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A User Study on Sharing Physiological Cues in VR Assembly Tasks

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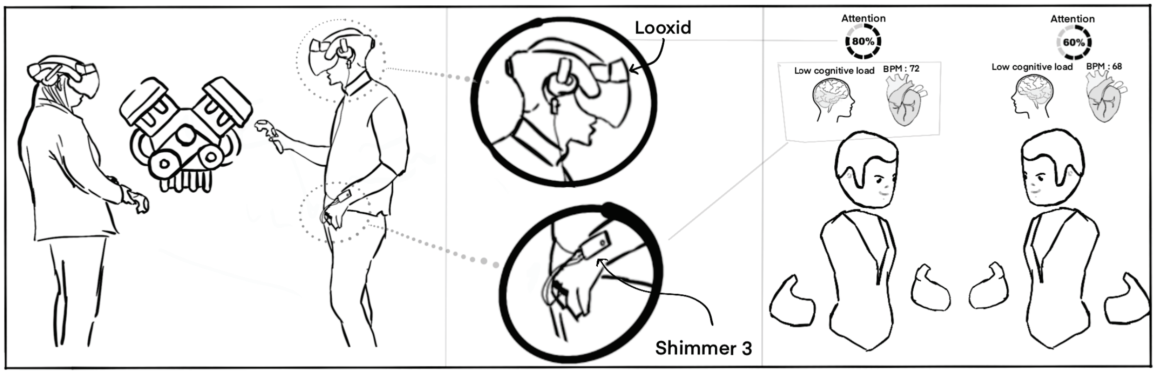

Fig. 1. a) Participants perform actions on a digital replica of an engine. b) First person view of the collaborator, c)Visual representation of physiological signals, d) Various states of cognitive load.

Abstract—In collaborative settings where multiple individuals are tasked with completing a shared goal, understanding one's partner's emotional state could be crucial for achieving a successful outcome. This is particularly relevant in remote collaboration contexts, where physical distance can impede understanding, empathy, and mutual comprehension between partners. In this paper, we demonstrate representing emotional patterns from physiological data in a shared Virtual Reality (VR) environment, and explore how it impacted communication styles. A user study investigated the potential effects of this emotional representation in fostering empathetic communication during remote collaboration. The study's findings revealed that although there was minimal variance in the workload associated with observing physiological cues, participants generally preferred monitoring their partner's attentional state. However, with the assembly task chosen, most participants only directed a minimal proportion of their attention toward the physiological cues displayed by their partner, and were frequently uncertain of how to interpret and use the information obtained. We also discuss limitations of the research and opportunities for future work.

1 INTRODUCTION

The widespread adoption of video conferencing due to the pandemic has increased remote work, study, and leisure activities. While web and desktop-based tools for remote collaboration are widely available, these platforms have limitations when attempting to convey three-dimensional spatial concepts or natural nonverbal communication cues. This can be especially challenging in fields such as technical training, where it can be difficult to understand complex machinery or equipment demonstrated through a real-time video. One potential solution is through using Virtual Reality (VR), which allows for a more interactive and immersive spatial representation of people and their surroundings, thereby providing a richer and more informative communication experience than traditional two-dimensional video feeds.

With the advent of low-cost VR devices, the number of collaborative VR platforms providing rich interactive experiences has increased. Applications such as Spatial[1], MetaHorizon Worlds[2], and Mozilla Hubs[3], among others, offer standalone platforms for collaboration in VR. A number of user studies have shown how VR platforms such as these can be useful for training, education, and other applications.

VR-mediated experiences can help people interact with one another in scenarios where participants are not located in the same physical space [46]. This typically take the form of several participants joining each other in an entirely virtual environment from separate physical spaces by entering the same VR world. However, current commercial collaborative VR systems don't support sharing of physiological cues, which could provide more insight into the user's emotional state and enable people to connect in new ways. This was one of the main motivations behind our research.

In this paper, we are interested in how sharing physiological cues in shared VR could improve the collaborative experience. Previous research has shown a positive impact from physiological cues in video conferencing [53]. Users can infer their emotional state and cognitive load from the physiological signals they see from their partner.

We have developed a VR collaboration system that enables sharing of physiological cues, such as heart rate, cognitive load, and attentional state, among collaborators, thereby facilitating a more comprehensive mutual understanding. Using this system, we conducted an empirical

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[1] `https://spatial.io/`
[2] `https://www.oculus.com/facebook-horizon/`
[3] `https://hubs.mozilla.com/`

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study to test the hypothesis that visualizing physiological cues would significantly impact collaborators' empathy levels. Our approach uses the ability of VR technology to convey natural nonverbal communication cues and physiological signals, thereby providing a more immersive and informative experience compared to traditional remote collaboration platforms.

The main novelty of this research is the sharing of physiological cues for remote collaboration in VR. To our knowledge, there has been very little research regarding how these cues can be conveyed, how it applies to a realistic collaborative task, and its effects on the collaboration. In short, our contributions are the following:

1. We developed a prototype collaborative VR system that shared physiological cues between users
2. We conducted an empirical evaluation of various physiological signal visualization methods (heart rate, cognitive load and attention) in a real-time collaborative task in VR.
3. We evaluated these methods using a realistic assembly task of a virtual engine where users need to collaborate across twelve tasks with three difficulty levels.

2 RELATED WORK

Our research is based on earlier Social VR work, physiological cues sharing, and its visualization. This section reviews key works from each area and highlights the research gap we are exploring.

2.1 Social VR

Early studies focused on understanding user interactions in Social VR environments. Collaboration is one of the most compelling use cases for interactions in immersive VR. This is mainly due to the ability of VR systems to track and represent the user naturally, similar to a face-to-face experience. Some early academic VR systems demonstrated the potential of collaboration in VR [7, 34]. One of the key lessons learned from this was the importance of representing the user and how the virtual avatar chosen could greatly impact the ease of collaboration. For example, a study by Churchill et al. [5] highlighted that the choice of virtual avatars significantly influenced the ease of collaboration in VR environments. Collaboration felt more natural and intuitive when users were represented by humanoid avatars with realistic features and movements. On the other hand, when users were represented by abstract or non-human avatars, such as floating spheres, collaboration became more challenging.

As a result, many researchers have studied the representation of the user as an avatar and the social response they generate. Studies have demonstrated that a higher level of embodiment, where users feel their avatar's movements and sensations as if they were their own, leads to increased empathy and social behavior [13, 15, 16, 40, 60]. This embodiment can be achieved through real-time motion tracking, haptic feedback, and realistic rendering of body movements [49, 59]. Zibrek et al [65] found that realistic characters are favored in virtual reality, overcoming Uncanny Valley issues. Other studies [25, 35, 56, 61] have shown that the link between avatar representation and immersion in virtual environments is complex, and better visual quality of avatars doesn't necessarily lead to higher perceived realism. This suggests that factors beyond the visual quality of avatars influence the immersive experience. Based on these findings, we designed our system drawing inspiration from Sebastian et al. [14]'s approach, which uses simpler avatars for social interactions. This approach implies that simplicity in avatar design can be effective for social engagement in virtual environments.

Researchers have explored various communication modalities in Social VR, aiming to create more immersive and natural ways for users to interact. These include voice communication, spatial audio [63], gesture recognition [36], and haptic feedback [58]. Studies have examined the effectiveness of different communication modalities in enhancing social presence, user engagement, and the overall quality of social interactions in virtual environments [39].

Studies have explored collaborative tasks, such as problem-solving or creative activities, and investigated the effectiveness of Social VR in fostering cooperation and teamwork [3]. Moreover, research has examined shared experiences in Social VR, exploring how the sense of co-presence and shared activities contribute to social bonding and forming social relationships [54].

As an indication of the popularity of Social VR, there are over 100 systems listed in the XR collaboration directory that works with a minimum of two collaborators [1]. However, despite significant progress in Social VR, several research gaps remain. For instance, understanding how to effectively integrate physiological cue sharing and visualization techniques within Social VR environments is an ongoing challenge.

2.2 Effect of sharing physiological cues

Thompson [55] denotes empathy as a sense of similarity between the feelings that an individual experiences and those expressed by others. There a number of few systems that enable the collaborators to share physiological cues [4, 12, 17, 41]. Most of these systems share heart rates to enhance various collaboration experiences. For example, Dey et al. [10] explored the effects of sharing manipulated heart rate feedback in collaborative VR. The study involved creating two types of virtual environments, active and passive, each with different levels of interaction. The study found that the manipulated heart rate feedback had a significant impact on the perception of scariness and nervousness. Increased heart rate feedback was perceived as higher valance (positive emotion) and lower arousal, and resulted in a decrease in the real heart rate. By analyzing the influence of varied heart rate feedback on social presence, emotional response, physical heart rate, and overall experience, this research underscores the significance of integrating physiological data in enhancing collaborative interactions and outcomes. Similar studies also examined manipulating the heart rate information to enhance social presence [9, 11].

Researchers have also looked into using Galvanic skin response (GSR) as an index of cognitive load [47], and various physiological cues like EEG have been used to enable adaptive training systems using VR technologies [8]. Our system combines these physiological cues to study the effect of sharing them in a collaborative setting.

By tracking and analyzing physiological signals such as heart rate, skin conductance, and body movements, it is possible to infer a user's emotional state in VR [22, 23]. This mapping can enhance the immersive experience, enable personalized content, and potentially improve mental health interventions. However, one of the main challenges in accurately mapping physiological cues to emotions is the development of robust algorithms and machine learning models.

2.3 Visualization of physiological cues

Visualizing physiological cues involves meaningfully representing the collected data [52] and has been a key aspect of HCI for a long time [33]. Effective visualization techniques can help users understand and interpret the shared physiological cues, thereby enhancing the communication and social interaction experience [32]. Visualizations of heartbeats range from realistic, to text/numerical, or screen overlay, and holographic displays [17, 21, 31]. Portable EEG headsets have been used to study emotional states and cognitive workloads in VR environments [30, 51]. Most EEG-based systems for displaying attention, cognitive load, and stress, predominantly use pie charts for visualization [27]. Prior research has explored different visualization methods, such as data-driven visualizations, real-time feedback displays, or avatar animations that reflect physiological states [6, 37, 43]. Our study references these existing works to address limitations and gaps in previous visualization techniques.

2.4 Summary

From this previous research, we can see that the use of virtual avatars can provide significant benefit for remote collaboration in VR systems. Embodiment is particularly important for sharing natural communication cues and creating a sense of empathy. Previous researchers have explored sharing physiological cues in video conferencing and Social

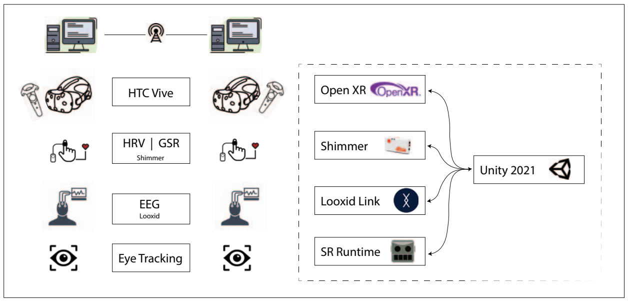

Fig. 2. System overview - Hardware implementation on the right side and software components on the left

VR applications. However, there has been no study of the use of sharing physiological cues for VR training applications. One of the main benefits of sharing physiological cues is enabling a person to better understand their partners emotional and cognitive state. Previous research has shown that this can be achieved through effective visualization methods, however this has also not been explored in a VR training application. Thus one of the main research gaps from the related work is sharing physiological cues in a shared VR training application, and developing appropriate visualization cues. This is what we address in this paper.

3 SYSTEM IMPLEMENTATION

Inspired by existing VR collaboration applications, we developed an open-source and modular remote collaboration system for an engine assembly training task. In the virtual space, virtual objects, including the engine, tools, and surrounding environment, are aligned and synced, creating a co-located experience for users. To facilitate fast data exchange, all devices are connected to the same private network. An overview of the system can be seen in Figure 2.

Hardware Implementation The prototype of the system was built using the Unity 3D Game Engine[4] and executed on two HTC Vive Pro Eye VR headsets[5], which were tethered to two Windows 10 computers. For physiological measurements, participants wore Shimmer3[6] sensors to capture their Galvanic Skin Response (GSR) and heart rate. In the next section we explain how the GSR was used to compute Low, Medium and High cognitive load. Additionally, Looxid[7] add-on attachments were mounted on the Vive headsets to collect EEG data, providing attention values of the collaborators. The attention values were computed by a propriety model that is shipped with Looxid SDK. The eye tracker from the HTC Vive Pro Eye was used to monitor users' gaze and measure their attention during the experiment.

System Components The prototype implementation can be divided into three independent components: (1) the Remote Collaboration System, (2) the Physiological Sensing Manager, and (3) the Virtual Environment. The Remote Collaboration System facilitates communication and synchronization between users, allowing them to interact in the shared virtual space. The Physiological Sensing Manager integrates and manages the data from the various physiological sensors used in the system. The Virtual Environment provides a realistic and interactive setting for the engine assembly task. These components work together to enable seamless collaboration in the remote training task.

Networking Strategy Networked VR systems aim to share consistent virtual worlds in real-time, and various networking strategies exist [48, 50, 57]. After considering different platforms and toolkits [18, 29, 64], we selected Ubiq [14]. This is an open-source framework that offers core functionalities for social VR, including connection management, voice communication, and avatar support. Although Ubiq supports networked systems over the internet, we created a local server for optimal bandwidth in our setup.

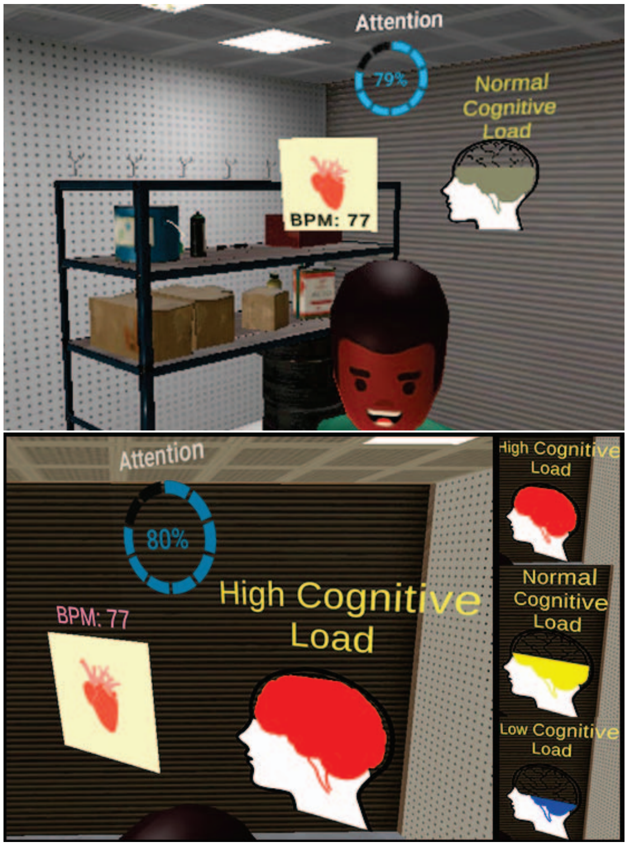

Fig. 3. Top: Visual representation of physiological signals from partner's view. Bottom: Visualization of various states of Cognitive load

Physiological Data Integration To integrate multiple physiological sensors and ensure synchronous data collection, we developed helper classes within the framework. Specifically, for this study, we implemented three streaming units: one for heart rate, one for GSR, and one for attention. These streaming units capture the physiological signals from the sensors and enable their visualization within the virtual environment.

Visual Representation of Cues We used three visual representations of physiological cues: a dynamic, animated heart icon displaying the heart rate alongside it; a brain representation with three levels indicating low, medium, and high cognitive load; and a moving circle indicating attention levels. We used a method similar to Dey et al [11] for visualizing heart rate. To represent attention allocation, we adopted the visual approach provided by Looxid in their Unity package [24]. Different levels of cognitive load were depicted using color-coded indicators, resembling a traffic light system [62]. In addition, we explored the use of animated avatars or characters to visually convey distinct cognitive states. These visual representations offer an intuitive and engaging means of communicating cognitive load levels [2]. Figure 3 illustrates the visual representation of physiological signals from the partner's perspective and displays various states of cognitive load.

Data Streaming Tools We created a standalone application to gather data from the Shimmer3 sensor and Looxid EEG device. This collected data from the Shimmer3 sensor via Bluetooth and streamed it to Unity through the Lab Streaming Layer (LSL). We also adapted the Looxid Link Unity plugin, making it compatible with OpenXR.

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[4] `https://unity.com/`
[5] `https://www.vive.com/nz/product/vive-pro-eye/overview/`
[6] `https://shimmersensing.com/product/shimmer3-gsr-unit/`
[7] `https://looxidlabs.com/`

COM Port: COM13

Shimmer State: Streaming

Fig. 4. We created a standalone application to collect data from the shimmer3 sensor via Bluetooth and stream the data to unity through LSL [28]. On the right side, the Looxid link unity plugin adapted to work with OpenXR to collect the attention data from EEG.

This modified plugin allowed us to collect attention data from the EEG device (see Figure 4).

Virtual Environment To improve the collaborative experience, we created a virtual engine comprising over 50 individual parts that could be assembled or taken apart. This virtual engine was developed using playback techniques inspired by Sasikumar et al's work [44]. To enhance realism, we designed a replica of a workshop environment, complete with an engine stand holding the mounted engine. Essential tools for working on the engine were strategically positioned within the workshop space. Throughout the study, participants followed instructional cues and collaborated on the engine, using the tools available in the virtual environment.

4 SYSTEM EVALUATION

During the user study, we employed shared heart rate alone as the control condition, without any additional physiological cues. The comparison condition involved sharing heart rate along with the other physiological cues. Here, our main independent variable was the type of physiological cues shared among collaborators, leading to four distinct collaborative conditions:

- (A1) Heart rate (Base Condition)
- (A2) HR + Cognitive Load
- (A3) HR + Attention
- (A4) All (Heart rate + Cognitive load + Attention)

In our user study, we aimed to investigate the following questions: 1) How does sharing physiological cues (along with HR) among remote users affect collaboration in a VR remote collaboration interface? 2) What benefits does integrating cognitive load and attention with heart rate offer for VR remote collaboration compared to using each cue separately? Our hypotheses are as follows:

- H1 - Viewing physiological cues improves the performance of the remote collaboration system.
- H2 - Viewing physiological cues enhances the sense of co-presence within the remote collaboration system.

4.1 Experiment Procedure

At the beginning of the experiment, participants provided informed consent, completed a demographic questionnaire, and provided details on their experience with virtual and augmented reality. Next, they received brief training on navigating the virtual space and completing the tasks before wearing the VR headset and the Shimmer sensor.

Before commencing the experiment, participants were instructed to fixate on a black screen for one minute and perform one-back and two-back N-back tests. The n-back test is a cognitive task that measures working memory and attention [26], and so this exercise measures the mean values of low, medium, and high cognitive load. In this test, participants are presented with letter stimuli, and they must indicate whether the current stimulus matches the one that appeared n positions back in the sequence. The difficulty level can be adjusted by changing the value of n, with higher values requiring more working memory capacity and attention. To assess the minimum and maximum GSR values during three user states (fixating on a blank screen, performing one-back tasks, and performing two-back tasks), we established thresholds for low, medium, and high cognitive loads corresponding to these states.

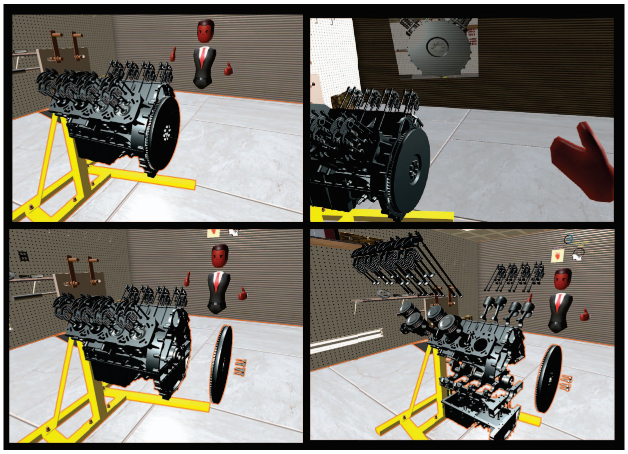

Fig. 5. Tasks, clockwise from top, the engine assembly before operation. b) instruction on which part to remove. C) the corresponding part removed. d) Engine with components taken apart.

During the study, we continuously categorized the current GSR value, which represents the average of the past 10 seconds, into one of three cognitive load levels: low, medium, or high. This categorization is based on predefined thresholds(from n-back). Our approach draws inspiration from research suggesting that GSR is a reliable indicator of cognitive load [38, 47]. To compute the attention, we used Looxid's commercially available toolkit. However, due to uncertainties regarding its accuracy, we have acknowledged this as a limitation in the limitations section of our study.

Previous research has indicated that balancing assembly tasks by categorizing them and ensuring equal representation from each category leads to task equilibrium [45]. Following this approach, we randomly selected 12 tasks (four easy, four medium, and four hard) from a pool of possible engine assembly tasks (see table 1) for each condition. This task was selected as it is manageable and focuses only on identifying two key elements: the tool and the specific part of the engine to work on. It also holds real-world relevance which would make it likely to be an enjoyable experience for the participants. After completing each condition, participants removed the VR display and filled out subjective questionnaires. After going through all the conditions, participants ranked them and provided overall feedback.

4.2 Measurements

We used a within-subject design between four trials of different cue conditions. For each pair of participants, one person provided the other with the task information for half the tasks and then swapped roles. To prevent a scenario where a participant performs two easy tasks as the task giver and then switches to two easy tasks as the task receiver, the system ensures that the same difficulty range is maintained when roles are swapped. This aims to maintain consistency in the task difficulty participants experienced throughout the experiment. We chose this design because it reduced the time for the study, participants would feel less tired or bored, and it alleviated the learning effect.

We collected both objective and subjective measures. The task completion time was recorded in a system log file to measure performance objectively. After each trial, participants were asked to complete subjective questionnaires to measure their perceived cognitive load, task difficulty (NASA TLX [20]), and sense of presence in the vir-

Task	Tool	Difficulty
Remove flywheel bolts	Drill	Easy
Remove flywheel	Hammer	Easy
Remove oil pan bolts	Socket Wrench	Medium
Remove Oil pan	Pry bar	Easy
Remove crank case	File	Medium
Remove bearings	Socket Wrench	Medium
Remove Crankshaft	Toque Wrench	Medium
Remove Valves	Pliers	Easy
Remove Pistons	Spanner	Hard
Remove rear plate	Pry bar	Hard
Remove balancer	Spanner	Hard
Remove Crankshaft bearing	Torque Wrench	Hard

Table 1. Tasks that are performed on the virtual engine, tools required to perform the task, and difficulty level

tual environment (NMM Social Presence Questionnaire [19]). These were chosen to provide a more comprehensive and multi-faceted understanding of participant experience and task performance. In addition, participants were interviewed at the end of the experiment using open-ended questions to obtain their subjective evaluation of their experience and provided a ranking of the conditions in terms of their preferred physiological cues.

4.3 Participants

We recruited 28 participants (19 male, 9 female) in 14 pairs from the local campus community, ranging in age from 20 to 47 years old (M = 29.5, SD = 6.66). Most participant pairs knew each other well. Seven participants had been using video conferencing daily, Fifteen used it weekly, and the rest used video conferencing a few times a month. Four participants used AR or VR applications daily, nine used them once a month, and the rest used them a few times a year. Three participants were familiar with AR or VR interfaces, scoring 4 or higher on a 7-point Likert item (1: novice 7: expert).

5 RESULTS

In this section, we report on the results of the user study regarding the performance and usability of all communication cue conditions and summarize the subjective feedback collected from the participants. The mean difference was significant at the .05 level, and adjustment for multiple comparisons was automatically made with the Bonferroni correction unless noted otherwise.

5.1 Task Completion time

The Shapiro-Wilk test indicated that all task completion time data of HeartRate ($p = .65$), CognitiveLoad ($p = .164$), Attention ($p = .233$), and Combined ($p = .078$) were normally distributed. Mauchly's test ($\chi^2(5) = 14.2231$, p = .015) indicated violation of sphericity. So we ran the Friedman test, and the result (2(3) = 2.168, p = 0.558) showed no significant difference in the task completion time across the four cue conditions.

5.2 Subjective Questionnaire - Social Presence

From the NMM Social Presence Questionnaire, we used the sub-scales Co-Presence (CP), Attention Allocation (AA), and Perceived Message Understanding (PMU) to evaluate the participant's social presence experience (see table 2). The questionnaire has 18 rating items on a 7-point Likert scale (1: strongly disagree–7: strongly agree). Friedman tests, and Kendall's W tests showed significant differences in CP($\chi 2(3) = 11.225$, $p < 0.011$) and AA($\chi 2(3) = 74.3375$, $p < 0.001$), but not for PMU($\chi 2(3) = 6.328$, $p < 0.097$).

A post hoc analysis with the Wilcoxon signed-rank test for CP showed significant pairwise differences for A2-A1 (Z = -2.175, p = 0.030), A2-A3 (Z = -2.862, p = 0.004), A2-A4 (Z = -2.712, $p < 0.009$). Similarly, AA showed significant difference between A1-A2 (Z = 6.364, $p < 0.001$), A1-A4 (Z = 6.465, $p < 0.001$), A2-A3 (Z = 3.640, $p < 0.001$) and A3-A4 (Z = 4.834, $p < 0.001$). This shows that the combined condition (A4) induced the highest sense of co-presence (Mean = 6.589, SD = 0.736) while heart rate alone (A1) induced the highest perceived message understanding (Mean = 5.988, SD = 0.991) among the conditions.

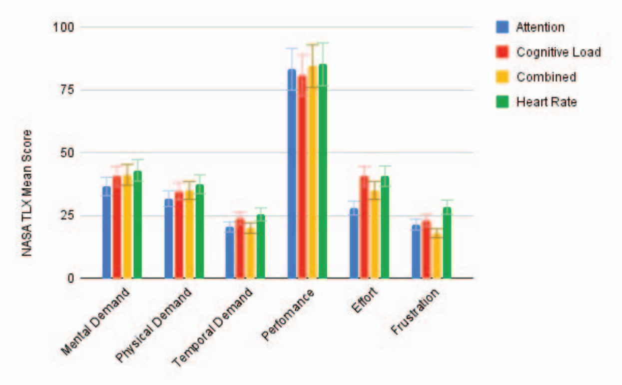

Fig. 6. Individual components of NASA TLX

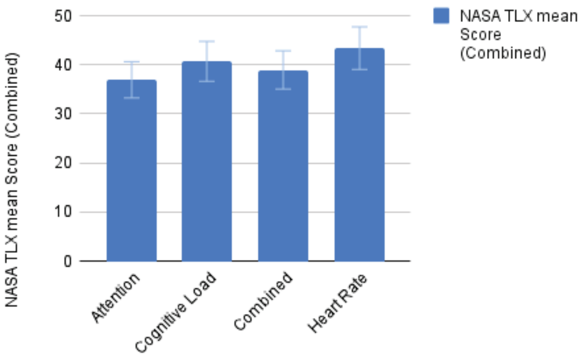

Fig. 7. NASA TLX

5.3 Subjective Questionnaire - Work Load

To compare the participant's mental and physical workload in each condition, we used the NASA Task Load Index Questionnaire (TLX) [20], which consists of six scales (mental demand, physical demand, temporal demand, performance, effort, and frustration) within a 100-point range with 5 point steps (0: very low 100: very high, the lower, the better). These six scales can be considered as dependent variables, and the task or activity being assessed as the independent variable. A MANOVA method showed no significant difference in workload between the communication cues conditions. Following this, we analyzed the mean values of each component of the NASA TLX. Our findings suggest that the study participants experienced a reduced perceived workload and reported an improvement in their sense of performance. We examined the NASA TLX's mean scores to gain further insight into these results, as illustrated in figure 6.

5.4 User Preference

At the end of all trials, we also asked participants to rank the four visual conditions in terms of their preference for the remote collaboration task. Overall, participants mostly preferred the attention cues (A3) (15 out of 28) as their first choice, followed by Combined, Cognitive load, and Heart Rate cues in sequence (Figure 8). Eight participants stated that the presence of the attention bar allowed them to assess whether or not the other person was comprehending the conversation. Four users

	Co-presence		Attention Allocation		PMU	
	Mean	Stdev	Mean	Stdev	Mean	Stdev
HR	6.565	0.731	4.369	2.00	5.988	0.990
HR + AT	6.395	0.943	5.75	1.413	5.75	1.251
HR + CL	6.583	0.729	4.482	2.223	5.826	1.21
HR+AT+CL	6.589	0.736	5.720	1.339	5.952	1.202

Table 2. Social Presence sub-scales

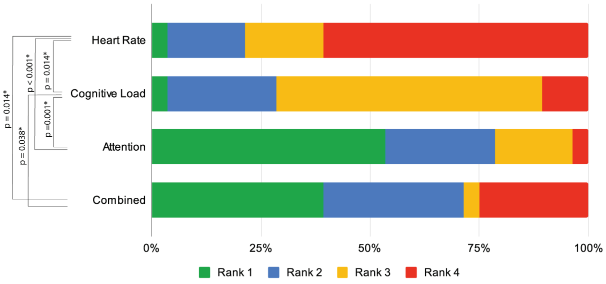

Fig. 8. User preference based ranking results (Rank1 is the most preferred, *: statistically significant).

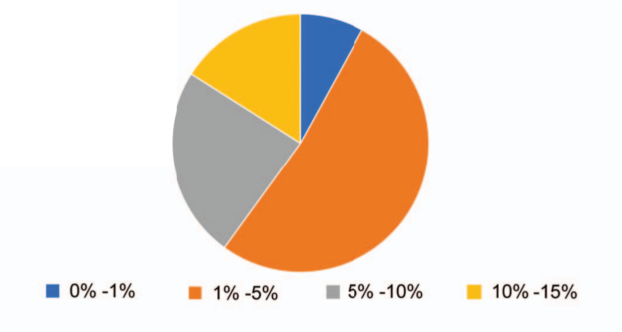

Fig. 9. The proportion of time spent by the participant focusing on the physiological cues displayed by their partner.

considered physiological cues redundant or distracting since they felt the instructions and the audio-visual communications were sufficient for most tasks. A Friedman test (2(3)= 26.229, p ¡ .001) showed there was a significant difference in the ranking results between the four cue conditions. We ran a Wilcoxon Signed-rank test, finding a significant differences between all cue pairs except Combined and Attention(Z = -0.945, p = .345). This shows that Attention cues were ranked and preferred in our tasks (by more than 50% of the participants).

5.5 Attention in Virtual Environment

We employed the use of eye gaze tracking to log and record the visual attention of participants. This allowed us to identify and document the specific objects or stimuli participants directed their gaze towards. Our findings indicate that most participants exhibited minimal attention towards physiological cues displayed by their partners, with the user's gaze directed towards such cues for less than 10% of the duration of the study. Figure 9 shows the percentage of time spent by the participant looking at the physiological cues of their partner.

This may be attributed to a phenomenon known as "habituation," in which the initial novelty of observing physiological cues displayed by one's partner diminishes over time [42]. We found that around 70% of the time spent examining the physiological cues occurred in the first minute of the observation, supporting the idea of habituation. After this time, participants may have become increasingly focused on completing the tasks at hand rather than directing attention toward these cues. In addition, the results may also be influenced by the nature of the tasks assigned, which may have required a higher degree of attentional demands, thus diminishing the allocation of attention towards physiological cues.

6 DISCUSSION

We asked open-ended questions like - "What the reasons are for their choice and the drawback and benefits of each system" to the participants upon completion of the study. One participant commented, "I would rather see everything first, then I can choose which is important for each task. Cognitive load tells me if my partner needs help... Heartrate tells me if my partner is excited... Attention tells me if he is focused." Most other participants shared this sentiment. Another participant commented, "The attention cue was the easiest to follow due to the dynamic nature of the representation. The constantly moving display attracted attention." This suggests that the dynamic nature of the attention cue played a key role in making it more engaging. A few participants also found it difficult to make accurate judgments of emotional states from the physiological cues and would prefer the system to do that for them. Additionally, some participants commented that processing too much information was challenging.

After conducting post hoc analysis, we found that the attention cue induced significantly higher copresence levels than the other conditions. This finding is supported by the open-ended questions, where participants expressed interest in the dynamic nature of the visualization and how the attention cue conveyed their partner's focus state. One participant stated,"The attention cue's ability to create a feeling of higher copresence in the collaborative environment is amazing. I felt more connected to my partner and it helped us work better together." It is possible that the attention cue's ability to create a feeling of higher copresence in the collaborative environment is due to these factors.

We did not observe a significant difference between the visual cues regarding mental and physical effort. However, the figures show that the mental and physical demands, effort, and frustration were generally low. Additionally, participants rated their performance higher, indicating that they had a generally pleasant experience overall. One participant commented, "The cues didn't require much mental or physical effort, which allowed me to focus on the task at hand. It made the collaboration process smooth and enjoyable." These positive experiences further highlight the effectiveness of the cues in facilitating collaboration and enhancing the participants' satisfaction with their performance in the study.

In addressing our research questions, our findings shows that sharing physiological cues led to an enhanced collaborative experience by enhancing the sense of co-presence. However, our study could not find advantages in integrating heart rate, attention, and cognitive load simultaneously, compared to employing them individually. In addiiton , we did not observe any performance improvements in collaboration resulting from the shared physiological cues.

7 DESIGN IMPLICATIONS

The present study provides several design implications for future remote collaboration VR systems that incorporate the sharing of physiological cues. This includes showcasing the importance of developing effective methods for interpreting physiological information. Our study found that many participants struggled to interpret the physiological signals of their partners. A lot of design work can be done on effectively representing physiological cues in virtual environments. Our study presented only a few visual cues, but future studies could explore different types of visualizations and their impact on user experience and performance. Training users to interpret physiological cues could also enhance their understanding and use of these cues in collaborative virtual environments. This would be especially important if such cues are to be used in real-world applications, where the accuracy and interpretation of the cues can have significant consequences.

Importance of Measuring and Visualizing Attention The study emphasizes the significance of measuring and visualizing attention in remote collaboration systems that incorporate the sharing of physiological cues. The participants in the study expressed a preference for being able to see the attention cues of their partners. This suggests that having access to information about the attention state of collaborators can enhance communication and coordination in virtual environments. By measuring and visualizing attention, remote collaborators can better understand each other's focus and engagement levels, leading to more effective collaboration. Designers of future systems should prioritize the development of accurate and intuitive methods for capturing and representing attention cues.

Dynamic Radial Visualization of Physiology is Preferred The study found that users preferred a dynamic way of visual representation for physiological cues. Specifically, a radial visualization was favored by the participants. This type of visualization could involve a circular display where different aspects of physiological information, such as cognitive load or emotional state, are represented by changing colors, patterns, or filling levels. The dynamic nature of this visualization allows for real-time updates and provides users with a clear and visually appealing representation of their partners' physiological cues. Future studies should explore different variations of dynamic radial visualizations to determine their impact on user experience and performance in collaborative virtual environments.

Avatar Should Represent the Emotional State In the study, the representation of cognitive load was depicted using a brain icon that filled up and turned red when the user experienced high cognitive load. However, some participants suggested an alternative approach, where the avatar's skin tone would change instead of using a brain icon. This change in skin tone would intuitively convey the user's cognitive load status without the need for participants to constantly look around their partners. This feedback highlights the importance of designing avatars that can accurately represent the emotional states of users. By incorporating such representations, remote collaborators can have a better understanding of each other's cognitive and emotional states, leading to improved communication and collaboration.

Overall, the study underscores the need for effective methods of interpreting and representing physiological cues in remote collaboration systems. Designers should focus on developing intuitive visualizations, such as dynamic radial displays, and explore alternative modalities, like auditory cues or haptic feedback, for conveying physiological information when visual cues are not feasible. Additionally, future research should investigate how these findings could be generalized to different domains and tasks to ensure the applicability of physiological cues in a wide range of collaborative virtual environments.

8 LIMITATIONS

This study has several limitations that should be acknowledged: One of them is that the use of generic avatars for representation in the collaborative environment has not been studied in terms of its effect on the overall experience. In our experimental setup, we employed the use of avatar representations to visually depict the partner in the collaborative context. The chosen representation was gender-neutral and generic in nature to eliminate any potential influence on the participants' behavior. The hands of the avatar models were animated to mimic the movements of grasping and holding, which could further enhance the sense of copresence. However, it is important to note that using more realistic avatars or volumetric representations may increase the participants' sense of co-presence further [44].

Another limitation of our study is that we presented heart rate information in all conditions, which may have allowed participants to infer stress or emotional state from this cue alone. As a result, participants may not have relied as heavily on attention or cognitive load cues. This could have influenced the results and may need to be addressed in future studies by varying the cues presented in different conditions.

The type of tasks used in this study could also influence the findings. They were not particularly challenging and quite engaging for some participants, leading to a focus on completing the task rather than interpreting and utilizing physiological information to collaborate with their partner. While conducting a pilot study with the system, we found that participants could complete the tasks faster when eye gaze was shared. However, in the main user study, this feature was not provided to encourage participants to interpret the physiological cues of their partner. Also, we used a physical activity, where knowing the partner's emotional state or cognitive load may not be as important as in a negotiation or decision-making task. In such tasks, the partner's emotional state may be more relevant to the interaction, and thus the importance of the physiological cues could be more pronounced. Therefore, future studies should consider the task and context of the interaction when examining the impact of physiological cues in virtual environments.

The Looxid Link is engineered to monitor and interpret a range of cognitive and emotional states. However, it does not provide specific details about the variable delay and epoch size used in its calculations. To assess cognitive load, the system averages data over a 10-second epoch. This approach results in a delayed representation of the user's emotional cues. In contrast, heart rate data is presented in real-time. This discrepancy between the immediate display of heart rate information and the delayed processing of cognitive load data represents a limitation of the system. In essence, while the device effectively tracks and analyzes cognitive states, there is an inherent delay in reflecting these states, in contrast to the instantaneous display of physiological data like heart rate.

A final limitation of our study is that we did not analyze conversational patterns or user behavior, which could have provided insights into how the conversation changed in response to perceived physiological cues. In addition, studying the effect of instruction delivery could have been interesting to explore. Future studies could include these aspects to enhance further our understanding of physiological cues' impact on collaborative virtual environments.

9 CONCLUSION

We describe a novel collaborative system designed to enhance the experience of remote participants engaged in VR assembly tasks. The system's main objective was to facilitate the sharing of physiological cues among users, specifically focusing on metrics such as heart rate, cognitive load, and attention. By enabling participants to share these cues, we aimed to provide a more immersive and connected experience akin to being physically present in the same environment.

We conducted an experiment to evaluate the effectiveness of our proposed system. The findings revealed that while users had the capability to share their physiological cues, they only allocated a limited amount of time and attention to actively observing and interpreting these cues. Despite this, participants reported an overall positive perception of their performance in the assembly tasks. One significant observation was the impact of co-presence on the sharing of attention. We observed that participants preferred sharing attention, indicating that they valued the ability to direct each other's focus within the VR environment.

In the future, we plan to investigate further methods to optimize the presentation and interpretation of shared physiological cues to enhance user engagement and attention. We would also like to explore the potential integration of machine learning algorithms to automatically detect and respond to changes in users' physiological states, improving the overall collaborative experience in VR assembly tasks.

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