Enabling Users in Virtual-Reality-Based Human-Centered Design Processes: The Role of Objective Validation on Acceptance, Usability, and User Experience

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Abstract. Involving stakeholders and users into design processes has been an ongoing effort to align product expectation with a novel value proposition to users. Utilizing virtual reality to find what users need and want can be crucial to reduce costs while gaining insights into their needs and demands for products that have not yet been physically produced. We propose a phase-segmented simulation design to guide users to find their preferred design in an iterative reevaluating objective. To facilitate the guidance, we introduced an objective validation as visualized overview to add information for users to evaluate their own design decisions. Our study evaluates the process in terms of acceptance, usability and user experience regarding the validation phase and simulation experience as a whole. Our results concluded that the simulation achieves high usability (System Usability Scale > 80.0 points) and positive user experience (User Experience Questionnaire mean=1.63). Finally, we look at the limitations of the study and improvement in comprehensibility and how further information can improve the user experience

Keywords: Human-Centered design, Usability, User Experience, Human Factors, Virtual Reality

1 Introduction

The advancements of virtual reality (VR) application have been seen a surge in the last decade with more and more research and industrial applications. Fields including medicine [1, 2], education [3][4–6], industry [7] and the research context itself undergo rising usage of modern and affordable VR gear to test, simulate and experience different scenarios in virtual environments. The advantages of embracing immersive experiences have been shown in multiple studies and analyses [4, 8] including faster development in industrial applications and cost-effective testing and prototyping. Combined with the increased trend and effort in society to include all stakeholders into a development process [9, 10], this suggest that further user involvement in development processes, e.g. with support of VR technologies, can elevate people to be an active part in the design and testing cycle.

Beyond enabling immersive experiences, VR tools have also evolved to support independent design workflows, allowing users to create and iterate without the need for external collaborators. Spatial interaction tools and adaptive design environments further empower users to navigate complex design tasks independently, fostering innovation and efficiency [11]. This shift toward user-driven VR design raises questions about how virtual assistance such as embedded guidance and interactive toolkits can enhance the creative process. Understanding the impact of these features is crucial in developing more effective VR design environments that empower users to explore, prototype, and refine their ideas intuitively.

1.1 User Involvement in Virtual Reality

Enabling more productive tasks in virtual reality has been an ongoing effort in science and industry due to its efficiency, low costs and reproducibility. While user-centered design defines practices in which users are at the core of development, methods like participatory design (PD) involve users directly during all design stages. This, in return, increases the likelihood of the product meeting users' expectation. The cooperative and complementary work between experts (e.g. design experts, developers) with users (which as the product consumer can be titled an expert in their regarded domain), more ideas can unfold and the inclusive environment enables an overall better outcome in terms of customer expectation and need.

Key principles of the PD process include actively integrating users into complex design development cycles by creating processes to empower users during decision makings, in active involvement strategies and learning stages [12]. While in a co-design VR space, more principles are been embedded such as mutual learning and power redistribution, for single-user applications users may have to work on their own. These use-cases can be important if time and expertise availability are limited. In order to reach the counterpart in a collaborative design process without having a second person present, an automated and objective entity would be useful. This can help users receiving valuable input, give them new ideas and preferably communicate the consequences of the user's design decisions. Because of the replacement of a human-cooperative counterpart, we will define the term knowledge-augmented design process (KADP) to differentiate from the predefined participatory design.

KADP, especially in VR, arises from the challenge that virtual environments necessitate multiple actors to work on the same simulation to achieve their task which is the same principle in the real-world application. However, we believe that we can utilize the immersion in a way that users can work on more complex tasks and support them by creating an appropriate virtual work flow. Users could interact with other knowledge bases to learn and get support from these to achieve their task. This could not only bring an overall more neutral or holistic point of view into the communication but also enables a more cost-efficient and time- and space-independent approach.

1.2 Integrating Assistance into KADP

VR design tools and methods are gaining more recognition due to its lowering cost of hardware and applications and therefore increased interest and accessibility. In recent years, research has been done with integrating participatory design processes including two actors simultaneously working in a virtual environment [13], new VR tools have been assessed in industrial design settings [14] and researchers explored the telepresence, immersion and interactivity in users designing new hotel room designs [15]. There also has been work introduced highlighting the importance of assistance in during VR task execution [16, 17] to keep users immersive while providing sufficient support and information. In previous work, we also presented a phase-oriented design process to show potential frameworks for researchers and users to evaluate design decisions [18]. The importance of assisting tools in VR can be argued to be important as it enables users to drive design sessions and help them in the absence of another expert entity. It can help users to better navigate the simulation, develop new ideas and learn new perspectives and concepts through the learning process.

1.3 Implementation of the Validation

To facilitate a simple KADP solution, we integrated an objective validation into an existing four-step-development cycle for PD in VR. The procedure is a continuation of our previous work [18] which comprised two distinct phases where each phase serves a different user interaction and experience. The first phase is the scenario phase which is based on the principle of scenario-based testing in industrial applications [19][20]. This introduces the design objects in an appropriate simulated environment to encourage users interacting with it like in a real-life scenario. The second phase introduced the agent simulation and was therefore named the validation phase. For that, we have designed the view for the user simply by providing an bird's-eye view over the scenario to evaluate the distribution of other travelers (see Figure 1).

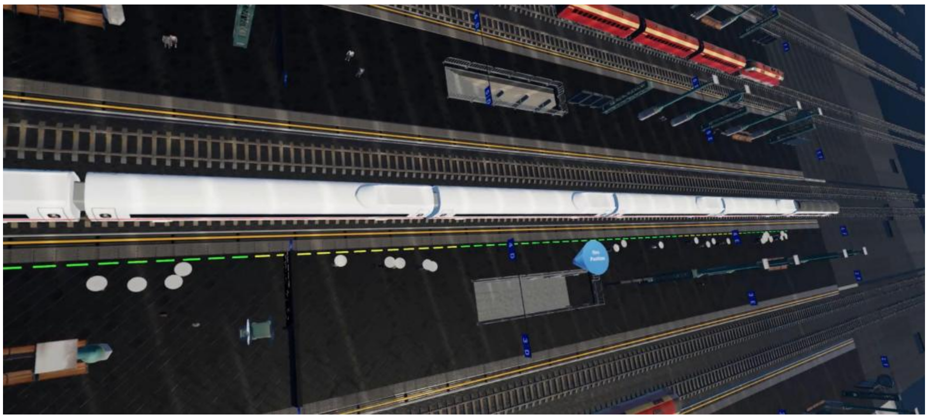

Fig. 2. Participant view in the validation phase (agents highlighted with gray circular markers).

To facilitate a validation phase with objective-driven information, we implemented 50 agents mimicking the behavior of other travelers. The agent simulation is based on a simple behavior tree including behavioral animations such as standing and walking. Agents are programmed to start to walk in the moment the scenario phase starts and move to their designated target location on the platform which is calculated based on the current design parameters. The design decision influences the distribution bias which in return increases the likelihood of agents moving to the green area of the light band. This approach introduces minimal noise to the end location of each agent. Movement speeds of the agents were also randomized within a predefined range to avoid clumped crowd formation while maintaining a naturalistic flow of people walking.

1.4 Study Objective

As a lack of appropriate methods and framework for VR design sessions exists, we want to contribute to the field by extending our previous research with the goal to integrate a more immersive assistance solution. In this study, we want to evaluate the introduction of the validation phase and its impact on users' decision during the simulation phase. To cover the basis, our goal was set to test the simulation based on acceptance and user experience while focusing onto the perceived experience with the validation phase. For that, we chose a travelling scenario on the topic of overcrowding trains and how information elements can help positioning on the platform.

Overcrowding on train station platform is a common challenge in the railway sector for years [21–23]. While there exist different solutions from prediction models, and smartphone-based data aggregation, we are using this information demand use-case to immerse participants into the scenario of crowd congestion.

2 Methods

The study was accomplished as within-subject design with one independent variable which is placed in the validation phase. The control group (CG) experienced a randomized agent simulation where agents evenly distribute along the platform which still forms a line parallel to the arriving train but no influence from the design parameters. In the experimental group (EG) participants received the aforementioned agent simulation which is influenced based on the design choices.

2.1 Participants

We invited a total of 46 participants (N=46, female=13, male=33) with an average age of 26.9 (standard deviation [sd]=6.2). The sample size was split into two groups where 26 participants experienced the condition with the influenced agents (EG) while the other 20 experienced the randomized agents (CG). The average height of participants was 177 cm (sd=10.9) and height differences were kept when entering the simulation. In a demographic questionnaire (introducing a 5-point-likert scale where 1 is "very little" and 5 is "a lot") we assessed that most participants had some experience with gaming products (mean=3.41, sd=1.24), VR experiences (mean= 2.48, sd=1.09) (i.e. experience in VR which also includes CAVE-type VR) and specifically head-mounted displays (mean=2.39, sd=1.81).

2.2 Simulation Environment

The primary environment of the simulation is based on the main station in Cologne, Germany, which consists of 12 platforms. The station is designed as an underfloor station without shops or other significant areas of interests as participants are only at the underflow for a short period of time. Participants started the scenario phase right at the stairways and had no interactions in the underpass of the station. The upper level of the train stations inhabits a few static actors standing on the platform while the rest are surrounded by the participants when the simulation starts. Three other trains have been also added to the other platforms to fill the environment.

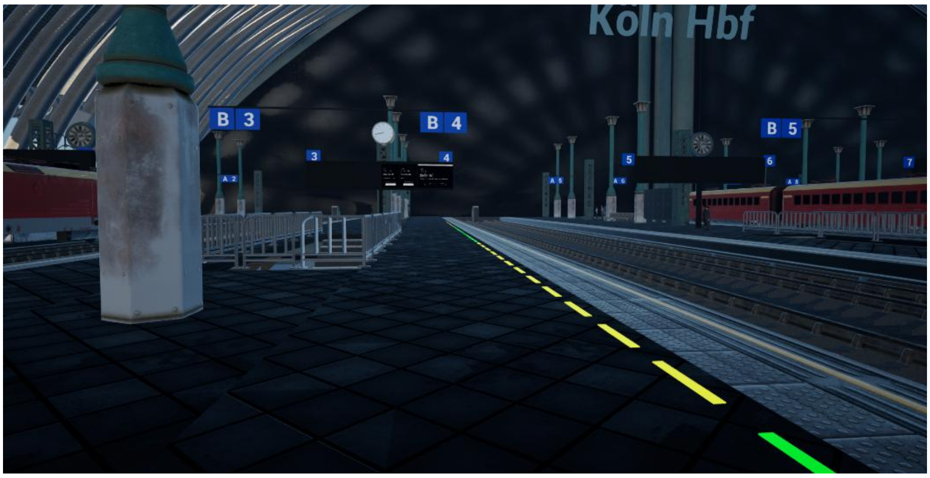

Fig. 2. Screenshot of the platform in the simulation (light band shown as the diagonal dashed line in yellow and green).

2.3 Design Object

We set up two visual design objects for participants to interact with and design. The first one is an information sign containing all relevant information about the next incoming three trains. The design is loosely modeled after the information signs implemented on the recently renewed information sign in Germany since 2022 [24]. We added eight visual information icons for participants to choose (see Figure 2). Design options could be combined or left out entirely. The squares within the train silhouette were displaying three different colors (red, yellow, green) depending on the congestion per train compartment. The right part of the information sign with the next two incoming train information were only for static visualization and could not be modified. Participants were able to select up to all symbols (multi-choice, no minimum required selection).

Fig. 3. Information sign display (optional elements highlighted in red).

For the second design object, we implemented a light band as a visual guidance on how congested each compartment of an upcoming train will be (see Figure 3). The general concept is based on a current pilot project [25], of which we implemented only the overall visual design and with no additional light animation and stages, e.g. transiting animation for arriving, departing or passing trains. The light band is stretched along the platform parallel to the train's trajectory and maps the entire length of the incoming train. Each diode of the light band indicates the congestion of the arriving train according to the same color pattern as the pictogram on the information sign (red, yellow, green). Participants were able to select one design type (single-choice). Selectable options were primitive geometrical shapes such as line, circle, square and star shape. The default shape of the light band is the line shape.

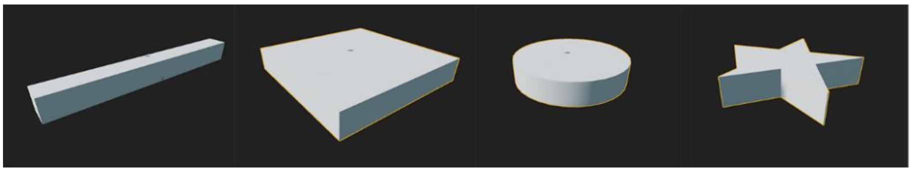

Fig. 4. Four selectable diode shapes for the light band.

2.4 Simulation Hardware and Software

We developed the simulation using Unreal Engine v5.3, built for Windows 64-bit operating system to create the environment and procedures. The simulation was run on a mid-performant PC with an RTX4060Ti (16 GB) which enabled a stable frame rate (>60 fps). To avoid loading time between different phases we used the concept of level streaming and shifted different phases out of user sight when introduced to the next phase. Participants used the head-mounted display (HMD) HTC Vive Pro Eye to enter the simulation and the complimentary motion controller for additional interaction with the UI menus and movement actions.

Data collection was handled by a small web socket server connecting the simulation client to a database management system. Questionnaires outside of the simulation were collected with the online tool SoSci Survey 3.4.02.

2.5 Movement and Interaction

To reduce wide movement on the physical plane while participants are immersed, we created an approximately 2m x 2m confined space in our lab, where participants were allowed to make at most one step in either direction as well as turn their bodies. Primary movement in virtual reality was done with the touchpad on the motion controller (Model HTC Vive Motion Controller 2.0). Interactions were also provided with the motion controller with two dedicated buttons (trigger and menu) to confirm a selection and open or close the design menu (in the design phase, see below).

2.6 Simulation Procedure

The table below shows an overview of the phases regarding estimated durations (see Table 1). The introduction can only be done once at the beginning of the simulation entry. After that, the phases are played in succession for every following iteration. The phases are detailed below.

Table 1. Simulation Design with (tilde indicates dynamic duration).

Phase	Estimated Duration (sec.)	Objective | Instruction
Introduction	~240	Introduction to movement, UI, task and design objects
Scenario	240	Immerse into traveler role to move and position on a platform
Validation	60	Overview (bird's eye view) onto all placed agents
Survey	~180	Filling out three questionnaires
Configuration	~180	Modifying design choices for both light band and information sign

Scenario Phase. The scenario phase consists of a self-oriented walking trajectory from the underpass of the train station towards to platform. As the phase already starts with participants being positioned near the stairs of the platform 4 and agents walking upstairs, participants follow the flow of people and position themselves on the platform after they have spotted both design objects on the platform. The train (Model ICE 3) arrives shortly before the timer ends. Participants do not need to enter the train as it fades into the next phase.

Validation Phase. The concept of the validation phase is based on the idea that users should be given a second opinion which is based objectively on the outcome of their design decision. For that, the validation phase is a minimal approach to visualize such influence by giving participants an aerial view onto the whole platform after the train arrived and all agents have been placed on their target position. Participants are transitioned during a fade-in/fade-out animation to the top of the platform where they hover over the platform to view all agents. Because of the greater distance between the participant's view and the platform, all agents have been added a visible circle above their head to better view the agent distribution.

Survey Phase. Although various surveys were carried out before and after the simulation, in-simulation questionnaires were also queried for each iteration. For that, we decided to develop a modular VR-friendly widget which pulled questionnaire data from a simple .csv data to display small questionnaires with at most 12 items. This was due to the current development process of the simulation but gave enough leeway to integrate more questionnaires with the advantages of VR interaction (in comparison to a web browser implementation).

Configuration Phase. The last phase is an open game-state where participants were able to walk freely on the station platform with no other agents. This was to give an unobtrusive view onto the platform while participants were able to open the design menu at will using the controller. The two design objects in consideration had different types of customization options and the design menu could be accessed via the controller. Furthermore, no time pressure was given during this phase as participants were able to re-enter the iteration when interacting with the menu options.

2.7 Assessment of Quantitative and Qualitative Data

Participants were instructed to fill out a pre-simulation demographic survey to gather some general data about the diversity of the sample. We evaluated three in-simulation questionnaires, NASA TLX-raw for task load, van der Laan Acceptance Scale (VDL) [26] for user acceptance and Simulation Sickness Questionnaire (SSQ)[27] after each iteration. The SSQ provides information about possible simulator sickness symptoms which may hinder user experience throughout the simulation. At last, the System Usability Scale (SUS) [28] and User Experience Questionnaire (UEQ) [29] were surveyed at the end of the simulation after participants put off the HMD. Both questionnaires cover the assessment of usability and UX of the overall simulation. It is important to note that we shortened the SSQ from 16 items to 9 items. This is due to our decision to include as little text space as possible for participants to read in VR. Additionally, the validity of the shortening has been shown in previous work to yield with similar results in an omnidirectional video setting (using hardware such as HMDs) while preserving the questionnaire's components [30].

2.8 Study Procedure

After the initial briefing and introduction in phase design, simulation environment, task and controls, participants were given the HMD to enter the simulation. During their first iteration, all design objects shown were set to default. This means that the information signs showed no additional information while the light band was set to the default mode (line-shaped). Congestion colors for the light band were always enabled.
When participants finished all four phases the simulation restarted the process with a new congestion preset. This could be repeated up to eight times before the researcher ended the simulation, instructing the participant to take off the HMD. Each next iteration introduces another preset of congestion which were expressed by the light band, information sign as well as agent behavior (for the experimental group). Congestion presets were not randomized per run between participants and included a variety of low, medium and full congestion presets. Participants spent on average 30.88 (sd=11.18) minutes in the simulation (excluding the familiarization phase). We also observed no participant taking a break by removing the HMD during the simulation.

The data collection and treatment were in line with the European Data Protection Regulation General. The study procedure was approved by the institutional ethic's board (Reference no. 18/23).

3 Results

3.1 Questionnaire Results

For the VDL, participants scored similar for all conditions with scale values which can be interpreted as good acceptance. However, the EG evaluated slightly worse as the simulation continues. TLX showed medium subjective task load with little deviation throughout all participants. All condition groups showed a decline in perceived task load for every subsequent iteration. The entire list can be found in Table 2.

Table 2. Questionnaire Results.

Questionnaire	VDL		TLX raw		SSQ		SUS	UEQ
Condition	EG	CG	EG	CG	EG	CG	Combined	Combined
Mean (sd)	3.61 (1.28)	3.61 (1.29)	3.27 (1.52)	2.88 (1.21)	1.19 (0.22)	1.26 (0.12)	81.90 (9.02)	2.63 (1.10)
Regression slope	-0.21	0.21	-0.13	-0.15	-0.02	0.01	-	-

The UEQ-short showed similarly high hedonic and pragmatic qualities. Because the UEQ is based on a 7-point Likert scale ranging between -3 and 3, the data (hedonic-mean=1.57 (1.14), pragmatic-mean=1.69 (1.06)) suggest an overall good user experience. The slightly higher pragmatic quality can be interpreted as participants finding the overall simulation usable and helpful.

3.2 Qualitative Results

An in-depth view into the qualitative analysis of the post-simulation interview showed a positive tendency towards the acceptance and inclusion of the validation phase and an overall positive evaluation of the simulation tasks with its phases. We evaluated the answers of all participants using the Mayring content analysis on two categories: Feedback on the validation phase and the overall simulation experience. The results are as shown in the following points in Table 2. There is a tendency in answers that participants preferred the validation phase (69.56% of all participants) and a similar positive preference onto the overall simulation experience (69.56% of all participants). It is important to note that a third of participants reporting positive agreement on the validation phase also added that they would include the validation phase but not because of the agent simulation but because of the visual overview was perceived as helpful.

When asked about the validation phase and its usefulness in design decision making, participants expressed uncertainty about the impact of their design choices on the agent distribution and are not sure how to interpret the validation as a whole. In case of the overall simulation, participants responded positively, agreeing that they enjoyed the simulation. In terms of feedback, some suggested more design choices, less idle time and a more comprehensible validation phase. When comparing both EG and CG, there is a difference in perceived usefulness of the validation phase. Participant in the EG had an overall more positive experience with the validation phase and simulation experience. 15 Participants who agreed on having a positive experience with the overall simulation also responded positively regarding the validation phase (see Table 3).

Table 3. Mayring Content Analysis of post-simulation quantitative interview (% according to the respective group).

	Experimental Group		**Control Group**	
Condition	Positive Agreement	Negative Agreement	Positive Agreement	Negative Agreement
Feedback of the Validation Phase	20 (76.92%)	6 (23.08%)	12 (60.0 0%)	8 (40.00%)
Feedback of the overall Simulation Experience	19 (73.08%)	7 (26.92%)	13 (65.00%)	7 (35.00%)

3.3 Design Decisions

In order to calculate the distance between chosen designs and the optimal design, we converted each design decision regarding the information sign into a binary representation. Because the agent distribution follows a set algorithm to match its distribution to a design combination, we can calculate the distance between two designs using the Hamming distance. The distance can show the difference of two binary numeric values and is used in error detection after data has been transferred. The results in this study show no significant difference in trend between both groups and the unified optimal designs which is the set of top four optimal designs (see Figure 4).

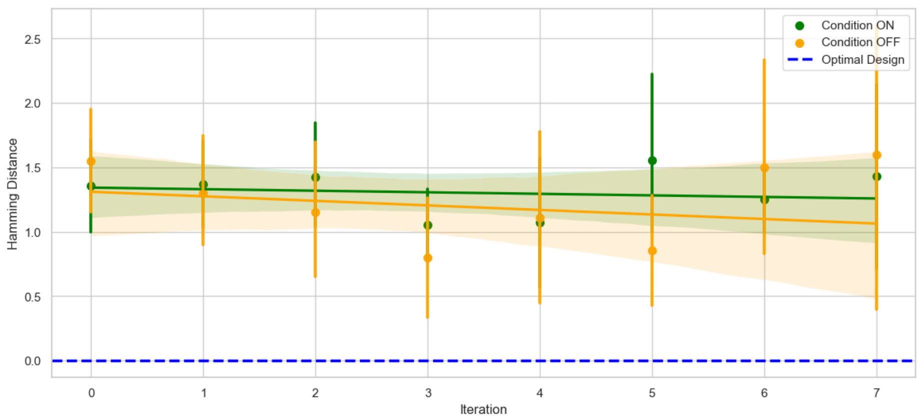

Fig. 4. Hamming distance between the optimal design and designs made over the iterations.

The design choices for the light band have been overall more linear with the majority preferring the light band with the line-shaped diodes. This is shown during the iterations as well as for the final choices made. It can be emphasized that (see Figure 5) the control group tends to choose more diode shapes as their final design than the experimental group where three participants also chose the star shape.

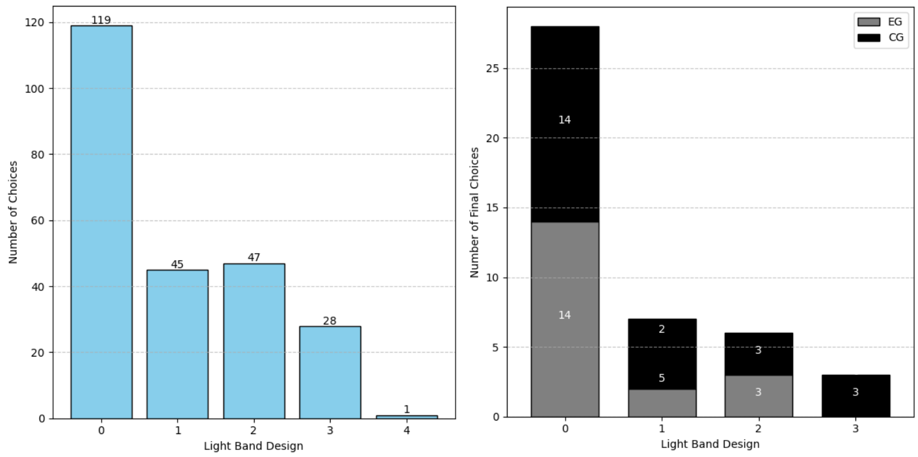

Fig. 5. Light band choices made for all iterations (left) and the final design choice (right).

4 Discussion

In this study we highlighted the importance of increasing inclusion users in design development processes and the utility of virtual reality for user empowerment. While our goal is to introduce principles of participatory design into user workflows, we want to emphasize the autonomy of users designing on their own. For that, we evaluated the acceptance, usability and user experience of user designing in VR simulation in cooperation with objective measures. This measure should serve as beneficiary complementary phase, helping users to get to a design which aligns with more common design principles. We developed and evaluated the integration of an in-simulation validation phase to aid participants in finding a balance between their subjective preference and objective influence of other behavioral observations. The results showed mixed tendencies, but overall, an influential factor that contributes to the simulation experience as well as design choices made. Participants overall rated high qualities regarding usability and user experience regarding the simulation phases, its interactivity and engagement.

Although the quantitative analysis showed that most people were unsure about the evaluation of the agent behavior, they would still prefer the inclusion of such validation phase to have a second opinion and not a result based solely on their own assessment. The effect size of a design decision based on a visual overview can be interpreted based on the usefulness of the information provided. In this case, most participants may not able to acquire enough information to adjust their designs but still rated the overall acceptance of the validation phase high. This suggests that a more visible difference in distribution may lead to higher acceptance and usability of the validation phase. Furthermore, data from the questionnaire showed significant differences in their evaluation.

Task load in the experimental group scored higher mean values while both having negative trends as the iterations increases. This could be interpreted as participants followed the phases, they got familiar with the environment and interactions. It is also interesting to evaluate the difference in the final designs made between both experimental and control group.

4.1 Limitations

Although agents were changing behavior based on participants' decision, the visualization may have not been significant enough for them to notice. One important factor is the calculation on how agents distribute which depends heavily on the specific optimal design choices as well as the congestion preset. Due to this, we found that the low visual difference between specific design choices may not be enough for participants to notice and evaluate. Furthermore, the comparatively low number of agents swarming the platform may limit the distribution spread resulting in a significant difference in target distance. No other form of explanation in text or image were provided to support the distribution change of agents. These combinations could lead to the unawareness of participants to acknowledge and accept the agent crowd decision.

The usage of standard or more commonly known pattern as well as priming designs may also influence the design decision. The light band having its line-shaped diodes was strongly preferred over all conditions as it was introduced first. The simple and narrow shape unlike other simple geometries may contribute to its high selection rate. Biases and preferences based on prior experiences may also influenced participants' impartiality. Additionally, the set timers in the scenario phase and validation phase received a number of critiques for being too long to wait through. While we understand the prolonged waiting time, it was determined beforehand to set it for comparability in scenario experiencing as well as simulating travelers waiting for a train to arrive. Regarding the aspect of usability study designs could implement other non-related side tasks to keep participants in flow until they can face the next phase.

4.2 Outlook

The overall results of the study suggest good acceptance and usability of the four-phase-procedure regarding user feedback. Participants continued to engage with all phases and the majority would use the validation phase again for its overview capability. The concept of KADP by injecting easy to understand information has been shown to receive high subjective acceptance and usability. Regarding the validation phase, we would recommend for future research to exacerbate the visual impact from agent validation depending on design choices made, making it more pronounced for participants to recognize. Another suggestion would be to introduce textual information to describe the impact e.g., on a percentage basis so that a confirmation of changes is more explicit.

Although the impact of the validation phase has only been limited tested in this study, influences regarding simple single-choice design decisions have been shown and is validated in the data. The overall experience in the simulation has also been reported as positively and the environment design plays an important role in facilitating an immersive experience when walking within the train station use-case. Further research needs to address a more appropriate implementation of an agent simulation or validation phase as a whole. Furthermore, we suggest that even with a more expressive or realistic validation design, users still need a form of additional explanation or guidance to grasp not only the reasoning for the validation but also some form of suggestion or ideas.

Disclosure of Interests. The authors declare no competing interest.

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