedback of the system made participants aware of both partners' stress states and prompted questions about their own stress changes. This indicates enhanced self-awareness, as participants began reflecting on personal changes through visual signals. Biofeedback tasks have long been considered effective in promoting self-awareness [31, 61]. Second, the system facilitated participants' social perception. After interpreting the visual information, participants discussed and evaluated each other's signal changes and attempted comparisons. Third, upon noticing changes, participants explained abstract visual signals through concrete events (e.g., work, sleep) and shared their views through verbal expression. We encouraged free conversation during this process to promote mutual expression, as expression in interaction helps regulate emotions [47]. Finally, many participants noted that interpersonal touch created intimacy and strengthened their sense of connectedness. Haptic nonverbal communication was viewed as enhancing closeness [38]. This suggests that the system transforms stress from a purely individual issue into a shared process that can be perceived, discussed, and jointly managed, thereby bringing people closer together. To complement the modality-based analysis above, Figure 7 depicts the three stages of the installation, mapping for each stage the primary modality, observed behaviors, reported experiences, and stress sharing facets evident in participants' talk.

Participants also raised several concerns and suggestions about the system. Some participants felt that the system did not accurately reflect their stress changes in real time. This may explain why co-regulation efficacy was not significant in the quantitative results. Co-regulation efficacy refers to individuals' belief in their ability to manage stress [109]. Participants reported that inaccurate stress feedback reduced their confidence in managing stress through the system. In addition, some participants emphasized the importance of data privacy and noted that stress sharing itself may introduce new stress. Finally, participants envisioned integrating the system with more accessible devices. We believe that integrating the system with smart wearables for long-term stress management would be particularly meaningful.

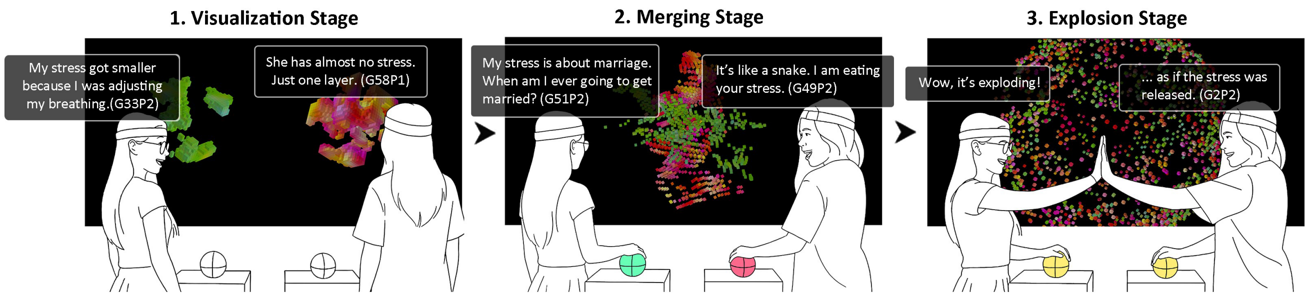
7.3 Embodied Modalities Promote Stress Sharing

Minus×*Minus=Plus* engages three embodied modalities and draws on Höök's somaesthetic design work on expressive interaction, bodily involvement, and balanced ambiguity [43]. Our findings show that visual feedback, interpersonal touch, and object-mediated input each shape participants' experience of stress sharing in distinct ways. Together, they make stress feel more tangible and relational, yet they also surface tensions in interpretation, emotional impact, sense of agency, and relational boundaries. Below, we discuss the strengths and challenges of each modality and derive design considerations for future exploration.

Visual feedback emerged as the most influential modality in participants' experience of stress sharing. Quantitatively, it was the primary channel participants selected as contributing to stress sharing, consistent with accounts of visual dominance in perception [9, 42]. Qualitatively, participants described the visuals as novel, intuitive, and scientific, noting that the imagery made otherwise invisible aspects of stress feel tangible and measurable. A key feature of our design was a dynamic form that showed how two stress signals combined and changed together, adding a relational layer on top of individual stress. This shared transformation prompted joint attention, active comparison, and playful expression. This suggests that visualizing social entanglement in this way may serve as a positive social cue that encourages communication and supports a sense of shared impact, extending prior work that mainly shows individuals side by side or as aggregated traces [50, 105, 106].

At the same time, two key tensions emerged around interpretation and emotional impact. Several participants reported a mismatch between the visuals and how they actually felt, questioning the meanings implied by the patterns. A small number even felt more stressed when confronted with dense or rapidly changing visuals, showing that stress visualization can be double-edged. Guided by a somaesthetic design lens, our visuals were expressive and deliberately somewhat ambiguous, inviting participants to attend to their bodily states and the shared atmosphere rather than treating the display as a simple meter. Our findings indicate that this expressiveness and ambiguity need to be carefully calibrated with enough clarity and reference cues to support meaningful interpretation, so that people can understand what the visuals suggest about their stress without becoming confused or overwhelmed. This resonates with somaesthetic design and calm technology, which both emphasize subtle, slow transformations and attunement to felt experience rather than strong, alarm-like feedback [44, 101]. Our results add nuance to this work by showing that, in dyadic stress sharing, this balance is particularly sensitive, because unclear or intense visuals shape not only self-perception but social perception, with downstream effects on co-regulation efficacy.

Interpersonal touch functioned as a positive social cue in the installation. Quantitatively, it was the second most frequently chosen



	1. Visualization Stage	2. Merging Stage	3. Explosion Stage
Modality	Visual Feedback	Object-mediated Interaction + Visual Feedback	Interpersonal Touch + Visual Feedback
Observed Behaviors	Observe own stress visuals and reflect on changes; Attend to partner's visuals and compare; Try simple regulation.	Press balls and watch visuals change; Use metaphors to compare stress; Discuss stress in everyday life; Share regulation strategies.	Touch hands while holding balls; Watch the explosion; Comment on release.
Reported Experiences	Curiosity and novelty; Occasional tension and confusion.	Playful and sometimes competitive; Sense of joint influence.	Relief and closeness for many; Awkwardness or skepticism for some pairs.
Main Facets	Self-perception; Social perception; Expressiveness.	Ongoing self- and social perception; Expressiveness; Emerging connectedness and co-regulation.	Connectedness; Co-regulation Efficacy.

Figure 7: Three-stage experience of the stress sharing installation, with example participant quotes and a summary of modalities, observed behaviors, reported experiences, and main stress sharing facets for each stage.

modality contributing to stress sharing. Qualitatively, participants described hand-holding and shared touch as conveying presence, closeness, and a sense of joint release, echoing prior work that links touch to affective communication and emotional relief [36, 41]. For pairs with an existing bond, touch felt like a natural way to comfort and regulate stress together. Strangers often found it awkward or not especially effective and preferred conversation or the shared object instead. These contrasts highlight both the promise and fragility of touch in social biofeedback. Seen through a somaesthetic design lens, interpersonal touch can ground stress sharing in felt bodily contact and a shared rhythm of interaction. Our findings extend this by highlighting the importance of considering relationship, timing, and consent when using touch to support stress sharing. We also see potential in more nuanced, gradated touch interactions that can be tuned to different relational contexts, rather than relying on a single, one-step gesture [77, 104].

Even though our initial intention in incorporating shared object manipulation was to foreground joint effort and co-regulation, participants tended to experience it more as an individual channel. They described pressing the ball mainly as a way to "release" stress and to feel a clear sense of bodily agency, aligning with somaesthetic accounts of bodily action as a meaningful route to emotional regulation. However, the sense of doing something together was weaker than we expected, likely because the ball offered little feedback about the other person's involvement, even though the mechanism required both to press. Our findings suggest that subtle feedback signaling a partner's input could make the shared nature of the interaction more perceptible, supporting joint meaning-making in dyadic touch [77]. Softer, more deformable materials could also better support a felt sense of release, echoing work on tactile expressions of emotion [48]. Together, these observations highlight an underexplored potential of tangible interaction in social biofeedback. With richer haptics and carefully considered material qualities, object-mediated input may better support bodily relief while making joint action more perceptible, adding a somaesthetic perspective on how shared artifacts can be tuned for dyadic stress sharing.

7.4 Design implications for Social Biofeedback System

In this subsection, we move from modality-level observations to broader implications for designing social biofeedback systems. We focus on four issues: navigating the complexity of stress, attending to social comparison, making modality choices relationship-sensitive, and aligning application scenarios with appropriate privacy and consent.

7.4.1 Navigating the complexity of stress through education, accuracy, and duration. Although we presented the visuals as showing "stress," many participants were unsure what this actually referred to. Stress spans physiological and psychological domains and unfolds across acute, daily, and chronic timescales, so a single biosignal in a brief six-minute interaction can only offer a partial indication of it [27]. At the same time, the "scientific" appearance of the installation led some participants to treat the feedback as precise, echoing concerns that self-tracking systems can encourage overtrust or misinterpretation of uncertain data [1, 56, 83]. Rather than focusing on technical accuracy alone, our findings point to experiential strategies. Short, embedded explanations may help orient participants to what is being measured, how mappings work, and what limitations remain, while access to longer-term patterns may support reading momentary states in relation to their own history instead of as isolated snapshots [15, 29]. Framing these encounters as opportunities to build "stress literacy" about both stress and its sensing may invite more nuanced interpretations and reduce the risk of misalignment or induced stress.

7.4.2 Attending to social comparison in shared stress feedback. In social settings, participants rarely interpreted stress feedback in isolation. They made sense of it by comparing and negotiating with others, validating, evaluating, and informally "diagnosing" their own stress level against a partner's display and, in some cases, an imagined wider population (for example, reading "below average" as "being fine") [34]. This gives social comparison a double-edged role: it can help people understand stress relationally, but it can also create pressure and misjudgment when differences are treated as normative benchmarks [21, 34]. Our findings suggest that social comparison is an inherent part of shared stress feedback that designers can attend to deliberately. Systems can support joint sense-making by prompting people to talk about possible reasons for differences and how they might support one another, while avoiding visual forms that suggest rankings. Framing shared views as showing different stress profiles rather than better or worse scores may help maintain the benefits of relational awareness while reducing the risk of stigma, self-blame, or pressure to "match" a perceived norm [28]. Brief cues that stress data are approximate and uncertain, rather than definitive diagnoses, may further temper harmful comparisons [56, 83].

At the same time, efforts to support stress literacy through clarification and explanation (Section 7.4.1) may have mixed effects: while they can contextualize interpretation, they may also make differences between participants more salient. Attending to social comparison, therefore, involves balancing clarity with care in how differences are rendered, to support shared understanding without reinforcing implicit norms.

7.4.3 Making modality choices relationship-sensitive. Our results show that the same modality can feel supportive or inappropriate depending on the relationship between participants. For example, interpersonal touch was welcomed by close partners but often felt awkward or unnecessary with strangers, whereas object-mediated interaction and visuals were more broadly acceptable. Social biofeedback systems should therefore avoid a one-size-fits-all set of channels and instead treat modality as something that is tuned and developed through relational context [41, 77]. Over time, modalities and relationships can shape each other, so designers need to consider how different channels might gradually reinforce, stretch, or strain a relationship as it evolves.

7.4.4 Aligning application scenarios with privacy and consent. Finally, our findings point to the importance of application context. Participants imagined potential uses of social biofeedback for stress sharing in medical settings, family life, and encounters among strangers, emphasizing that people should be able to decide whether to share their stress data and who can access it. Many felt comfortable with the technology as long as this control was respected. While stress sharing within close relationships aligns with prior work on intimate affective sharing [50], extending it to strangers introduces different expectations around exposure and intrusion. Designers of social biofeedback systems should therefore align interaction modalities and data practices with context [70]. In high-intimacy settings such as families or therapeutic relationships, richer embodied channels and more detailed feedback may be appropriate when data ownership and use are transparent and negotiable. In low-intimacy contexts, such as public spaces or interactions among strangers, designs should emphasize opt-in participation, minimal data retention, and simple ways to refuse or withdraw sharing. Across contexts, people should retain meaningful choices about whether to join, what to disclose, and who can view and interpret their stress data [71, 78].

8 Limitation and Future Work

In this study, we present *Minus×Minus=Plus*, an interactive system designed to facilitate stress sharing among participants and to demonstrate its potential for promoting mental health. However, several limitations must be acknowledged.

First, the duration of the experience was limited. Previous studies on biofeedback and immersive experiences often employed sessions longer than 20 minutes to enhance engagement [55, 90]. Therefore, the short duration of this interactive experience may have hindered participants from fully sharing their stress.

Second, the experimental site was a public area. For the same task, individuals often behave differently in private versus public contexts. Even the mere presence of others increases arousal and influences behavior [2, 76]. Thus, conducting the study in a private space may elicit different or more open responses.

Third, our study did not include a separate no-feedback or sham-feedback control group, which means we cannot fully attribute the observed effects to the system experience alone. Like many in-situ deployments, our museum setting made such control conditions difficult to implement, as they would have required parallel hidden versions of the experience and more complex orchestration for short, walk-up visits, and could also have degraded visitors' overall experience [46, 50, 64]. Moreover, conducting user studies in real-world contexts such as public spaces is generally regarded in HCI as a way to enhance ecological validity. The qualitative findings of our study also provide some evidence that participants subjectively felt that the stress sharing experience was facilitated through the system. However, future work could introduce comparison conditions in a more controlled setting to better isolate the effect of the system experience.

Additionally, the EEG signal quality in our system is limited by the use of a TGAM-based dry-electrode headset. We chose this headset because it is easy to wear and allows real-time access to EEG data; its built-in filtering and our windowed averaging reduce a substantial amount of noise. However, the signal remains incomparable to clinical-grade EEG, and eye blinks or muscle activity can leave visible traces in the visuals. As a result, the installation should be understood as an expressive, approximate reflection of participants' stress rather than a precise real-time measurement. Future work could explore higher-precision, multi-channel EEG in controlled laboratory settings to examine whether this further facilitates the experience of shared stress.

Moreover, the SSEQ used in this study had limited psychometric richness due to its intentionally brief length. We initially constructed five items to capture different facets of stress sharing, and psychometric refinement resulted in a three-item scale. This brevity reflects a pragmatic choice for an in-the-wild museum deployment, where longer questionnaires would likely discourage participation. Brief self-report instruments are commonly used in high-burden contexts; for example, the Satisfaction With Life Scale (SWLS) is a widely used five-item measure [23], and single-item life-satisfaction scales have demonstrated acceptable validity in large-scale surveys

[13]. Nevertheless, the reduced length of the SSEQ constrains the depth of measurement.

Based on these limitations, future research will include controlled laboratory experiments with longer extended interaction durations and improved EEG signal-to-noise ratios. We also plan to incorporate no-feedback or sham-feedback control conditions to better isolate the system's effects. Finally, we will develop a more comprehensive stress sharing scale by expanding the item pool and examining the construct across different contexts and populations.

9 Conclusions

In this study, we developed *Minus×Minus=Plus*, an interactive system based on neurofeedback technology, and examined whether it could facilitate interpersonal stress sharing. To capture this process, we developed the Stress Sharing Experience Questionnaire (SSEQ) with five facets. The results showed that stress sharing was enhanced after the experience, with expressiveness playing the most prominent role. The system also fostered self-perception and connectedness. Modality comparisons indicated that visual feedback most strongly supported perceived stress sharing, followed by haptic interaction, while communication alone was least effective. These findings highlight the importance of embodied modalities in designing technologies that mediate social and emotional processes. Taken together, this work provides empirical evidence for investigating stress sharing in HCI contexts and offer insights for designing social neurofeedback systems that can support mental health.

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