Feels like Team Spirit: Biometric and Strategic Interdependence in Asymmetric Multiplayer VR Games

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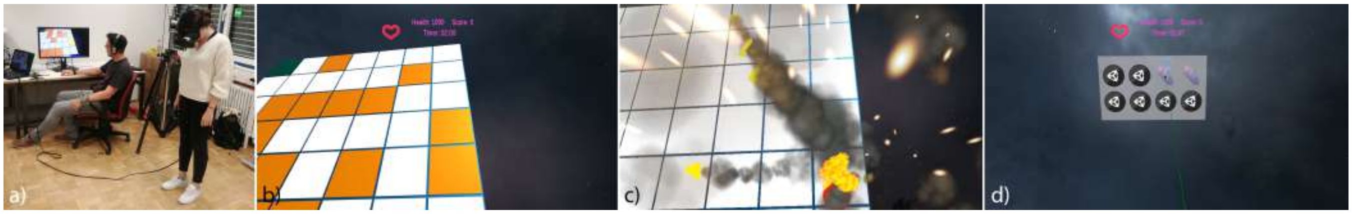

Figure 1: Illustration of our asymmetric VR game concept: (a) both players share the in-game view (controlled by the HMD player), but only the non-HMD player can see additional information such as traps (b, orange tiles) to be avoided by the HMD player (c) and puzzle pieces that need to be paired in a memory game (d).

ABSTRACT

Virtual reality (VR) multiplayer games increasingly use asymmetry (e.g., differences in a person's capability or the user interface) and resulting interdependence between players to create engagement even when one player has no access to a head-mounted display (HMD). Previous work shows this enhances player experience (PX). Until now, it remains unclear whether and how an asymmetric game design with interdependences creates comparably enjoyable PX for both an HMD and a non-HMD player. In this work, we designed and implemented an asymmetric VR game (different in its user interface) with two types of interdependence: *strategic* (difference in game information/player capability) and *biometric* (difference in player's biometric influence). Our mixed-methods user study (N=30) shows that asymmetries positively impact PX for both player roles, that interdependence strongly affects players' perception of agency, and that biometric feedback—while subjective—is a valuable game mechanic.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**; • **Software and its engineering → Interactive games**.

KEYWORDS

VR; virtual reality; multiplayer; asymmetry; interdependence; strategic; biometric

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1 INTRODUCTION

Current virtual reality (VR) systems for home entertainment such as the HTC Vive [41] support high audiovisual sensory immersion for the player who wears the head-mounted display (HMD) [6, 87]. For this setup, mirroring this player's view on a TV screen/monitor is a common way to provide external access to the VR world to users outside of the VR environment. This setup limits bystanders' interaction to passive consumption rather than active participation because the external display form factor does not provide the same kind of sensory immersion. In some cases, this limited or passive participation is the preferred option for bystanders because they can learn from and enjoy watching others [92] and some people

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may be more hesitant to try out new games or systems [45]; this may also apply in VR [96]. However, increasingly, VR systems and games that include bystanders more actively have reported positive effects on player experience (PX). For example, Gugenheimer et al. [34] previously introduced an exploratory HMD prototype that allows both passive and active participation in the same physical space for an HMD and a non-HMD player. Their results indicate that integrating a non-HMD player in a VR experience is feasible, yielding improved enjoyment and presence for both players. However, in their study, PX remained more immersive and enjoyable for the HMD player. This raises the question of whether it is possible to design a VR experience that induces similar engagement for both users regardless of how the virtual world allows them to interact (either with or without an HMD).

Similar approaches to merging the real world with the virtual world have been explored by other researchers [16, 29, 83]. Still, the empirical work often focuses on the novelty and innovation of the HMD implementation, while comprehensive evaluations of PX in asymmetric VR game design remain sparse. Nevertheless, asymmetric games have an enormous potential to increase social interaction between—and thereby wellbeing of—people with different abilities or hardware access. By applying asymmetric VR game design, researchers and developers can connect people despite a potentially single-owned HMD and counteract potential isolation stemming from its use.

To leverage the positive effects of asymmetric VR games, we draw on the conceptual framework by Harris et al. that describes ways to design asymmetric games and create interdependence between players [36–38]. While Harris et al. explored the effects of different *degrees* of interdependence, we focus on different *types* of interdependence. Therefore, we designed a VR game with an asymmetric interface (one player wearing the HMD; the other viewing the virtual world on a monitor). We created two types of asymmetry: *strategic* (different information and interaction opportunities) and *physiological* (different biometric influence).

Multiplayer games have often featured asymmetry as a difference in interaction opportunities and information provided to players (e.g., *Keep Talking and Nobody Explodes* [32], *Panoptic* [69], *Black Hat Cooperative* [88], or *Battlefield 1942* [30]). A notable example is *Savage: The Battle for Newerth* [31], which placed one user in a commander's role. Other users played a first-person shooter (with third-person perspective for melee) role, following the commander's orders. In our design, the non-HMD player is provided with additional information about the VR world that needs to be communicated to the HMD player to navigate and win the game. We expect that this asymmetry will result in interdependence that we term: **strategic interdependence (SI)**, which requires one player to rely on another for information and capability.

We further expand our game design's asymmetry to include a novel, physiological aspect: a difference in biometric influence, resulting in **biometric interdependence (BI)**; it requires one player to rely on another one's physiological responses. The non-HMD player's heart rate (HR) is linked to the game difficulty, increasing it when it passes a predefined threshold (determined in a pilot study; n=10). The game industry has explored this integration of biometric feedback into games in commercial VR games (e.g., *Left4Dead 2* [1, 90], *Alien Swarm* [1, 2, 91], *Nevermind* [26], and *Bring to Light* [73]) and academic research has reported a positive impact of biometric feedback on PX and user experience in games [39, 40, 59, 67]. However, variants that support multiple users or players remain largely underexplored [22], and its usage in asymmetric games has not been investigated yet. We expect BI between players to intensify the players' feelings of responsibility for the other and enhance social PX (similar to previous research exploring physiological linkage and increased social presence among participants [24]). Further, we argue that VR is a fascinating context for this feature because using the HMD isolates the users from the real world while improving embodiment and immersion into the VR world [7, 75].

To evaluate the levels of enjoyment, presence, affective state, and immersion this game design could create for *both* players, regardless of the player role (between-participants: HMD or non-HMD), we conducted a mixed-design user study (N=30). Our findings show how game designers and researchers can use asymmetry (and resulting interdependences) to create enjoyable and engaging experiences between users inside and outside of VR. We further explored PX with or without biometric influence. Moreover, we investigated the effects of different multimodal indicators of this influence (within-subjects: visual, auditory, and audiovisual biometric indicators) to determine how best to provide this kind of feedback for emotion regulation without distracting from gameplay.

Our results indicate that enjoyment, presence, affective state, and immersion scores were comparably high for both player roles, showing that interdependence can help integrate players across different displays of the same medium. While the physiological influence did not yield significant effects, we can nevertheless draw implications for biometric integration in VR game design; for example, a need for familiarization and less subtle impact. Furthermore, our participant interviews emphasize the importance and variety of communication between players despite the interface's asymmetry, players' understanding of agency in the different roles, and the multitude of preferences for biometric indicators. Our key contributions are as follows:

- we demonstrate and discuss how a non-HMD player can be integrated into a VR game while enhancing PX for both the HMD player and the non-HMD player,
- discuss qualitative design considerations for this design goal,
- and report a first exploration of biometric influence as an interdependence type in asymmetric VR.

2 RELATED WORK

There have been attempts to include non-VR users in collaborative VR settings, and there is prior work showing asymmetries in games can enhance PX; however, there are few comprehensive explorations of asymmetric VR games. Further—while biometric feedback has been explored in games—there is little work exploring its integration in VR.

2.1 Collaborative VR Experiences that Include Non-VR Users

Asymmetric VR setups have been explored outside of games in many contexts. Stafford et al. [85, 86] propose the addition of a top-down view for a non-HMD user, so that they can provide more effective instructions for the HMD user. Their results indicate that purely auditory instructions, which are often used for guidance [3, 53], are less efficient than visual cues for the HMD user, but they did not explore effects on presence and enjoyment of either user.

To share the VR experience of an HMD player with the outside world—beyond simple mirroring of the point-of-view [42]—previous work has proposed approaches for the active participation of non-HMD players. Yang et al. [95] addressed the challenge of non-HMD users crossing the tracking area of an HMD player by visualizing them as "shields" within the virtual environment [95]. Their focus, however, was on reducing interference with the VR experience rather than integrating non-HMD users.

Physical interfaces have been explored as mediums for interaction in VR in multi-user scenarios. For example, Mai et al. proposed enabling the collaboration of HMD and non-HMD users through a physical surface that serves as an interface to the virtual world via two-dimensional, bi-directional input and output [53]. Their results suggest that communication between HMD and non-HMD users improved task performance and presence of the HMD user. However, the non-HMD user's presence was not evaluated, which hinders comparison between the roles.

In general, the focus of these systems is on the user experience of the HMD-wearing user and ignores the experience of the non-HMD user. In a game setting, however, integrating non-HMD players into a VR game makes them players; this creates an additional crucial design goal in creating an engaging experience for *both* players.

2.2 Asymmetry in Games & VR Games

With increasingly reliable technology, multiplayer gaming environments have become virtual meeting places where people can socialize. They can also contain a multitude of differing abilities, interfaces, and preferences of players, and it can be challenging to foresee how these differences interact with or affect PX. Yet these differences, or *asymmetries*, can also significantly enhance PX and social connectedness, by inducing interdependences between players, for example, making one player rely on another. Many game designers and developers are integrating and catering to asymmetries that foster interdependence between players to facilitate multiplayer engagement.

Harris et al. [38] have introduced a first conceptual framework of asymmetric game design, in which they address how video game elements can cater to differences between players: asymmetry of mechanics, dynamics, and aesthetics. Moreover, they observed higher social connectedness and social presence values for asymmetric gameplay where the players have asymmetry of ability, information, and interface, when compared to a symmetric one [36].

VR is particularly suited to explore asymmetry in game design. It is highly immersive, yet research indicates that immersive VR experiences can also be isolating [7, 62, 75] because people feel self-conscious in front of potential onlookers. Several commercial VR games already include asymmetric displays of the VR world to provide a less isolating experience, involving both an HMD and one or multiple non-HMD players (e.g.,*Ruckus Ridge VR Party* [27], *Acron: Attack of the Squirrels* [74], or *Carly and the Reaperman—Escape from the Underworld* [68], all praised for being engaging).

In academic research, Sajjadi et al. [78] showed comparable PX for both the HMD player and the non-HMD player using Sifteo cubes as an interface, showing equal levels of satisfaction for different interaction modes. Some papers have examined the contribution of sharing both first-person and third-person points-of-view to the non-HMD players' PX, yielding comparable levels of PX for both players in terms of presence and social interaction [44, 50]. A recent prototype, *SilhouetteVR* [47], presents the VR world to non-HMD users through a dynamic view frustum displayed on a one-way mirror/screen which reflects the HMD player's embodiment within the VR world. While they do not yet integrate the non-HMD users as players, their initial results for the enjoyment of the non-HMD user are promising. Furthermore, VR prototypes *FaceDisplay* and *FrontFace* allowed non-HMD players to participate in the virtual world through touch-screens that were attached to the HMD, enabling co-located interaction techniques for both users [14, 35]. In an evaluation of *FaceDisplay*, both roles reported enjoyment, however presence and arousal were significantly higher for the HMD player than for the non-HMD player. The concept of integrating non-HMD players was implemented more comprehensively with *ShareVR*, which extends room-scale VR with whole-body interaction for non-HMD players via top-down projection and a hand-held monitor; an example of an augmented-reality approach [34]. The researchers found that both the HMD and non-HMD player experienced higher presence and enjoyment than in the baseline (wherein the non-HMD player used a game pad and a TV set). However, the non-HMD player still reported significantly lower presence and enjoyment than the HMD player for both conditions. The cause of this imbalance remained undiscussed but might be explained by the specific design of interdependence between roles.

These findings motivated us to further explore asymmetry of information and ability (strategic dependence) with different interfaces (HMD-VR and monitor-display): we aimed to design a comparably enjoyable and engaging experience for *both* players, and explore which factors in game mechanics and dynamics contribute to highly engaging PX.

2.3 Biometric Feedback

Integration of biometric feedback has been shown to increase engagement and immersion in single-player games [39, 67]. A common approach is that an increase in player arousal (measured with physiological metrics) leads to a more difficult game, classified as "challenge me" gameplay by Gilleade et al. [33]. Further, these games often require players to self-regulate [52] which can improve stress-management skills [9]. Nacke et al. propose that indirect physiological input such as HR and galvanic skin response should be mapped to features of the game world rather than direct actions [63]. This finding motivated us to link the current game difficulty to the non-HMD player's HR signal.

Kuikkaniemi et al. found that explicit biometric feedback allows players to self-regulate and increases immersion [48]. Sinclair et al. [80, 81] showed that use of HR metrics effective in controlling an exergame to meet the level of exercise desired by players. To aid self-regulation, previous work explored different cueing mechanisms that represent the current biometric state [57, 79]. In *Life Tree*, Patibanda et al. [70] provide biometric feedback about the player's breathing through changes in the VR environment (e.g., a tree object that expands and contracts to match their breathing pattern). Sra et al. [84] have used breathing as a physiological input mechanism in VR, and suggest that this kind of physiological factor can increase presence and players' connection to the physical world. Chen et al. found that players enjoy audio feedback of their HR, while visual cues were described as distracting [15]. Similarly, Dey et al. explored the influence of an artificially accelerated and decelerated auditory HR cue on players' physiological signal [21]. Their results indicate that auditory cues could affect player emotions but did not affect their HR. These findings prompted us to explore the impact of biometric cues on PX in our user experiment.

In multiplayer games, sharing each other's HR was found to have no significant influence on players' emotional state [22] but did improve engagement with an exertion activity [93]. While previous work has explored biometric feedback for symmetrical multiplayer games [22], it has not yet been explored in an asymmetric VR game setup, wherein we argue that it could represent a novel type of interdependence. Therefore, we expand the asymmetry of our game design's SI to the physiological aspect by using HR metrics of the non-HMD player[1] to influence the game world and difficulty. We expect this BI to increase the players' experience of relatedness, as well as the non-HMD player's feeling of responsibility for the HMD player, thereby intensifying the experience of *both* players.

3 RESEARCH QUESTIONS

Our primary research question concerns an asymmetric collaborative VR game, in which only one player acts in the VR world via HMD, yet both players feel engaged and immersed. This holds some game design challenges, because when only one player is actively immersed in VR, the HMD player could easily feel isolation or self-consciousness because of the immersive nature of VR. We thus aimed to design asymmetry of information to include a non-HMD player in the VR game. Thus, the non-HMD player has information required by the HMD player, creating player interdependence.

Hence, the first research question **(RQ1)** asks:

- *Can imbalanced asymmetric information between players lead to one player feeling less in control (i.e., like they are following the other player's instructions without their own agency)?* Agency is an important factor in PX [61], making this a game design challenge for our development team.

For the second research question, we were interested in the effect of biometric feedback in this asymmetric VR experience. **RQ2**:

- *Does biometric influence over game difficulty dynamically affect PX in VR (compared to static difficulty)?* Further, does it make a difference *a)* whether players are provided an in-game indicator of whether their own biometric state is currently increasing game difficulty, or *b)* in *what modality* this indicator is represented in-game.

As a final overarching research theme, we were interested in comprehensively exploring players' experience of an asymmetric VR game, to gain insight into design factors that shape balanced PX between both players.

4 ASYMMETRIC VR GAME IMPLEMENTATION

To explore our research questions in an empirical study, we designed and implemented a VR game as a stimulus. The collaborative VR game for two players featured a design, in which only one person is wearing an HMD (see Figure 1a). The game mechanics are distributed asymmetrically: the player wearing the HMD plays a more active role but has to rely on information provided by the player outside of VR (non-HMD player). The non-HMD player has more information about the game world (which they view via a PC monitor), and their physiological state—indicated by their HR—affects the game parts described below.

Technical Setup. The game was implemented using C# in the Unity game engine (version 2018.3.8f1) [89], with the addition of Valve's SteamVR v1.2.3 [17] and the Virtual Reality Toolkit (VRTK) v3.3 plugin [28]. The experiment was conducted using an i7-7700HQ CPU and a GeForce GTX1060 graphics card.

The VR setup consisted of the HTC Vive [41] with the usual two base stations and one controller for the HMD player. For the non-HMD player, the setup consisted of a PC with a 27-inch monitor (2560x1440 resolution) and headphones. The HR of the non-HMD player was acquired using an Empatica E4 wristband [25]; the corresponding software and a Windows Bluetooth low-energy (BLE) server were used to stream the HR data to the game. The wristband has a 64 Hz sampling rate for blood volume pulse measurement, yielding HR values (sampling rate 1 Hz) and inter-beat interval.

4.1 Game Design

The game was designed as a custom collaborative game that features different roles and asymmetrical information for two players. We chose to focus on collaborative gameplay as the literature highlights improved PX and increased interdependence for HMD and non-HMD users in such scenarios [35, 96]. Following that, the game design choices (e.g., sharing the same camera view, employing memory puzzle) were made to promote communication and increase interdependence between players.

The game consists of three levels. In each level, players are given limited resources (i.e., two minutes time and three lives) to fulfil the tasks: navigate a virtual grid and complete a memory puzzle. The grid is populated with traps; their layout varies with each level. The game world also spawns lasers (at the current height of the HMD player's headset) with a default frequency of 15 seconds.

Asymmetric Roles. The player in VR (*HMD player*) physically navigates the game space grid (Figure 1b). This includes avoiding lasers (Figure 2), traps (Figure 1c), and activating buttons in the memory puzzle (i.e., uncovering images, see Figure 1d). However, they are reliant on their co-player's knowledge of the game world: they cannot see the traps on the grid, nor approaching lasers.

The non-VR player (*non-HMD player*) watches the HMD player's view of the game world via a PC monitor, but has additional information—that is not visible in VR—overlaid on top of this on the monitor display. This player's view includes traps (i.e., the orange-coloured grid cells in Figure 1b), the remaining time (see Figure 1c,d), and they are able to see and hear incoming lasers. They are also able to see uncovered images in the memory puzzle (see Figure 1d).

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[1] In early pilot tests, we explored the feasibility of gathering biometric data of both player roles, but only the more stationary non-HMD player's data resulted in reliable measurements.

Figure 2: Lasers (only visible to the non-HMD player) spawned at roughly HMD height, at a distance of 50m from the grid (distance marked by Earth object as a reference point). The HMD player ducked based on the non-HMD player's instructions on timing.

Biometric Influence: Lasers. The HR of the non-HMD player dynamically affects the difficulty of the game, by affecting how frequently lasers appear (every 15 seconds by default). Prior to the game, the non-HMD player's HR is collected as a baseline over a time period of 5 minutes. The non-HMD player wears the wristband on their non-dominant hands, and they were instructed not to talk or move to avoid noise in the data (during the game, they were allowed to talk, but were still instructed not to move). For the rest of the game, a time interval of two seconds is used as a sliding window to acquire continuous HR data from the non-HMD player. Their current HR is then compared to the baseline measurement to calculate a multiplier[2]. This multiplier was used to dynamically affect the frequency of the lasers. *CurrentHeartRate* here refers to the variable that is averaged over a two-second time interval of continuous HR data using the sliding window approach, while *BaselineHeartRate* is the average of the 5-min baseline measurement prior to gameplay. In this way, a multiplier is <1 when the non-HMD player's HR is higher than the baseline, and >1 when it is lower. Values higher than the baseline HR[3] thus triggered more frequent lasers.

Lasers were then spawned at a height of 1–3 cm below the player's current headset height, 50 meters away from the current playing field and reaching the main play area after ~7–8 seconds. They were accompanied by a laser-style sound effect, to give the non-HMD player an understanding of its active position. When the laser was at a distance of 10 meters to the HMD player, an additional sound effect was played for the non-HMD player (3-beat proximity alert).

Furthermore, a secondary measure was applied to ensure participants could not continuously crouch once lasers had spawned. We applied a logarithmic function between the laser and the HMD positions on the playing field so that the former moved toward the latter, adjusting for vertical changes. As a result, the co-players had to communicate with the HMD player to avoid lasers in a timely fashion. The non-HMD player could observe the visual approach of the laser (when the HMD player looked up), and use the laser sound effects as a more continuous auditory warning.

Indicators of Biometric Influence. In some variants of the game, indicators were used to represent the participants' excitement level, and acted as a warning signal for the higher frequency of lasers that accompanied increased excitement. The game variants featured different types of indicators (and combinations thereof) which were then compared in the study: auditory cueing, visual cueing, and combined audio-visual cueing.

Auditory Cueing: The sound of heart beats was used to represent the increased excitement level of the players. When the non-HMD player's excitement exceeded the baseline measure, heart beat sounds were played via the headphones. The sound was played at a constant frequency irrespective of the player's actual HR: the time between beats was 0.65 seconds; each beat consisted of two amplitude peaks separated by 0.25 seconds[4].

Visual Cueing: A red frame flashing around the in-game view—visible only for the non-HMD player (see Figure 3)—was used as a visual cue to represent the increased excitement level of the non-HMD player, and thus conveyed the increased likelihood of lasers. The frequency of the visual cueing was identical to the auditory variant: The red frame always flashed twice separated by 0.25 seconds; the time between paired flashes was 0.65 seconds.

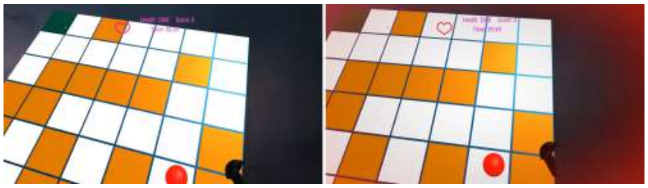

Figure 3: With visual cueing, the non-HMD player's view (left) is augmented with a flashing red overlay frame (right) to indicate an increased HR (and higher frequency of lasers).

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[2] Following the equation by Dekker et al. [20]): *Multiplier = 1 / (CurrentHeartRate / BaselineHeartRate)*

[3] In a pilot study (N=10) we found that higher thresholds set the laser frequency too low, inducing less enjoyment.

[4] These values were determined via another pilot test with three pairs of participants in the early tests.

5 USER STUDY

The goal of the study was to explore whether the game design would elicit a positive experience for both player roles, and gain some insight into the factors that resulted in this experience. Further, we wanted to test the influence of the asymmetrical biometric feedback loop on PX. To inform the design of in-game representations of biometric influence, we compared biometric indicators of different modalities (auditory, visual, audiovisual) with regards to their effect on both player roles' experience and the non-HMD player's ability to control their physiological arousal.

Methodology. A mixed design was used for the study, with *player role* and *type of biometric influence* as independent variables. Player roles (HMD and non-HMD) were randomly assigned at the beginning of the study and not switched (between-participants), while the type of biometric influence (including its in-game representation) varied as a within-participants variable over five playthroughs.

We chose a mixed-methods approach followed a triangulation-convergence model [18], which places the quantitative and qualitative measures of our study at equal importance. With the quantitative aspects of our study, we aimed to measure and compare PX across player roles and conditions. In complement to this, there is no questionnaire for measuring underlying factors to PX in asymmetric VR games, so we used qualitative methods (semi-structured interviews) to more deeply and flexibly investigate players' understanding of the roles and the designed asymmetry.

5.1 Conditions

The participants played the game with five different conditions in the study:

1. *Baseline Game—No Biometric Interdependence (NBI).* In this variant, the non-HMD player's HR had no influence on the frequency of lasers (i.e., set at the default frequency of 15 seconds). To keep conditions comparable (and for later analysis), the non-HMD player still wore the Empatica wristband and their biometric data was recorded.
2. *Biometric Interdependence (BI).* In this variant, the collected biometric data affected the frequency of lasers in the form described above. However, the non-HMD player was not informed of their current physiological state through any in-game representation (no auditory or visual cueing).
3. *Biometric Interdependence with Auditory Indicators (BI-A).* This variant was identical to *BI*, however the non-HMD player was informed of their heightened excitement via auditory cueing as described above.
4. *Biometric Interdependence with Visual Indicators (BI-V).* Here the game employed visual cueing to indicate heightened arousal on part of the non-HMD player.
5. *Biometric Interdependence with Audio-Visual Indicators (BI-AV).* This variant employed both auditory and visual cueing to signal excitement levels above the baseline.

An overview of these conditions (when biometric influence was present, and how it was indicated to the non-HMD player in their monitor-display overlay) is presented in Table 1.

	Conditions of the Experiment				
Attributes	*NBI*	*BI*	*BI-A*	*BI-V*	*BI-AV*
Biometric Manipulation	—	x	x	x	x
Indicator Usage	—	—	x	x	x
Auditory Indicator	—	—	x	—	x
Visual Indicator	—	—	—	x	x

Table 1: An overview of the conditions of the experiment.

5.2 Participants

The study was conducted with 30 participants (13 female, 16 male, 1 non-binary) with an average age of 26.03 years (*SD*=3.18). 18 participants (10 in the HMD role) had prior VR experience while 12 of the participants (5 in the HMD role) did not. Gender was roughly similarly distributed within the assigned player roles (HMD player: 7 female, 8 male; non-HMD player: 6 female, 8 male, 1 non-binary). All participant dyads reported that they knew each other.

5.3 Measures

We used physiological and psychometric measures for all participants. For a subset of 14—7 male (4 HMD player, 3 non-HMD player); 6 female (3 HMD player, 3 non-HMD player); 1 non-binary (non-HMD player)—the study was concluded with an optional interview asking in more detail about their experience of the different game variants.

Physiological Measures. We calculated two HR metrics for our analysis, *average HR* per condition (regardless of baseline), and *variance in HR difference to baseline.* The average HR was calculated by averaging the data points collected for each condition, while the variance in HR differences subtracted the individual baseline measurement from each data point, prior to calculating their standard deviation. This type of HR measure has been evaluated and found to represent player arousal in various game research studies [23, 54–56, 58].

In-Game Metrics. We logged descriptive values for each condition/playthrough: how often the player teams died in each condition, and how many levels they completed, the playthrough duration, and experienced number of lasers and trigger events. While we do not report these in the results for scope, we provide a table with average values per condition in the supplementary materials.

Post-Game Questionnaires. After each playthrough, we assessed participants' affective state, immersion, and presence via questionnaires. Affective state was measured as arousal, valence, and dominance with the three 7-point pictorial scales of the self-assessment manikin (SAM) [10]: 1=*calm*/*unhappy*/*controlled*; 7=*excited*/*happy*/*dominant*. For immersion, we employed the Immersive Experience Questionnaire (IEQ) [43], which consists of the subfactors real-world dissociation, challenge, control, emotional and cognitive involvement (7-point Likert scales: 1=*not at all*; 7=*a lot*)[5] as well as

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[5] The labels here are presented as examples, as they differ depending on item phrasing for the IEQ as well as the SUS (e.g., *very often* or *definitely no*), but higher numbers represent positive scores.

Figure 4: The study procedure followed a mixed-design and assessed psychometric, physiological, and interview data. For a subset of 14 participants, we conducted an interview on their experience of the different game variants.

a single-item measure of immersion (10-point scale of same direction). A presence rating was acquired via the Slater-Usoh-Steed Questionnaire (SUS) [82]; the questionnaire consists of 6 items on a 7-point Likert scale (1=*not at all*; 7=*very much so*). We also employed a custom single-item measure of enjoyment ("*I enjoyed the experience in this condition*") on a 7-point Likert scale (1=*not at all*; 7=*very much so*).

Interview. An interview with a total of 32 pre-determined questions (14 questions posed to the HMD player; 18 posed to the non-HMD player) was conducted to explore the participants' experiences towards collaborative game attitudes, their experience of their player role, the different game variants, and the asymmetrical feedback. While we followed the interview guideline, we also diverged from it for follow-up questions or clarifications based on the participants' responses (semi-structured interview). The full list of questions is provided in the supplementary materials.

5.4 Procedure

We announced our experiment in many different digital distribution forms: mailing lists, messaging groups and the university boards. Subsequently, the participants voluntarily participated in the experiment by contacting the experimenter or registering for an empty time slot using an online portal.

At the beginning of the study, participants were asked to sit in front of two separate monitors, and introduced to the study purpose via handout. After signing the consent form and filling out a demographic questionnaire, participants read a form describing the two different player roles, and then watched the corresponding video tutorial (ca. 2 minutes) for their (randomly) assigned role. Following that, the non-HMD player was asked to sit in front of the designated monitor, where a 5-minute baseline measurement was taken of their resting HR. The participant was instructed not to move or talk during the measurement. At the same time, the HMD player was instructed on how to put on the Vive HMD, and given time to become accustomed to the controllers.

Once the baseline measurement was complete, the experiment was run for the five conditions in counterbalanced order (*5x5 Latin square*). Each condition consisted of gameplay (with the corresponding game variant) and subsequent post-game questionnaires. Further, participants were asked if they wanted to participate in the optional interview to inform us of their experience of the different game variants. To ensure the comfort of participants, we offered an opt-out in case participants preferred not to be interviewed afterwards (e.g., due to time constraints or hesitation in speaking English, which was the second language for most participants). As a result, the interview was conducted (separately) with 7 HMD and 7 non-HMD participants (1 non-binary, 6 female, and 7 male).

The study procedure is illustrated in Figure 4. Participants' remuneration for study (75-90 minutes duration) consisted of 10 EUR.

6 ANALYSIS AND RESULTS

The analysis of the psychometric and physiological data was conducted with parametric tests where data were normally distributed. For not normally distributed cases, we employed non-parametric tests as suggested by Wobbrock and Kay [94]. This is described in more detail below.

For the interviews (n=14: n=7 HMD and n=7 non-HMD player; 2:02 hours of audio recordings total), we applied a thematic analysis methodology using an approach that uses elements from both the *reflexive* and *codebook* orientations of thematic analysis [11, 13]. Our approach consisted of the following: an *a priori* deductive categorization of codes, a reflexive perspective on inductive code and theme generation, and two coders for both consensus and nuanced, collaborative construction of codes. We defined three overarching deductive categories at the beginning of our analysis: *collaboration in VR*, *asymmetry of player roles*, and *biometric asymmetry and indicators*. The interview data were then inductively coded by the first two authors independently, with codes placed into the three *a priori* categories. In four meetings (after coding four interviews in each batch, except the last one), the authors discussed all applied codes, and resolved different readings by adding codes, removing them, or merging/splitting them. We note that discrepancies were thus not necessarily seen as a conflict to be resolved, but instead could be reflected through additional and alternative codes. Themes were then developed from the codes by re-reading and synthesizing the coded quotes and discussed between the first two authors.

6.1 Player Experience

For the mixed-design analysis of PX measures, we used ANOVA-type statistics (ATS) for non-parametric mixed designs from the `nparLD` R package [66], which is reported with adjusted degrees of freedom[6]. None of the factors (for immersion, presence, enjoyment or affective state) showed a significant effect of role or condition, nor an interaction effect. Descriptive statistics separated by role are listed in Table 2; results by condition in Table 3.

Effects of VR Experience. Related work has suggested that novelty may be an initial factor in VR experiences [64, 72, 76], we

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[6] "*The adjusted degrees of freedom [(DoF)] used for the approximation of the distribution of ATS may appear to be quite different from the conventional [DoF] employed in the traditional repeated measures ANOVA. However, such an adjustment [...] can be viewed as a generalization of the conventional [DoF] in the heteroscedastic case.*" [66]

Role	Arousal		Valence		Dominance		Enjoyment		Presence		IEQ Single Item	
	Mdn	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*
HMD	6	4–6	6	5–7	5	3–6	7	6–7	5	4.17–5.5	9	6.5–10
non-HMD	5	4–6	6	5–7	5	4–6	6	5–7	4.67	3.92–5.17	8	7–9
	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p
Main effect	0.04	0.85	0.00	0.99	0.42	0.52	1.40	0.24	0.66	0.42	0.03	0.86
	Control		Challenge		Cogn. Inv.		Emot. Inv.		Real-World Diss.		IEQ Sum	
	Mdn	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*
HMD	5	4.4–5.8	5	4.5–5.5	6.22	5.56–6.44	5.67	4.67–6.33	5	4–5.86	174	150.5–182.5
non-HMD	5	4.4–5.6	5.25	4.5–5.5	6	5.28–6.62	5.5	4.92–6.17	4.86	4.14–5.64	165	149.5–184
	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p	$F_{ATS}(1)$	p
Main effect	0.00	0.99	0.65	0.42	0.00	0.95	0.00	1	0.01	0.93	0.00	0.97

Table 2: PX results were positive and did not differ significantly between player roles.

Condition	Arousal		Valence		Dominance		Enjoyment		Presence		IEQ Single Item	
	Mdn	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*
NBI	5	4.25–6	6	5–7	5	4–6	7	6–7	4.67	3.92–5.67	8	7–9.75
BI	5	4–6	6	6–7	5	4–5	6	6–7	5	4.17–5.33	8	7–10
BI-A	6	4–6	6	6–7	5	3.25–5.75	6	5.25–7	4.67	4.21–5.13	8	7–9
BI-V	6	4–6	6	5–7	5	4–6	6	6–7	4.83	4.08–5.33	9	7.25–10
BI-AV	6	4–6	6.5	5.25–7	5	3–6	6.5	6–7	4.83	4.08–5.33	8	7.25–10
	$F_{ATS}(3.30)$	p	$F_{ATS}(2.86)$	p	$F_{ATS}(3.10)$	p	$F_{ATS}(3.34)$	p	$F_{ATS}(3.35)$	p	$F_{ATS}(2.80)$	p
Main effect	0.62	0.61	0.88	0.44	1.31	0.27	1.14	0.33	0.42	0.76	0.75	0.51
	Control		Challenge		Cogn. Inv.		Emot. Inv.		Real-World Diss.		IEQ Sum	
	Mdn	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*
NBI	5	4.6–5.4	5.25	4.75–5.5	6.17	5.61–6.5	5.58	4.67–6.29	4.71	4.04–5.57	170.5	150–183
BI	5	4.25–5.4	5	4.5–5.5	6.06	5.36–6.64	5.75	4.83–6.29	5.07	4–5.82	169.5	148.8–180
BI-A	5.1	4.45–5.6	5.25	4.56–5.75	6.17	5.44–6.44	5.58	5–6.29	4.86	4–5.43	169.5	151–179
BI-V	5	4.4–5.75	5	4.56–5.25	5.89	5.33–6.33	5.58	4.88–6.13	5.14	4.04–5.86	168	147.2–182.5
BI-AV	5	4.4–5.8	5.13	4.5–5.5	6.22	5.58–6.56	5.5	4.88–6.25	4.71	4.14–5.71	169.5	152.2–184
	$F_{ATS}(3.59)$	p	$F_{ATS}(3.61)$	p	$F_{ATS}(3.51)$	p	$F_{ATS}(3.01)$	p	$F_{ATS}(3.82)$	p	$F_{ATS}(3.06)$	p
Main effect	0.71	0.56	2.07	0.09	0.65	0.61	0.32	0.81	1.48	0.21	0.25	0.86

Table 3: PX results also similarly positive across conditions.

VR Experience	Valence		Emotional Inv.		Challenge		Real World Diss.		IEQ Single Item		IEQ Sum Total	
	Mdn	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*
with VR Experience	6	5—7	5.33	4.33—6	5	4.5—5.5	4.5	3.86—5.71	7	6—9	162.5	147—180.5
without VR Experience	6.5	6—7	6	5.33—6.54	5.25	4.75—5.5	5.14	4.54—5.89	8	7—9	175.5	163—183.25

Table 4: Prior VR experience had effect on some factors of PX.

	Baseline (resting)		*NBI*		*BI*		*BI-A*		*BI-V*		*BI-AV*	
Measures	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*	*Mdn*	*IQR*
Average HR	76.80	72.94–78.87	79.42	72.51–84.22	78.60	75.9–83.95	76.48	73.5–84.41	77.15	74.1–83.78	77.38	75.37–84.32
Variance in HR difference to Baseline	–	–	10.48	8.9–11.93	9.6	8.64–10.71	8.33	7.74–12.47	9.84	7.62–12.3	10.22	7.8–12.32

Table 5: HR measurements per condition (bpm, non-HMD player only).

therefore tested to see if participants' prior VR experience had an effect on their PX. For this between-participants comparison (with vs. without VR experience), we conducted Mann-Whitney U tests. The VR experience was analyzed for all participants (both roles, not separately) because of the subsample size. Data points were treated as independent as players within dyads experienced distinct gameplay (i.e., task, medium, physical engagement). The results indicated that having VR experience significantly affected the SAM valence scale, U=2185, p=0.04, d=-0.30, resulting in higher scores for players without such experience with the technology. Furthermore, there was a similar significant effect of VR experience on five subfactors of immersion: emotional involvement (U=1779, p<0.001, d=-0.69), challenge (U=2179, p=0.044, d=-0.34), real-world dissociation (U=1886.5, p=0.001, d=-0.54), the single-item immersion (U=2020.5, p=0.008, d=-0.54), and IEQ Sum Total (U=1995.5, p=0.007, d=-0.55). The descriptive statistics can be found in Table 4.

6.2 Heart Rate Analysis

This section reports analyses carried out only for the non-HMD player role. The descriptive data (including the baseline measurements prior to gameplay) are listed in Table 5; this includes both the average HR, and the variance in participants' difference to their baseline HR.

We conducted a one-way repeated measures ANOVA on the averaged HR data. There was no significant effect of condition on average HR. We then calculated participants' variance metric, meaning the difference of their HR measurement per condition respective to their own baseline measurement. Following guidelines by Wobbrock and Kay [94] for non-parametric test assumptions, we conducted a Friedman's ANOVA across the gameplay conditions; there was no significant effect of condition.

6.3 Learning Effects Across Playthroughs

To check for learning effects in the data, we conducted the following tests to determine how PX was affected across the five different playthroughs based on the order in which players experienced the game. For scope, we only report the main and post-hoc tests; the descriptive values and visualizations of the significant differences are presented in the supplementary materials.

Heart Rate Metrics. We conducted one-way repeated measures ANOVA with the within-subjects factor of playthrough order to explore learning effects on participant HR. There was a significant main order effect on average HR, $F(4,56)$=11.93; p=0.001, η_p^2=0.11. Bonferroni post-hoc tests showed that average HR was significantly higher in the first condition when compared to third, fourth, and fifth playthroughs, as well as the second in comparison to the last.

Player Experience Questionnaires. There was a significant order effect on presence, $F_{ATS}(2.74)$=9.72, p<0.001. Post-hoc, the first playthrough differed from all other playthroughs; later playthroughs displayed an increase in presence. Furthermore, a significant order effect on enjoyment was observed ($F_{ATS}(2.88)$=8.21, p<0.001). Here, the first playthrough also differed from all subsequent playthroughs, displaying a similar increase over time. Moreover, there was a significant order effect on the SAM valence scale, $F_{ATS}(3.22)$=8.43, p<0.001. Post-hoc comparisons revealed the same pattern: the first playthrough was significantly lower than all subsequent playthroughs. The SAM arousal scale also showed a significant order effect, $F_{ATS}(2.72)$=4.05, p=0.008. Here, though, the first condition again scored lower compared to the second and fourth playthroughs. The SAM dominance scale was significantly lower for the first condition compared to the last condition, $F_{ATS}(2.17)$=4.81, p=0.007.

There was a significant order effect on several immersion subfactors, displaying similar increases in scores over time. Cognitive involvement was significantly lower for the first playthrough than all others, as was the second for subsequent ones, $F_{ATS}(3.04)$=11.51, p<0.001. Emotional involvement was significantly lower for the first playthrough than when compared to the fourth or fifth playthrough, $F_{ATS}(2.67)$=6.36, p<0.001. There was a significant order effect for challenge, $F_{ATS}(3.21)$=3.99, p=0.006, which post-hoc comparisons indicated lay between the first playthrough compared to the third and fourth playthroughs. The order effect was also observed on control, $F_{ATS}(3.06)$= 4.82, p=0.002; the first playthrough was again significantly lower than all other playthroughs. For IEQ Sum Total, the first playthrough was again significantly lower than all subsequent playthroughs, $F_{ATS}(3.33)$= 7.83, p<0.001. For real-world dissociation there was also a significant order effect, $F_{ATS}(3.80)$=3.40, p<0.01 (disappeared after post-hoc), as well as an interaction order effect with player role, $F_{ATS}(3.80)$=5.31, p<0.001. The interaction effect shows that real-world dissociation tended to increase for the non-HMD player (first playthrough: *Mdn*=4.14, *IQR*=3.93−5.07; last: *Mdn*=5, *IQR*=4−5.57), while there was a slight decrease for the HMD player (first: *Mdn*=5.29, *IQR*=4−5.71; last: *Mdn*=4.43, *IQR*=4.14−5.79).

No significant effect was found for order effect and role on the single-item immersion score.

6.4 Summary of Quantitative Findings

Our quantitative results show that PX metrics (i.e., affective state, enjoyment, presence, and immersion) were comparably high for both players, with no significant difference between player roles or conditions and their interaction effects. Further, our physiological measures did not yield a significant difference across conditions.

We also observed novelty effects of VR for some subcategories of quantitative metrics (see Table 4), indicating higher values for the players without prior VR experience. Finally, learning effects results show how PX—for most of the factors—improved over five playthroughs (see supplementary materials).

6.5 Interview Findings

We report quotes based on the session number of the participant pair and add their role (HMD as *h*; non-HMD as *nh*) as subscript (e.g., $\mathrm{P1}_h$ for the HMD player of the first pair). Our thematic analysis reflects the quantitative results in that both roles were considered "*enjoyable*"-$\mathrm{P5}_{nh}$, and "*engaging*"-$\mathrm{P4}_h$ and confirms the increase in positive PX over playthroughs. The results also support positive impacts of multiplayer interaction ("*I like the social aspect a lot [...] I have that feeling of achieving something together [...] so it was really cool to have to experience together and achieve that together.*"-$\mathrm{P2}_h$). Additionally, we constructed four themes through an analysis of our inductive coding.

6.5.1 *Theme 1:* ***Collaborative asymmetric VR experiences require time for adaptation because of the challenge of communication and coordination, yet this is also a key factor in their appeal.***

Players found communication essential to their enjoyment and to succeed in the game: "*Without [it], I think the game wouldn't be as much fun*"-$\mathrm{P7}_{nh}$ and "*it was necessary at all to play the game. And for me it made it more fun*"-$\mathrm{P2}_{nh}$. Developing strategies for effective communication, however, took some time: "*I would* *also give some adjustment trial, but not to the virtual reality, but to the team players, [...] getting to know each other and how well they can perform how well they can play together, because I think this is requires time as well*"-P5$_h$. This also explains the increase in enjoyment over time: "*the engagement kind of rose with, with playing time [...] So I got more engaged because I knew what I was doing at some point*"-P7$_h$.

Participants attributed several factors to their inter-communication (and the attached learning curve). They described these as part of the experience's appeal: first, the dynamic characteristics of each gameplay depending on their co-player ("*it's another degree of input or another degree of output, which is pretty interesting, pretty dynamic because I'm pretty sure when I would be playing with someone else [...] the experience would be pretty different*"-P4$_h$); second, the reliance on another person ("*you have a team mate, who you have to have very good communication with, and that could also be a weakness because your team mate is entirely dependent. I mean, the person who's wearing the VR is dependent on the person who's on the screen [...] it works as both a strength and a weakness*"-P5$_{nh}$). Third, some HMD players attributed enjoyment to having a human co-player: "*if we imagine that the game itself is giving me these orders like consistently and without variation that would be I think less interesting than a real human giving me these orders and varying a strategy, varying the wording [...] If all these commands were coming from an onscreen user interface or like audio recordings, there were not dynamic or anything, it would be probably way more boring*"-P4$_h$. However, for some HMD players, their co-player as a voice entity reduced their immersion in VR: one mentioned it was "*a little bit difficult to focus on the voice*"-P5$_h$, while two mentioned it as a potential break in immersion, and a reminder of the artificiality of the game: "*this communication is something that is to me, not part of the game, but more part of the physical environment I'm in*"-P4$_h$ and "*I hear him [non-HMD role] through the room rather than through the HMD. So I was still connected to the real world so the immersion suffered a little bit, but enjoyment was increased because I had social interactions while playing*"-P3$_h$.

6.5.2 Theme 2: ***Asymmetry in interface and information can affect players' perception of agency, dominance, and control in varied ways. However, this is not necessarily a bad thing, and it induced feelings of interdependence.*** Our players demonstrated different opinions of which player role had more prominent agency, dominance, or control in the game. There was, however, a greater tendency towards the perception that non-HMD player had more control. Players that attributed greater agency/control to the HMD player based this on the explicit interaction with the game world: "*[As the non-HMD player] I never really felt like I was actively engaging in the game cause I had no control in terms of the immediate environment because the HMD player is like the intermediary. So because of that, I felt like I was maybe not as immersed as he was*"-P1$_{nh}$. However, a larger number of HMD players felt that agency/control had been transferred to the non-HMD player through the asymmetry of information: "*First, I thought I would have the more active role [as the HMD player] because I have to do the actions but in the end, I was more like the actor and he was commanding me. I basically just followed the instructions*"-P2$_h$, and in contrast "*[as the non-HMD player] I felt like Houston on the mission control, telling him what to do [laughs]*"-P3$_{nh}$. Moreover, one player made a distinction between dominance and importance: "*I don't think my role [as HMD player] was the dominant one but it was like the key role so the game can continue. I think this was my success if we die or not*"-P5$_h$.

Regardless, players' perception of this asymmetry in agency or control did not necessarily translate to inadequate PX. Some HMD players enjoyed that giving up control was accompanied by a more physically active role ("*I had a lot of fun playing that, like moving through the maze, watching out, talking in the right moment. I felt really like adventurous and cool [...] so I really liked that I couldn't see anything and like move through the maze*"-P7$_h$). Inversely, the greater control of the non-HMD player role was also perceived as "*engaging, but very stressful*"-P1$_{nh}$, "*more challenging and more unsettling*"-P7$_{nh}$. Some of the non-HMD players felt a strong sense of responsibility due to their game role, which not all of them appreciated: "*I would love to be HMD player, because [my non-HMD role] is so much responsibility*"-P6$_{nh}$.

Further, it led to interdependence, as expected based on our design and on theoretical work; both player roles reported this: "*I couldn't have moved through the maze without my partner telling me what to do [...] I needed the guidance*"-P7$_h$, "*I felt kind of bad sometimes because for most of the feedback variants, I was pretty excited and thus, we had to deal with a lot of the lasers [...] but I think we manage quite good*"-P7$_{nh}$, and "*It adds to the fun that you [as non-HMD player] are not the person who is controlling everything. you have to make sure that the person you're a good partner to, the communication has to be good enough for the game to be successful [...] everything is not in your control and it's fun*"-P5$_{nh}$. This perception of the interdependence of roles reflects on the different but complementary way that the game incorporated their strengths: "*adding skills to each other [...] you're playing kind of different games*"-P7$_h$.

6.5.3 Theme 3: ***There is high subjectivity in whether players notice biometric influence, especially HMD players. But when present and noticed, biometric influence affected PX (enjoyment, immersion, stress) and performance.*** Whether players noticed the biometric influence when it was present was highly subjective, which may explain the lack of effects found in the quantitative results. Particularly the HMD players, lacking direct visualization of the biometric feedback, reported that while their engagement was high, they did not notice an effect of the biometric influence condition: "*for me, there were no really differences in the conditions because I couldn't see lasers or anything*"-P3$_h$. However, the interviews provide insight into the effects of biometric influence when it *was* present and noticed.

Some players reported an effect—albeit indirect—on performance: "*when she was tense, there were more lasers coming and I was like dying all the time [...] And like when she was tension, for instance, you can say like left instead of right. Like she can mix the directions*"-P6$_h$. We also observed some players trying to calm down with breathing exercises during the game. More commonly, players (particularly non-HMD players) mentioned an effect on PX, largely immersion: "*[biometric feedback] definitely helped with the immersion just because it felt more real [...] you were aware that you as a being even though you're not in the virtual environment yourself, I'm just looking at the screen but you have—your body has an impact on the game*

[... I] was constantly aware that I am triggering the laser basically, which was exciting for me"-P7$_{nh}$. This biometric influence was often perceived as both immersive *and* stressful: "*Game engagement was very high. The experience was incredibly stressful [laughs]*"-P1$_{nh}$. For some players, effects on their co-player's emotions then, in turn, affected their own: "*when she gets more excited, I also felt more excited and I think it was more enjoyable both for me*"-P5$_{h}$.

6.5.4 Theme 4: ***Preferences for the modality of indicators of biometric feedback for the non-HMD player are highly subjective, whereas some HMD players surprisingly extracted biometric feedback information from the non-HMD player's voice.*** There was no consensus among non-HMD players about the best kind of modality for biometric feedback. Some found the biometric feedback useful for self-regulation ("*help[ed] me to focus on keeping my breath low and trying to be not that excited*"-P2$_{nh}$). Many of the others, however, either did not notice the feedback or found it had an opposite effect on them: "*they made it worse because I was aware that I'm being excited, which made me more excited [...] it was not helpful, but it was interesting*"-P7$_{nh}$. For each of the different biofeedback modalities in our study conditions, a participant preferred it or disliked it.

However, a noteworthy aspect of the interviews is that some of the *HMD players* also remarked on biofeedback they perceived. They interpreted their non-HMD player co-player's emotional state from their voice, and reacted accordingly: "*when my coplayer panicking, I can hear it from his sound. So it will affect me at a time. It's like, okay, I have to go, go to this path faster*"-P1$_{h}$. They attributed this specifically to the tone of voice: "*I could sense her excitement from the voice and the voice of tone basically*"-P5$_{h}$.

7 DISCUSSION

In the following, we discuss the key takeaways about integrating a non-HMD player into a VR game, the impact of interdependence on player agency (including that neither high nor low agency is necessarily good or bad in our scenario), and how biometric interdependence can affect players' immersion and experienced stress.

Integrating a Non-HMD Player in a VR Game. Our VR game included the non-HMD player through some design choices with which we gave the non-HMD player a way to impact the VR world, and perceive results thereof. This impact was largely implemented by facilitating SI between the HMD and non-HMD player (i.e., through difference in information and difference in player capability) so that they have to communicate and strategize together. Further, we introduced and explored a novel type of interdependence—biometric—between the players. Hereby, non-HMD player's HR affected game difficulty (triggering lasers that the HMD player had to avoid). Our psychometric results suggest that this overall design worked well, successfully extending the findings of previous work [34, 35] to integrate a non-HMD player into a VR experience so that *both* players achieve high enjoyment and presence without a significant difference between player roles. All psychometric PX factors were not significantly different between player roles: presence, enjoyment, immersion, and affective states were highly rated for both players. While biometric interdependence did not impact quantitative PX (possibly because of a subtle implementation and high subjectivity in players' perception thereof), the thematic analysis shows it has promise as a game mechanic to impact immersion and stress (as we will discuss below). Thus, despite the difference in display (HMD vs. non-HMD) and task (executing actions vs. guiding them), both players shared a strong sense of engagement and presence. Further, the interviews highlighted the communication and interdependence between players as contributing to PX regardless of players' experienced high or low agency.

Further, our results indicate positive social interaction between both player roles, supporting our psychometric findings. We argue that this stems from both interdependences featured in our game. The difference in information in particular forced players to communicate and strategize. In future work, it would be interesting to explore effects of the game on players' experience of loneliness (as explored by Liszio et al. [51]), and their relationship between each other (as reported in an asymmetric game by Zhou et al. [96]).

We further observed novelty effects of VR, which should be considered in asymmetric VR games but also VR research in general: whether participants had prior VR experience affected their immersion and affective state. With low to medium effects sizes, a lack of VR experience elicited higher immersion and valence (arousal, dominance, presence, and enjoyment were unaffected). We speculate that these effects may occur because novices can be more distracted and potentially overwhelmed by the first exposure to VR [49]. This may be of interest to VR researchers, and motivates future research into exploring how to design interaction in VR to remain immersive and engaging over time, and even for players already familiar with the medium. Nevertheless, we note that the exploration of this dynamic in VR research is rather limited; it largely reported only as demographic information of participants and not investigated further. One of the few works that explore longitudinal VR usage found that while novelty wore off, immersion did not [72]; our results reflect and build on this finding for a shorter timeframe.

Interdependence Affects Agency—But Perceptions Thereof Vary. The SI in our game carried the risk of either player experiencing a lack of agency because the power between their roles is imbalanced. We had suspected that the HMD player might experience lower agency: synchronizing with the non-HMD player's instructions required concentration, timing, and physical interaction, yet they largely virtually enacted the non-HMD player's instructions, and had access to less information about the game world (i.e., the approach of lasers or trap layout). Nevertheless, most HMD players reported a positive PX and many saw their role as key to the game.

Inversely, while many non-HMD players described their experience in terms of high agency or control, this was not always an inherently positive factor: high agency was also experienced as strong responsibility towards their co-player and the outcome of the game, sometimes resulting in stress. This stress was mentioned in the context of both types of interdependence, but particularly often in the context of BI (which we discuss in more detail below). Overall, we found that players' perception of agency was strongly affected by the asymmetric design and resulting interdependence—however, "low" vs. "high" agency is not inherently bad or good, respectively. Therefore, our work contrasts with the identified design factors of Gugenheimer et al. [34], which suggest to create an equal "power distribution" between the players, especially for collaborative gameplay. Based on our findings, we argue that uneven power distributions can also create enjoyable gameplay experiences, and in fact, individual playing motivations may determine whether players prefer what they perceive as high or low agency roles. This could in part be linked to which role players feel more competent at and comfortable with, relating to players' need for competence [19, 77]; alternatively it could be linked to players' familiarity with either interface [78]. Finally, we note that our findings reflect on work by Benford et al. [4] on the value of uncomfortable interactions in human-computer interaction. Games constitute suitable scenarios for such interactions, as they often provide an environment for negative or unusual emotions [8] on purpose, and so power imbalances in games make sense as a mechanic to explore for the creation of engaging experiences.

Biometric Interdependence as a Game Mechanic. While BI did not impact quantitative measures, the interviews indicate high variance in whether participants perceived it within the game. There were no significant effects of biometric feedback (or the modality of its representation) on PX. We attribute this to a too subtle implementation of BI, and perhaps also a matter of requiring prolonged exposure to the stimuli (see limitations below). The results are perhaps unsurprising for the HMD players who had no biometric feedback; a less subtle implementation (e.g., increasing lasers and giving HMD players information about their co-player's biometric status) could yield different results. For players who did perceive the BI, however, interviews and gameplay observations revealed several interesting ways in which it did impact PX. Players that felt more immersed because their physiological state had an impact on the game world can be interpreted as a clear example of agency [61]: agency increased as they had a way to noticeably affect the game world, thus positively impacting their immersion. Further, in many cases, players reported a mirroring effect due to BI, as HMD players noticed the non-HMD player's increased excitement and/or stress. Interestingly, however, in addition to the designed biofeedback provided to the non-HMD player, some HMD players *also* perceived biofeedback about their co-player based on their tone of voice. Voice communication (specifically, hearing the voice of a bystander) has been reported as a factor of potential comfort for VR users [75], and has been used as a VR input mechanism [46] in prior work, but otherwise is largely unexplored in VR research.

Finally, while our results show promise for employing BI as a game mechanic in VR, we note that learning effects for HR must be considered. In our study, average HR dropped significantly after two playthroughs, indicating that participants were calmer after having played the game twice. This finding informs future research: it motivates letting players experience VR games twice prior to testing an experiment (if possible), as early measurements may be biased by an increased HR. Further, we conclude that more longitudinal data is necessary to measure and explore VR experiences (of which there are few examples [60, 71, 72]). This may be particularly relevant for game mechanics that include physiological measures and BI.

7.1 Limitations

We note that physiological measures can introduce some limitations. As stated above, there was a learning effect for HR measurements after two playthroughs. Future experiments should adjust their baseline dynamically or re-sample it after longer exposure. We also cannot rule out that some participants may have already been excited during the baseline measurement, introducing higher arousal as bias. Additionally, minor changes to physiological data could have been missed due to the sampling rate of the Empatica E4 device. Largely, however, we assume that the design of the biometric feedback was simply too subtle to make a strong impact—especially for this time frame of stimuli exposure. We will have to re-iterate on the design to refine this.

As roles were not switched within pairs, we cannot prove that PX would have stayed the same between roles in a within-participants design. While our study works as a proof-of-concept that a VR game can be designed to create comparable PX even for a non-HMD player, future work will have to explore the differences in these kinds of player roles in more detail (for example, when players take turns with the roles, with different degrees of directional dependence, or across different game genres).

The distribution of traps did not change with the different playthroughs (i.e., it differed only by level). As such, players could learn the path through each level by heart and then expend less effort in navigating the grid (or instructing its navigation). This could have partially induced the learning effects. Moreover, our participants pairs knew each other, which could also introduce bias. However, this adds to external validity as this kind of local game setup would very likely be played by players that are familiar with each other.

In terms of methodology, we employed a triangulation-convergence approach to leverage advantages of both quantitative (e.g., generalisation) and qualitative findings (e.g., deep details) [18]. However, combining the different types of data is difficult and can introduce bias. Further, we conducted the interviews as an extension of the study, and then conducted the analysis afterwards. While no new codes emerged in the final analysis session, it is possible that new codes would have occurred for a larger sample (cf. [12] on saturation in thematic analysis). Finally, we note as a statement on reflexivity [5, 65] that the two authors who conducted the thematic analysis have a cognitive systems and computer science background, respectively. As both have prior experience of varying duration with VR and VR games, this may have introduced bias into the theme development phase.

8 SUMMARIZING CONCLUSION

This work introduced an asymmetric game design that integrates a non-HMD player into a VR experience. Our goal was to increase PX for *both* the HMD and non-HMD player via SI and BI. In a user study (N=30), we explored effects of resulting interdependences on PX and found that SI induces a comparably high amount of enjoyment, presence, immersion, and affective state for both player roles. BI and audiovisual indicators thereof were subject to learning effects and need more longitudinal data for a comprehensive analysis of its impact on PX. However, the qualitative findings point towards effects on both players' experience in terms of immersion and stress. Moreover, our interviews show that interdependences resulting from asymmetric game design affect player agency—yet also, neither high nor low agency is inherently perceived as good or bad in our game prototype and study.

Our results have shown that it is feasible to integrate a non-HMD player into a VR experience and achieve comparable PX levels to the HMD player. Further, we discussed design implications for future asymmetric game designs, by showcasing the potential of imbalanced strategic asymmetry in games, emphasizing the importance of agency for interdependence, and demonstrating the use of biometric asymmetry as a game mechanic. Our work can thus inform future VR developers as they create immersive asymmetric VR games and experiences, to create multiplayer engagement and shared social environments across interfaces.

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