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Again, Together: Socially Reliving Virtual Reality Experiences When Separated

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Figure 1. Three prototypes for sharing virtual reality experiences over distance: (1) Co-watching 360-degrees videos on desktop; (2) Co-watching 360-degrees videos in VR; (3) ReliveInVR: fully recreating the experience to relive it socially.

ABSTRACT
To share a virtual reality (VR) experience remotely together, users usually record videos from an individual's point of view and then co-watch these videos. However, co-watching recorded videos limits users to reliving their memories from the perspective from which the video was captured. In this paper, we describe ReliveInVR, a new time-machine-like VR experience sharing method. ReliveInVR allows multiple users to immerse themselves in the relived experience together and independently view the experience from any perspective. We conducted a 1x3 within-subject study with 26 dyads to compare ReliveInVR with (1) co-watching 360-degree videos on desktop, and (2) co-watching 360-degree videos in VR. Our results suggest that participants reported higher levels of immersion and social presence in ReliveInVR. Participants in ReliveInVR also understood the shared experience better, discovered unnoticed things together and found the sharing experience more fulfilling. We discuss the design implications for sharing VR experiences over time and space.

Author Keywords
shared experience, virtual reality, social, replay, shared experience, presence, immersion

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CCS Concepts
•**Human-centered computing** → **Virtual reality;** *User studies; Social content sharing;*

INTRODUCTION
It is common for people to capture and share experiences using photos or videos. Participants may do this in order to bring entertaining content to others, strengthen social connections or simply for the self-fulfillment of sharing [31]. With VR technology becoming increasingly available, more and more people can gain precious memories by experiencing different content in virtual environments. However, virtual reality offers new ways to capture and share memories or experiences. To share a VR experience over distance together, people usually record the VR experience from their point of view and co-watch the recorded videos later. However, co-watching recorded videos only allows users to relive memories from the perspective from which the video was captured. Bailenson and colleagues [2] introduced the concept of transformed social interaction and suggested that VR can enable unique experiences by altering the nature of "reality," such as modifying how spatial and temporal distance are experienced. One common feature of VR experiences is that the behavior that occurs in them can be tracked, recorded and replayed [18, 24, 9]. By recording a VR experience, we can allow people to return to the memory to re-experience it with others.

In this paper, we describe an experiment utilizing a prototype system, ReliveInVR, which allows recorded past events to be experienced socially. As shown in Figure 1, ReliveInVR allows users to relive the virtual experience together. However, each user can view the recorded experience from any perspective independently. Users may also pause, slow down or rewind the experience to locate specific moments. Although other systems [6, 29] allow physically separated users to communicate in a shared immersive virtual environment, how to utilize VR to support better remote VR experience sharing is still underexplored.

To explore this research question, we conducted a 1x3 within-subject user experience study with 26 dyads. Users experienced three conditions: (1) co-watching 360-degree videos on desktop, (2) co-watching 360-degree videos in VR and (3) ReliveInVR. Images from each condition are shown in the Figure 1. We compared each experience's ability to improve mutual understanding of details of the past experience. We also compared each experience on immersion, engagement and social presence. We conducted a semi-structured interview to elicit participants' qualitative responses.

To address these research questions, we synthesized the findings from both quantitative and qualitative analysis. The contributions of this paper are threefold:

- Describing a new type of sharing VR experience over distance which allows people to relive their recorded experience in VR socially.
- Understanding the user experience when people share their VR experience together remotely through a user study with 3 prototype systems.
- Identifying challenges and proposing design implications for sharing VR experiences remotely based on both qualitative and quantitative results

RELATED WORK

Our work combines and extends earlier research in sharing experience with digital media, remote interactions in VR, and recording and replaying in 3D virtual environments. In this section, we review key papers from earlier work and describe our novel research contribution.

Sharing experience with digital media

Family and friends often share memories with each other in a collocated setting by using printed or digital photographs. [5, 22]. Sharing typically is done as a social act to reminisce about one's experiences [8, 10]. People also share their experience via emails [10] and online [22] if sharer and sharee are separated. In addition to photos, people share videos to enjoy an experience together [26], or to support conversation [23]. As an alternative to watching videos independently, other work has developed systems to allow co-watching traditional videos [20, 28, 12, 30] or 360-degree videos [32, 25]. This work [20] suggests that remote video cowatching is an engaging shared experience to increase psychological closeness when people are physically separated. While people can also capture their social activities with photos and videos on social VR platforms, in this study we focus on understanding how people can uniquely share their VR experience over distance.

Remote interactions in VR

The "Reality Built for Two" [4] is the first established work where more than one person could simultaneously interact with each other in a shared virtual environment. Although other systems were created for two or more users [11, 13], supporting online multiplayer VR systems for consumers didn't become commonplace until the recent development of consumer-grade virtual reality apparatus and technology.

However, such environments were still the subject of study. Collaborative Virtual Environments (CVEs) utilized networked virtual reality systems to support groups at a distance. The key concept behind CVEs is that of shared virtual worlds whose occupants are represented to one another in graphical form and who interact with each other and with the virtual environment [6]. A number of research projects have been dedicated to the use of embodied virtual reality to support real-time collaborations in immersive CVEs [29, 21, 15, 27]. Our work focuses on utilizing specific qualities of the VR networked environment and record-replay techniques to allow users to relive their VR experiences over distance with others.

Record-and-Replay in 3D Virtual Environments

Some 3D games use record-and-replay techniques to show highlights of previous game-play such as "resume from replay" offered by the real time strategy game Starcraft II or the "edit replay" feature present in the martial arts game Toribash. Leveraging record-and replay techniques to support asynchronous activities in 3D virtual environments and create content out of synchronous activities was acknowledged as early as in the late 1990s. For example, Greenhalgh et al [14] proposed temporal links that define a relationship between present and past events so that the past events can be replayed in a virtual environment. The CAVE Research Network soft system had an application called Vmail which supported recording of an avatar's gestures and audio together with the surrounding environment [18]. More recently, vAcademia [24] allowed teachers to create 3D virtual recordings of their presentations. The social platform AltspaceVR also enables people to replay VR events with its VR capture tool. Mozilla's A-Frame has introduced a motion capture component for recording and reproducing VR tracking data. However, most previous work focuses on system implementation or considers the record-and-replay technique as a useful developer tool for automated testing and system demonstrations. In this paper, we utilize the record-and-replay technique to allow people to remotely relive their VR experience together, and examine the ability of this experience to support new kinds of social interactions.

PROTOTYPES AND VR ARCHERY GAME

VR archery game

To provide participants with VR experiences to share in our study, we designed an archery game where the participants played using Oculus Rift CV1 headsets and Touch controllers. In the VR archery game, participants performed multiple different movements (nocking an arrow, drawing the bow, aiming, etc.) which utilizes the tracking ability of VR devices and also made the experience more engaging and worthy of sharing. This task also worked for users with different skill levels since they could move closer to shoot the target.

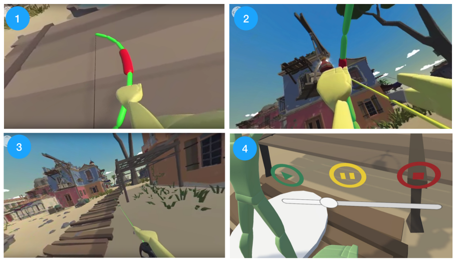

Figure 2. The basic interactions in the archery game; (1) picking up a bow, (2) grabbing an arrow, releasing an arrow, and (3) teleporting. ReliveInVR provides controls such as play, pause, seek to certain time stamp (4).

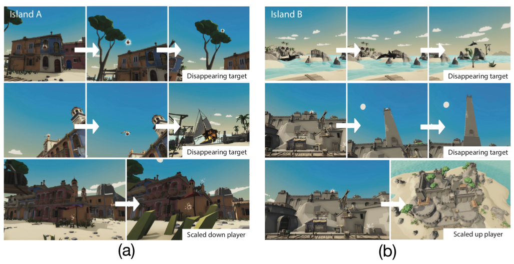

Figure 3. All the surprising events in the both islands.

Basic interactions in the archery game

In the archery game, the player uses a bow and arrow to try to hit targets in the shape of a brightly glowing pot. (Figure 2). Players can "teleport" through the VR environment to navigate and get close to a target.

Environments and surprising events

In order that each participant in a pair has a unique experience to share, each participant experienced the same game (in terms of mechanics and points) but in different environments with different events. We designed two islands for the archery adventure. One island has the feel of an old city-center with buildings, and the other island has a white mansion and a castle. We designed three shooting areas on each island where the player can find three targets. Thus, the participant can share the experience of one shooting area in one experiment condition. For each shooting area, we also incorporated a surprising event worthy of sharing with their partner to reduce repetition and prevent experience sharing from becoming boring. All "surprises" can be seen in Figure 3, All events were different on each island. For example, an orca comes out of the sea and tips over a target on one island, and a seagull catches a target and drops it on a ship on the other.

Full-body Avatar in VR

Since related work has established that movement realism can create a strong sense of social presence even in the absence of photorealism [3], we decided to use cartoon-like avatars for our study as shown in Figure 1. We made our cartoon avatars generic without specific hair and facial details. We chose unisex body types and skin colors that were non-natural (green and yellow) to avoid any tacit implications of race or gender, and ensure that our avatars were applicable to a wide array of participants. To generate full-body motion from tracking data, we used the VRIK plugin from RootMotion [1], which is a widely used analytic and heuristic Inverse kinematics solution.

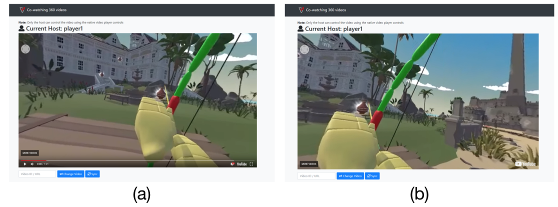

Figure 4. Co-watching 360-degree videos on desktop (Co-watchDT) prototype: (a) Sharer can have the video control. (b) Sharee can view a synchronized video with the sharer over distance. Sharer and sharee can have different perspectives of the 360-degree video

Recording the experience

When participants played the VR achery game, we captured the experience with 360-degree video from their points of view for Co-watchDT and Co-watchVR conditions. Regarding ReliveInVR condition, we captured the complete state of the virtual world, and then monitored and recorded all the changes at a rate of 12 times per second. More details will be discussed in the prototype implementation section. We also recorded audio streams including the game music, sound effects, and participant's conversations in all conditions.

Prototype Implementation

Existing tools such as Watch2Gether or Facebook Spaces allows users to co-watch 360-degree videos either on desktop or in VR remotely. However, in order to reliably compare study conditions, we implemented 3 prototypes for each condition to make the sharing mechanism consistent across all conditions. While sharing, only the sharer has control over the recorded video or relived experience. In other words, the sharer can decided when to pause or seek to the certain parts for sharing but the sharee can only view the recorded video or relived experience. Besides, users are embodied in the same avatars (i.e. the avatar used in the achery game) in both Co-watchVR and ReliveInVR conditions.

Co-watching 360-degree videos on desktop (Co-WatchDT)

We developed a web-based video synchronization application with NodeJS, socket.io and YouTube Player API. When the sharer uses video controls such as playback, fast-forward and pause, the video will be synchronized on other connected application through calling the same functions for each connected socket. For example, if a person calls play, it will call play for every connected socket so that each user can view the video with the correct time. However, previous study [32] have shown that users prefer to view independently while they co-watch a 360-degree video. Thus, we didn't synchronize the view angles between users as illustrated in Figure 4.

While sharing the experience in this condition, both participants opened our web applications and co-watched 360-degree videos with their partner on the desktop. In order to hear each other, since they were in separate rooms, they also used Line, a voice chat program to communicate with each other.

Figure 5. Co-watching 360-degree videos in VR prototype (CowatchVR). Users can watch the 360-degree video together and see each other's avatar at the same time.

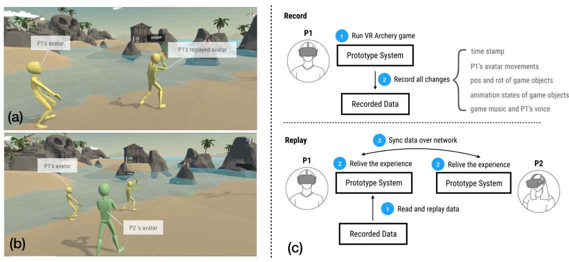

Figure 6. Reliving experience in VR prototype (ReliveInVR).(a) P2's point of view when P1 and P2 relive P1's experience through ReliveInVR. (b) P1 and P2 can see each other and P1's replayed avatar. (c) VR networked environment and record-replay technique in the ReliveInVR prototype.

Co-watching 360-degree videos in VR (Co-watchVR)

We designed a VR prototype which allows users to watch recorded 360-degree videos together as avatars in a 360-degree video-based virtual and shared space as shown in Figure 5 (similar to co-watching 360-degree video in Facebook Spaces). The prototype was implemented using SteamVR plugins and Photon Networking framework in Unity. The prototype synchronized both users' movement data and video controls so users could see each other's avatar and watch a synchronized 360-degree video together. Voice chat was implemented with Photon Voice.

Socially reliving experience in VR (ReliveInVR)

As shown in Figure 6, we implemented a VR networked environment and a state-based replay system with SteamVR plugins and Photon Networking framework in Unity. The system initially captures the complete state of the virtual world, and then monitors and records all the changes at a rate of 12 times per second. Changes recorded include the position and orientation of VR headset and controllers, the position and orientation of all objects in the environment, and the animation states of in-scene objects. All changes to the virtual world are written to disk via serialization mechanism as they are enacted, together with a time-stamp. To allow participants to "relive" past activity, the system uses the recorded information to reproduce the scene and re-enact recorded operations. The recorded data is read in to recreate the activities which occurred in the original experience. By implementing buffering techniques, our prototype provides a "time machine"-like feature which allows users to play, pause, rewind and search for specific moments of the recorded experience. The system also replays recorded audio streams including the game music, sound effects, and user's conversations.

USER STUDY

We conducted a within-subjects controlled user study comparing shared VR experiences in three conditions: (1) co-watching 360-degree videos on desktop (Co-watch-DT), (2) co-watching 360-degree videos in VR (Co-watchVR), and (3) Reliving VR expereince together (ReliveInVR), as shown in Figure 1. Within-subjects design was chosen not only because it has greater statistical power but allows us to gain a better understanding of the unique strengths of ReliveInVR through participants' qualitative responses. To address issues in within-subjects design such as carryover effects and expectancy bias, we counterbalanced the orders of conditions, measured both qualitative and quantitative data and provided a unique game experience in each condition.

Participants

A total of 26 (N=52) participant pairs (29 m, 23 f) were recruited. All participants were recruited from the undergraduate student population of a medium-sized private university. In all cases, participant pairs were acquainted and were willing to share a VR experience with their partner. Participants were aged 18-24 (M=21.5, SD=3.0). Fifteen out of the 52 participants had tried VR before the study. Only 4 of them were considered to be "active" VR users, using VR devices more than 3 times per week. The experiment took 2 hours to complete and participants were compensated with gift cards. IRB approval was obtained ahead of the experiment, and all participants signed informed consent.

Procedure

After consenting, participants were paired with a partner. The researcher confirmed that both participants were friends and were willing to share VR experiences with each other. Participants were then instructed to put on an Oculus head-mounted display (HMD) and Touch controllers and were walked through the archery game mechanics with a short demo. Upon completion of the training, each participant played the archery game in separate rooms.

After playing the game and a 10-minute break, they then completed the sharing task in all three conditions while remaining in separate rooms. Conditions were counterbalanced according to a Latin Square design, and all sessions were video recorded. Participants had up to 6 minutes to share in each condition. First, each participant reviewed the recorded experience. Then they pressed a button indicating the end of the sharing experience. Participants could then choose to explore in the reliving environment until the 6 minute time limit, or stop the study session immediately.

After each condition, participants completed a questionnaire. Finally, semi-structured interview were conducted with each participant separately. In addition to discussing the overall experience of the study, we investigated the quality of sharing the experience along with its nuances and challenges. Interviews were audio recorded and transcribed.

Table 1. Exploratory factor analysis (EFA) was applied to our questionnaire items, where questions in bold indicate that these items are kept for the final analysis.

No.	Questionnaire items	F1 (SC)	F2 (DP)	F3 (PI)	F4 (BI)	F5 (CE)
2	**Select the picture which best describes your relationship with your partner**			**0.35**		
3	**I could fully understand what my partner was talking about.**	**0.85**				
4	**I was sure that my partner understood what I was talking about.**	**0.92**				
5	**I was easily able to share what I did in detail to my partner.**	**0.80**				
6	**I was easily able to understand what my partner did in his/her VR experience.**	**0.84**				
7	**I was easily able to refer to objects that I'd like to share with my partner.**	**0.74**				
8	**I was easily able to find objects that my partner was talking about.**	**0.79**				
9	**The sharing tool allows me to notice what I didn't notice while I played the game**	**0.42**				
10	**I was able to feel my partner's emotion during the sharing.**	**0.48**				
11	**I was sure that my partner often felt my emotion.**	**0.41**				
12	**I perceive that I am in the presence of my partner in the same space with me.**	0.30		**0.54**		
13	**I feel that my partner is watching me and is aware of my presence.**			**0.54**		
14	**I often felt as if I was all alone during the sharing.**					**0.80**
15	**I think my partner often felt alone during the sharing.**					**0.84**
16	My partner was paying a lot of attention to me.		0.34	0.31		
17	I could tell what my partner was paying attention to.		0.36	0.39		
18	**I was easily distracted from my partner when other things were going on.**		**0.86**			
19	**My partner was easily distracted from me when other things were going on.**		**0.84**			
20	**My partner was influenced by my moods.**			**0.55**	0.31	
21	I was influenced by my partner's moods.			0.47	0.32	
22	**My actions were often dependent on my partner's actions.**				**0.91**	
23	**The behavior of my partner was often in direct response to my behavior.**				**0.95**	
24	**I felt that I was really inside my or my partner's recorded experience.**	0.33		**0.55**		
25	**I did not notice what was happening around me during the sharing.**			**0.90**		
26	**I felt detached from the real world around me during the sharing.**			**0.85**		
27	**At the time, I was totally focusing on the sharing experience.**			**0.72**		
29	**I felt that sharing experience with this sharing tool enhanced our closeness.**			**0.49**		
30	I derived little satisfaction from sharing with my partner.			0.32		0.41
32	I really enjoyed the time spent with my partner during the sharing.	0.32		0.45		
	SS loadings	5.43	2.20	4.66	2.24	1.92
	Proportion Variance	0.18	0.07	0.15	0.07	0.06
	Cumulative Variance	0.18	0.47	0.33	0.40	0.53

Measures
For all conditions, subjects were recorded with a digital camera. The audio was recorded either with the smartphone microphone or through the HMD microphone. We also recorded the head orientation data in all study conditions. We recorded the orientation data of the 360-degree video (i.e. the yaw, pitch, and roll angels) in the Co-watchDT condition and captured the HMD tracking data in the Co-watchVR and ReliveInVR conditions. In the ReliveInVR prototype, we also captured participants hand movements and the transformations of each object within the scene.

Questionnaire
In recent work [19], Li et al. developed and statistically evaluated a questionnaire for measuring social VR photo sharing experiences, which identified 3 major components including Quality of Interaction (QoI), Presence/Immersion (PI) and Social Meaning (SM). We adapted their questionnaire to the context of sharing VR experience, and included additional items relevant for our study. In addition, we used a survey tool developed by Vastenburg et al [33] to capture multiple emotion categories with an easy-to-use pictorial mood-reporting instrument. The resulting 32-item questionnaire (including a self-report emotion question) is shown in Table 1.

RESULTS
A similar statistical approach was used for all data reported in this section. Because the experiment involved within-subject manipulations and participants sharing their experience in pairs, the data are likely to violate the assumption of independence and is thus inappropriate for ANOVA and regression approaches. Multilevel Modeling (MLM) was conducted to account for the interdependencies of the dyad human members in each pair. We used the 'nlme' package in R to conduct a linear mixed-model analysis. We accounted for the random effects that arise from the individual subjects who are nested within dyads and used a compound symmetry structure for the within-group correlation structure. The different conditions were dummy-coded and treated as a fixed factor (sharing condition) with three levels (i.e.,Co-watchDT, Co-watchVR, ReliveInVR). After we built linear mixed models for each dependent variables, we applied ANOVA on each linear mixed

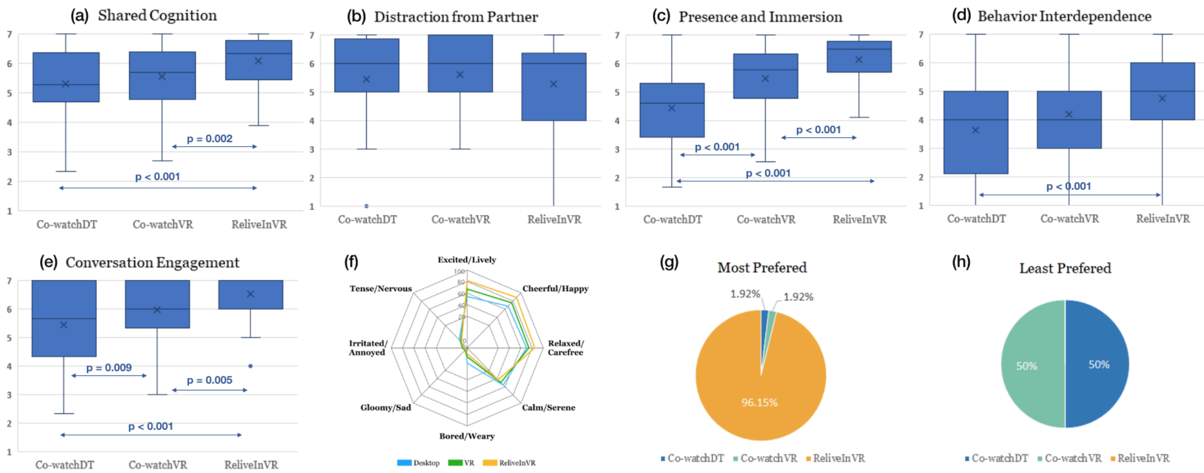

Figure 7. (a)-(e) boxplots for each factor across sharing conditions. (f) Self-reported emotion ratings for each condition. (g) Most preferred sharing tools. (h) Least preferred sharing tools.

model. When significant variation was found, pairwise comparison with Bonferroni adjustments was done by obtaining estimated marginal means(i.e. EMMs) for linear mixed models. All analyses below are results from linear mixed-effects models, with the exception of the head orientation since we averaged two participants' head orientation and treated each pair's mean of head orientation as the unit of analysis (UOA). In this case, we ran the Friedman rank sum test since the data were not normally distributed.

Factor Analysis for Questionnaire Data

We ran an exploratory factor analysis (EFA) [7] to better understand the important factors in our questionnaire. Bartlett's test of sphericity was significant ($\chi 2(2,465) = 5017.837, p < 0.001$) indicating that it was appropriate to use the factor analytic model on this set of data. The Kaiser-Meyer-Olkin(KMO) measure of sampling adequacy showed that the strength of the relationships among variables was greater than 0.5 (KMO=0.9), thus it was acceptable to proceed with the analysis. Additionally, Q28 and Q31 were removed based on low KMO scores and the low communality value. Both an analysis of the scree plot and Kaiser's criterion suggested a five-factor structure. Furthermore, since we assumed that factors would be related, we used oblique rotation ("oblimin") along with standard principal axes factoring. To ensure the factors are meaningful and redundancies eliminated (removing collinearity effects), we only took items with factor loadings of 0.3 and above, and the cross-loadings differ by more than 0.2. As shown in Table 1, the cumulative explained variance of the three factors is 53%. The 29 questionnaire items in bold were used for our evaluation of the three conditions (Co-watchDT, Co-watchVR, and ReliveInVR). The factor analysis result yielded 5 factors: *Shared Cognition (SC)*, *Distraction from Partenr (DP)*, *Presence and Immersion (PI)*, *Behavioral Interdependence (BI)*, *Conversation Engagement (CE)*. Chronbach's alpha was calculated on each factor and demonstrated high internal reliability with respective alpha's of 0.93, 0.94, 0.93, 0.96, and 0.9.

Questionnaire Response Analysis

We consider the effects of the sharing conditions (Co-watchDT, Co-watchVR, ReliveInVR) on each factor with 7-point likert-scale measure: *Shared Cognition*, *Distraction from Partner*, *Presence and Immersion*, *Behavioral Interdependence*, *Conversation Engagement*. The results are shown in Figure 7. The horizontal lines within each box represent the median, the box bounds the Inter-quartile (IQR) range, and the whiskers show the max and min non-outliers.

Shared Cognition

Shared Cognition assesses the quality of communication, mutual sensing of emotions, and the ability to understand or share the details of the recorded experience. The means and standard deviations for the Shared Cognition questions (9 items) for each sharing condition are: Co-watchDT=5.31(1.22), Co-watchVR=5.55(1.06), ReliveInVR=6.11(0.81). As shown in the Figure 7 (a), the ANOVA for the linear mixed model of Shared Cognition yielded a significant effect of the sharing condition, $F(2,102) = 13.01, p < .001$. Pairwise contrasts showed significant differences between ReliveInVR and Co-watchDT ($p < 0.0001, t = 4.97$), between ReliveInVR and Co-watchVR($p = 0.0002, t = 3.48$), but not between Co-watchVR and Co-watchDT ($p = 0.42$). These results indicate ReliveInVR was perceived to be significantly better at aiding partner understanding as well as details of the shared experience, than the Co-watchVR or Co-watchDT conditions.

Distraction from Partner

For the Distraction from Partner measure, higher scores are better and indicate that participants were less distracted from their partners while sharing. The means and standard deviations for the Distraction questions (2 items) for each sharing condition are: Co-watchDT=5.44(1.38), Co-watchVR=5.63(1.16), ReliveInVR=5.29(1.48). Although participants felt more distracted in the ReliveInVR condition (i.e. lowest scores in the ReliveInVR condition), the MLM analysis did not show significant effect of the sharing condition.

Table 2. ANOVA results on each emotion's linear mixed model and pairwise comparison with Bonferroni adjustments results

Emotions	ANOVA results	Pairwised comparison
Excited/Lively	$F_{2,102} = 31.30, p < .001$	ReliveInVR > Co-watchVR ($p < .001$) ReliveInVR > Co-watchDT ($p < .001$) Co-watchVR > Co-watchDT ($p = .004$)
Cheerful/Happy	$F_{2,102} = 31.30, p < .001$	ReliveInVR > Co-watchVR ($p = .003$) ReliveInVR > Co-watchDT ($p < .001$) Co-watchVR > Co-watchDT ($p = .017$)
Relaxed/Carefree	$F_{2,102} = 31.30, p < .001$	ReliveInVR > Co-watchDT ($p = .001$)
Calm/Serene	$F_{2,102} = 31.30, p < .001$	Co-watchDT > ReliveInVR ($p = .039$)
Bored/Weary	$F_{2,102} = 31.30, p < .001$	No significance
Gloomy/Sad	$F_{2,102} = 31.30, p < .001$	No significance
Irritated/Annoyed	$F_{2,102} = 31.30, p < .001$	No significance
Tense/Nervous	$F_{2,102} = 31.30, p < .001$	No significance

Presence and Immersion

Presence and Immersion questions measure the immersion of the reliving environment and the level of social presence during sharing.The means and standard deviations for the Presence and Immersion questions (9 items) for each sharing condition are: Co-watchDT=4.46(1.33), Co-watchVR=5.47(1.12), ReliveInVR=6.16(0.81). Figure 7(c) shows a significant effect of the sharing condition, $F(2,102) = 47.51, p < .001$. Pairwise contrasts showed significant differences between ReliveInVR and Co-watchDT ($p < 0.0001, t = 9.69$), between ReliveInVR and Co-watchVR($p = 0.0005, t = 3.91$), and between Co-watchVR Co-watchDT ($p < 0.0001, t = 5.77$). These results suggest that Co-watchVR and ReliveInVR both provided higher levels of immersion and social presence than Co-watchDT, and ReliveInVR provided the highest levels of presence and immersion.

Behavioral Interdependence

Behavioral interdependence in this study refers to the mutual impact that users have on each other during the experience. The means and standard deviations for the Behavioral Interdependence questions (2 items) for each sharing condition are: Co-watchDT=3.64(1.57), Co-watchVR=4.21(1.72), ReliveInVR=4.75(1.54). As shown in the 7 (d), the the ANOVA for the linear mixed model of Behavioral Interdependence yielded a significant effect of the sharing condition, $F(2,102) = 9.61, p < .001$. Pairwise contrasts only show significant differences between ReliveInVR and Co-watchDT ($p = 0.001, t = 2.14$). These results indicate that participants had substantially more interdependent behavior in ReliveInVR than Co-watchDT. However, co-watching videos in VR didn't result in higher behavioral interdependence than co-watching videos on desktop.

Conversation Engagement

The means and standard deviations for the Conversation Engagement questions (2 items) for each sharing condition are: Co-watchDT=5.44(1.35), Co-watchVR=5.97(1.08), ReliveInVR=6.54(0.65). Figure 7 (e) shows that the the ANOVA for the linear mixed model of Conversation Engagement yielded a significant effect of the sharing condition, $F(2,102) = 19.31, p < .001$. Pairwise contrasts showed significant differences between ReliveInVR and Co-watchDT ($p < 0.0001, t = 6.21$), between ReliveInVR and Co-watchVR(p = $0.0055, t = 3.20$), and between Co-watchVR and Co-watchDT ($p = 0.009, t = 3.02$). These results suggest that participants found conversations more engaging in both VR conditions than Co-WatchDT, and ReliveInVR was the most engaging experience among all conditions.

Emotion Ratings

The means and standard deviations of all measured emotions are shown in the Table 2 and we also visually compared the emotions with a radar chart as shown in the Figure 7 (f). Furthermore, we built linear mixed models for each emotion and we found significant effects of sharing condition on Excited ($F(2,102) = 31.30, p < .001$), Cheerful ($F(2,102) = 19.30, p < .001, Relaxed(F(2,102) = 6.98, p = .002)$, Calm ($F(2,102) = 3.22, p = .04$) as shown in Table 2. These results suggest that participants felt more excited and more cheerful in both VR conditions compared to desktop, and were most excited and happy in the ReliveInVR condition.

Preference

As shown in Figure 7 (g) and (h), when asked about most prefered sharing tool for sharing VR experience remotely together, 96% of the participants chose ReliveInVR, 2% of the participants chose Co-watchVR and 2% chose Co-watchDT. In terms of the least prefered sharing tool, 50% participants selected Co-watchVR and 50% participants selected Co-watchDT.

Behavior Analysis

In order to understand and compare the user behavior in each condition, we also computed the sharing time and the head orientation.

Normalized Sharing Time

During the sharing experience, participants were asked to press a button when they finished reviewing what happend and what

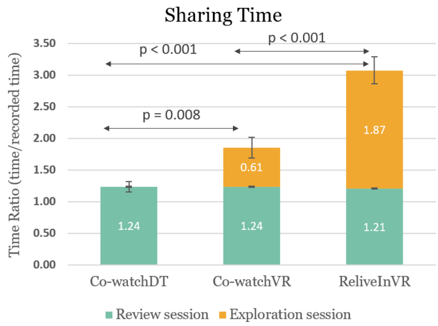

Figure 8. The result of normalized sharing time consists of the Review session and the Exploration session.

they did in the original experience together. Then they were allowed to keep interacting with each other if they wanted until the 6 minute time limit. Therefore, we divided the total length of sharing time into two separate time durations for each part: *Review* and *Exploration*. Note that the result of *Exploration* is 0 in Co-watchDT condition since no participants stayed and explored more after the *Review* session.

Since each participant spent different amounts of time in each target area, the length of the recorded experience differs. Thus, in order to have a reliable comparative analysis, we normalized both time durations of *Review* and *Exploration* with the length of the recorded experience. For instance, if the length of a recorded experience is 100s and the time duratios of *Review* is 200s, then the result will be 2.0 which indicates that participants spent twice the length of the recorded experience when reviewing the experience. The result of total sharing time can be greater than 1.0 in many scenarios. For example, participants might use the rewind control to view a interesting part of the experience multiple times, or they decided to explore more in the relived virtual environment.

As shown in Figure 8, the means and standard deviations for the sharing time ratios for each sharing condition are: Co-watchDT=$1.23(0.60)$, Co-watchVR=$1.85(1.15)$, ReliveInVR=$2.93(1.52)$. For both review time ratio and total sharing time ratio, we found a significant effect of sharing condition ($F(2,123.81) = 38.75, p < .001$). Pairwise comparison showed significant differences between ReliveInVR and Co-watchDT ($p < 0.001, t = 8.67$), between ReliveInVR and Co-watchVR($p < 0.001, t = 5.67$), and between Co-watchVR and Co-watchDT ($p = 0.008, t = 3.04$). However, there was no significant effect of sharing condition on review time. These results indicated that participants spent roughly the same amount of time on reviewing the recorded experience, but they explored together considerably longer in the relived virtual environment of ReliveInVR condition.

Averaged Head Orientation

To compute the averaged head orientation, we first computed the head direction from recorded yaw and pitch data in each sharing condition. Then we obtained the head orientation by calculating the angle between the two head directions in consecutive record data frame. Furthermore, we treated the pair's head orientation as the unit of analysis (UOA) and averaged two participants' head orientation per minute for both durations of *Review* and *Exploration*.

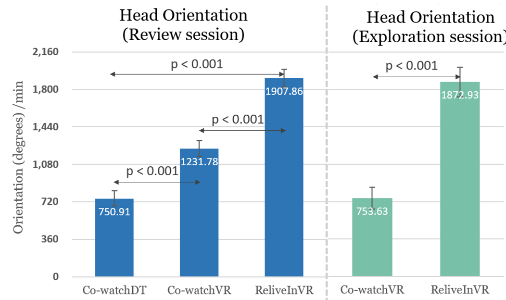

Figure 9. Head orientation result across all sharing conditions.

A Shapiro-Wilk-Test showed that our head orientation data is not normally distributed ($p < 0.001$). We thus performed a Friedman rank sum test. We found a significant effect of condition on head orientation($\chi 2(2) = 53.76), p < .001$). As shown in the Figure 9, a post-hoc test using Wilcoxon signed-rank with Bonferroni correction showed significant differences between ReliveInVR and Co-watchDT Spaces ($p < 0.001, Z = -5.61$), between ReliveInVR and Co-watchVR ($p < .001, Z = -5.12$) and between Co-watchVR and Co-watchDT ($p < .001, Z = -4.28$). These results indicate that participants were more likely to look around in ReliveInVR condition than Co-watchVR and Co-watchDT conditions; since they were immersed in the virtual environment.

In terms of the average head orientation in *Exploration* session, we only computed the head orientation for Co-watchVR and ReliveInVR condition since there is no Exploration session in Co-watchDT. Again, a Shapiro Wilk-Test showed that our data is not normally distributed ($p < 0.001$). As we compare two matched groups within subjects, we performed a Wilcoxon rank sum test. We again found a significant effect of sharing conditions. ($W = 427, p < 0.001$) as shown in Figure 9. These results indicate that participants looked around significantly more in ReliveInVR than Co-watchVR while exploring.

DISCUSSION

Immersion and social presence

Both immersion and social presence are crucial components of interactions that take place in computer-mediated communication. Our study results suggest that both VR conditions (Co-watchVR and ReliveInVR) provided higher levels of immersion and social presence than co-watching 360-degree videos on desktop (Co-watchDT) while sharing VR expereience remotely. Futhermore, although particiants can interact with each other through the same embodied avatars in both VR conditions, they felt significantly more immersive and closer to their friends when they can "enter" the relived expereince (ReliveInVR) than when co-watching the 360-degree videos in VR (Co-watchVR).

As P18 participant puts it:

> Some video games also have replay feature but this [ReliveInVR] is something completely new to me. I can actually go back to the experience. It's more immersive

> and fun. I can move inside my memories and it's just like a time travel. The best part is that I can take the time travel with my friends.....when we were able to explore togerher in our memories, I felt we were closer.

ReliveInVR technique can be easily adpated to reliving various VR experiences. Although more studies are needed to validate if ReliveInVR affords higher levels of immersion and social presence in while reliving different VR expereince, our study results shed light on how we can utilize the recording data in virtual worlds to enable a new and more immersive experience-sharing over distance with higher social presence.

Sharing details of the past experience

Based on our factor analysis result on *Shared Cognition*, ReliveInVR was perceived to be significantly better than both Co-watchVR and Co-watchDT, but there is no significant difference betwen Co-watchVR and Co-watchDT. Although embodied avatars in Co-watchVR enables users to use natural non-verbal communication cues in addition to verbal communication, participants still found it challenging to share experience by co-watching 360-degree videos due to the issues of fixed perpective and resolution.

As P28 participant puts it:

> The first one [Co-watchVR] didn't really helps me to share my experience than the second one [Co-watchDT]. In both situations, I was forced to explain what I did or what happened from a video. The video was kind of hard to understand what I did since I coudn't see my whole avatar's body like the third one [ReliveInVR]. The resolution is also worse in other 2 methods [Co-watchDT and Co-watchVR]

In addition to seeing each other's avatar, ReliveInVR further allows participants to view the replayed version of themselves performing every action they did in the past experience from any perspective. In order to investigate how participants leveraged this new ability, we analysized where participants viewed their replay avatars while they reviewed the expereience (i.e. *Review* session). Through analyzing the recorded participant's movement data, we calculated the head vector and check whether the replayed avatar was in the participant's point of view (i.e. 110 degrees field of view of Oculus Rift CV1) at every timestamp. Figure 10 (a) demonstrates the percentage of where participants viewed their replayed avatars during *Review* session in 4 different areas around the replayed avatar. The result suggests that participants tended to move around the replayed avatar and viewed it from different perspectives. Participants stated the freedom of moving helped them understand or share the experience better in the interview:

As P36 participant puts it:

> Viewing myself from the third-person perspective really helps me understand what I was doing at the time. I always tried to find a new best spot after my avatar [replay avatar] moved to a new place. Looking at the replayed version of myself performs every action I did is really interesting. I can see how I hold the bow and aim at the target by looking and I can easily discuss the shooting techniques with my friend.

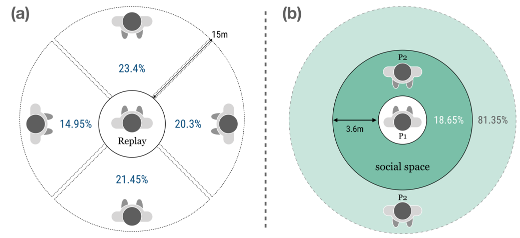

Figure 10. (a) The distribution of relative positions between participant's avatar and replayed avatar when the participant viewed the replayed avatar in the ReliveInVR condition. (b) The percentage of time when two participants were within the area of social space during the Exploration session in the ReliveInVR condition.

Although it's possible to record a 360-degree video from the third-person perspective, our study results indicate that participants enjoyed the ability of moving to different places to view and share the experience clearly in ReliveInVR conditions, which can't be achieved by viewing a 360-degree video with a fixed perspective.

Discovering unnoticed contents

During *Review* session, the head orientation results suggest that participants were more likely to look around to discover more contents in both Co-watchVR and ReliveInVR than Co-watchDT. Without non-verbal communication cues in Co-watchDT, most participants found coordinating their viewing perspectives was more challenging than in the two VR condtions. Thus, most participants only altered their viewing perspectives if they discussed the content outside of their field of view.

As P44 participant puts it:

> During the 2 VR conditions[Co-watchVR and ReliveInVR], you can directly see each other, turn around to see what's behind of your partner, can see what direction they're facing. That really help me understand the things she [partner sharing the experience] is talking about.

Besides, based on the normalized sharing time result, the total sharing time in ReliveInVR was significantly longer than Co-watchVR and Co-watchDT conditions since participants tended to explore the unexplored content in the reliving environment after *Review* session. Compared to the Co-watchVR condition, participants were limited in the perspective of the recorded video so that they were more focusing on playing with each other through their avatars during the Explore/Play session. The free movement enables participants to explore and allows the discovery of previously unnoticed contents. The ability to discover new contents makes the experience more fulfilling, especially when partners start "laughing about the same thing" (P2). This participant highlighted the impact of free movement on the quality of the sharing experience:

> He [partner who is experiencing the shared experience] can also have his own free will and also look around

> and experience new things. He can see things that I [the sharer] maybe didn't see. I can go around, and he can also walk around himself. He might have seen the ship exploding and something that I didn't notice. Both of us having our own free moving experience makes better (P5)

DESIGN IMPLICATIONS

Our study also found that the affordances of agency and independence create challenges which can affect the quality of the sharing experience. We synthesize the ideas that arise from our study, and suggest design possibilities for addressing these challenges.

Switching between views

Although participants can leverage non-verbal communication cues such as pointing gestures along with verbal communication to direct their partner's attentation in VR, the ability to move around and view the experience independently creates challenges for properly orienting and understanding spatial references especailly when they were far away from each other in the relived virtual environment. According to Figure 10(b), participants only had average 18.65% of the *Exploration* session within the social space area [16] (i.e. 3.7m) of their partners in the relived virtual environment. To address this issue, we should carefully design features that not only give users the freedom to explore, but allow them to create shared views easily such as group teleportation [35].

Improving awareness of avatars

28 of 52 participants pointed out the challenge of tracking the recorded avatar's and their partner's movement when they use teleportation as a travel method during the interview. This leads to lapses in communication as people lose track of the recorded avatars or of their partners and spend time finding them again. To enable a better sharing experience in a reliving VR environment, the system should include features that improve the user's awareness of their replay avatars and their partner's locations such as UI indicators.

Navigating to interesting moments

Participants were allowed to play, rewind or seek to certain moments of recorded experience throung the prototype in each study condition. However, several participants had issues on navigating to the content they wanted to share efficiently. For instance, P40 said that "I forgot when I saw the whale jumped out of the water. Let me try to find it first..." but he spent around 30 seconds to find the it. P17 also said that "I remember there is a bird catch it..." but he scrolled the slider too fast and missed the bird catching part. To address this issue, we can design features that allows users navigate to interesting moments easier such as time-based markers or location-based markers. Then users can quickly navigate to certain moments by selecting time-based markers or entering specific locations to trigger location-based markers.

Actively participating in relived experience

Although participants could move around and view the relived experience from different perspectives, the system prevented them from interacting with the flow of recorded experience. They could not shoot arrows themselves or block an arrow shot by the replayed avatar. This limitation guaranteed that participants relived their partners' recorded experiences in ReliveInVR just as they did in the other two study conditions, allowing us to fairly compare ReliveInVR with other study conditions. However, some participants wanted to actively participate in relived experience. For instance, P11 said that "I wish I could still play the game while we relived the experience. Then I can prove that I can shoot better than him." P2: "Your environment is more interesting than mine, I want to shoot that target." Allowing participants to actively participate rather than passively observe the relived experience would transform the original recorded linear experiences into complex and unique branching experiences where the entire relived experience can be shaped differently depending on how each user interacts with it. This could open up new social dynamics between the sharers and sharees as well.

LIMITATIONS AND FUTURE WORK

Our study examined a particular context in which users play an archery game in VR and share the experience with their friends. However, user behavior may vary when sharing different types of VR experiences (e.g a VR game as compared to an educational VR experience) or when sharing experiences with close others as opposed to strangers. In addition, other aspects of the study, such as different sharing motivations and the fact that participants were both in the lab, could affect social presence and the sharing experience overall. Thus, further research is needed to explore the validity of our results in other real world contexts. In addition, novelty bias may account for some of the differences between conditions.

The current ReliveInVR prototype used relatively low-fidelity, cartoon-like avatars. Allowing participants to use avatars with more identity cues could also affect the experience [17, 34]. Due to the tracking and rendering the simple avatars, participants gestures were not nuanced. For example, they could only perform pointing gestures with the whole hand models. This low-fidelity can impair the effectiveness of nonverbal communication cues. Thus, it would be interesting to see if behavior in sharing experiences changes with high-fidelity models that include facial expression and support various hand gestures.

CONCLUSION

ReliveInVR provides a new time machine-like experience which brings people back to their recorded VR experiences and allows them to relive and share them with others over distance. In order to understand how people capture and share VR experiences over distance, we designed a VR archery game and conducted a 1x3 within-subject study with 26 dyads to compare ReliveInVR with (1) co-watching 360-degree videos on desktop and (2) co-watching 360-degree videos in VR. This shared reliving experience may be more immersive and more engaging than other methods of sharing recorded experiences. The ability to move around and view the experience independently allows participants to find new things and make the sharing experience more enjoyable. We also propose design implications for addressing challenges when participants relive VR experience over distance.

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