Matching Levels of Task Difficulty for Different Modes of Presentation in a VR Table Tennis Simulation by Using Assistance Functions and Regression Analysis

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Abstract. UX is often compared between different systems or iterations of the same system. Especially when investigating human perception processes in virtual tasks and associated effects, experimental manipulation allows for better control of confounders. When manipulating modes of presentation, such as stereoscopy or visual perspective, the quality and quantity of available sensory cues is manipulated as well, resulting not only in different user experiences, but also in modified task difficulty. Increased difficulty and lower user task performance may lead to negative attributions that spill over to the evaluation of the system as a whole (halo effect). To avoid this, the task difficulty should remain unaltered. In highly dynamic virtual environments, the modification of difficulty with Fitts' law may prove problematic, so an alternative is presented using curve fitting regression analyses of empirical data from a within-subjects experiment in a virtual table tennis simulation to calculate equal difficulty levels.

Keywords: Virtual Reality, Performance, User Experience, Spatial Presence, Table Tennis Simulation.

1 Introduction

The user experience (UX) of a given technology is a central research question in HCI. For example, social and behavioral sciences are interested in cognitive and physiological short-term and long-term effects on the user and the role that the perception has in the user experience (UX) as a whole.

UX is often compared between systems or within different iterations of the same system. The experimental manipulation of investigated variables within the same system allows for better control of confounders [1] than when comparing different systems. Still, a general drawback is an unintentional difference in task difficulty in different experimental conditions. The more difficult the task and the less successful the user, the more negative his subjective UX with the system is: Negative attributions from failing the task spill over to the evaluation of the system as a whole (halo effect). A possible solution is to create equally difficult tasks in all experimental conditions.

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In this paper, we present a method to match difficulty using interval-scaled task assistance functions and regression curve fitting. A case study (within-subjects design with five participants) is presented, using an immersive table tennis simulation (3x4 m high resolution Powerwall with active stereoscopy and a table tennis racket as input device). Goal of the experiment is to use assistance functions of the simulation to achieve a subjectively equal difficulty of the user task within all presentation conditions of the simulation.

2 User Experience and Spatial Presence

UX is often defined as an umbrella term for all qualitative experiences a user has while interacting with a given product, and it reaches beyond the more task-oriented term usability (for an overview, see [2] or [3]). The ISO definition of UX focuses on a "user's perception and responses resulting from the use or anticipated use of a product, system, service or game" (ISO FDIS 9241-210:2010). Several other concepts are closely related to UX, such as immersion [4], flow [5], cognitive absorption [6] or (tele-) presence [7-9].

Presence is often referred to as a "sense of being there", and occurs, "when part or all of a person's perception fails to accurately acknowledge the role of technology that makes it appear that she/he is in a physical location and environment different from her/his actual location and environment in the physical world" [10]. Presence can therefore be understood as a part of the larger user experience framework. The sensation of being physically situated within an immersive and virtual spatial environment (self-location) and the perceived possibilities to act within such an environment are part of the spatial presence construct [9, 11]. The focus lies on the mediated spatial environment, which – instead of reality – is perceived as primary interaction space.

In the two step process model of spatial presence formation from Wirth and colleagues [9], the first step is the construction of a spatial situation model (SSM). This spatial situation model is a mental model [12] of the spatial environment that the user unconsciously constructs, based on different available spatial cues and relevant personal spatial memories and cognitions [13]. Spatial sensory cues are part of a theory of selective visual attention in cognitive psychology [14], linked mostly to the visual modality. Static monocular cues like relative size, height in the visual field, texture effects of objects, occlusion or accommodation are the most important cues to act as building blocks of a mental model of a spatial environment [15, 16]. Dynamic monocular cues like motion parallax or binocular cues like stereopsis and convergence also provide information for depth perception. Furthermore, spatial audio, haptic and vestibular cues can are incorporated into the SSM [11]. The quality of the SSM is determined by the quantity and consistency of spatial cues available [9]. Media factors, attention allocation processes as well as user factors (situational motivation, domain-specific interest, and spatial visual imagery) also influence the process of constructing a SSM.

The second step of the model relies on a rich SSM to construct spatial presence. Based on the theory of perceptual hypotheses [17], users constantly check their environment for inconsistencies in perceived representation and their sensory feedback. A rich SSM results in perceiving the mediated environment as the primary reference frame of action, and spatial presence is constructed as a consequence.

When referring to UX in this paper, we distinguish between UX as a general concept in terms of ISO 9241-210 and spatial presence as specific part of the overall UX. Several measures, especially questionnaires, have been developed to assess the UX of a given system. The AttrakDiff [18] and the User Experience Questionnaire [19] are both valid post test tools for quickly assessing hedonic or pragmatic qualities. For spatial presence, the MEC Spatial Presence Questionnaire [20] offers a suitable tool, which has been validated in a series of studies with different media environments.

3 Goals of the Simulation

In a series of studies, we investigate the effects of quality and quantity of spatial cues in Virtual Reality simulations on spatial presence formation, using an immersive table tennis simulation. Given the important role that visual perception of distance plays in a user's experience within a virtual environment, depth perception in particular was among the first topics investigated by VR researchers [21-23]. In order to support training and performance in virtual environments, it is essential to provide necessary sensory cues that are required for the task, e.g. hitting the ball in our scenario. These cues can be presented in a multitude of different modalities, including different viewing perspectives and stereoscopic presentation. Our research focus lies on the influence of perspectives and stereoscopy of game-related scenarios and different aspects of UX, such as presence or enjoyment.

Studies on the current trend to use stereoscopic presentation or natural user interfaces in the video game industry (Nintendo Wii; Microsoft Kinect; Sony Move) found mixed results on their effectiveness to enhance the UX [24-27]. But often, commercially available game systems lack the sensory quality of real immersive virtual environments such as VR, whereas most VR simulations lack the entertainment quality of video games. Tamborini and colleagues [28] as well as Persky and Blascovich [29] investigated presence and aggressive feelings in a video game and a comparable VR application. They found no relevant differences in perceived presence in VR or standard video games. VR applications however have the advantage, that they can be modified in much more detail to accommodate certain modalities. Also, in experimental research, the manipulation of investigated variables (like perspective) within the same system allows for better control of confounders [1, 30].

3.1 Difficulty, Challenge and User Experience

In VR, perspective and stereoscopic presentation are believed to significantly contribute to task performance [31]. Our research focuses on influences of spatial cues on perception and resulting effects (e.g. presence, enjoyment) and individual user factors (e.g. motivation, visual spatial imagery) instead of just performance. The task's difficulty is a confounder is this design: When the quantity and quality of spatial cues is reduced, there is less information available for the construction of a rich spatial situation model, which is one of the research questions of the experiment. But simultaneously, the difficulty of the task increases, because of less accurate information available to base user decisions on (e.g. where to position the racket, where to move, etc.) If the difficulty of the task is too high for the skill level of the user, it may result in failure and frustration [5]. The more difficult the task and the less successful the individual user is, the more negative is his subjective user experience with the system. Negative attributions from losing the game spill over to the evaluation of the system as a whole (halo effect). In order to investigate the user's perception of stimuli within the simulation in different presentation modalities, each modality should have the same subjective task difficulty.

A number of studies investigated performance and user experience in different media contexts. A review from Chen and Thropp [32] on frame rate effects of virtual performance and user experience identified critical thresholds for various tasks (e.g. tracking, placement, target recognition). Fu and colleagues [33] compared physical and virtual task performances of a 3D Fitts' point-to-point reaching task in different visualization conditions and between collocated and non-colocated workspaces. They found no difference in the task performance, as their task primarily relied on a single user's performance. Zhang and colleagues [34] found that appropriate auditory or visual feedback cues of a virtual assembly simulation improved task performance and improved user experience, confirming the importance of multimodal sensory cues for task difficulty.

3.2 Fitt's Law

Fitt's law [35] serves as a model predicting the time required to move an object into a target area with a rapid, aimed motion. It greatly contributed to user interface design and evaluation, including different input devices (e.g. [36]) and immersive 3D VR [37].

$$\mathrm{MT} = \mathrm{a} + \mathrm{b}\log 2\left(\frac{A}{W} + K\right) \tag{1}$$

Fitt's law allows to calculate the average movement time *MT*, with a given start/stop time of the device a, the inherent 1/speed of the device b, the amplitude A of the motion (distance to reach target), and the width W of the target area along the axis of the motion. Both a and b have to be determined empirically by fitting a straight line to measured data.

The equation poses a speed-accuracy tradeoff: Targets that are further away or smaller require more time to acquire. The "law of crossing" [38] is based on Fitt's law and relates to the time to move an object across two goals on a trajectory. Furthermore, the "law of steering" [39] also includes drawing curves, or movement paths in VR environments.

Altogether, Fitt's law provides a good rationale for adjusting the task's difficulty in the current user study. The approach employed in this paper is similar: To account for the difference in task difficulty, we implemented the ability to adjust the hit box size of the table tennis racket (racket radius) and optimize the ballistic trajectory of the ball (help level). A bigger hit box of the racket made the simulation more tolerant in positioning the swings. A higher help level results in the system adjusting the ballistic trajectory of the ball, so that it hits the opponent's side of the table with a higher probability.

The table tennis simulation is highly dynamic with different target positions and starting positions of the users (i.e. different distance to target in three-dimensional space) as well as dynamic movement time. Our approach therefore focused on average performance values, such as ball hit ratios. If racket radius and help level can be modified to achieve a similar average hit ratio, users would subjectively experience the same difficulty level, judging from their actual performance in the game. In this case, it is sufficient to focus on subjective difficulty instead of objective task difficulty for controlling frustration effects from poor subjective performance. Users may still perform differently because of different skill levels, but the confounder is controlled for in all experimental conditions. To achieve this, we used regression analyses on case study data to calculate appropriate levels the assistance functions of the simulation.

4 User Study

The simulation was developed to include different presentation techniques. It is possible to manipulate the perspective of the user: Beside a subjective ("first-person") perspective, an objective ("third-person") perspective can be employed, where the camera is detached from the tracked perspective of the user and can be positioned anywhere in the scene. This allows to construct a scene that resembles the standard presentation mode for most video games, such as Wii or Xbox Kinect games. Additionally, the stereoscopic effects can be modified freely.

The setup allows the investigation of several research problems concerning display modalities. Altogether, this allows not only to compare research results on video game systems with our setup, but allows for a systematic manipulation of different aspects of the table tennis experience, which is not possible with existing video games.

When playing table tennis without stereoscopic presentation, the spatial cues are reduced and it's more difficult to hit the ball in the game than with binocular depth cues present. A subjective camera allows the user to view the scene perspectively correct from any viewing angle while moving his head. A static camera limits the depth perception, as the user can only see a predetermined viewing angle, further reducing spatial cues – the game should get even more difficult. As it includes more spatial cues, the influence of perspective should be greater on the difficulty than the type of presentation

In order to investigate only the user's perception of stimuli within the simulation in different presentation modalities, each modality should have the same difficulty. We employed a 2×2 within-subjects design (presentation × perspective) where spatial information is partially reduced: A1B1 (monoscopic presentation/static camera), A1B2 (mono/dynamic camera), A2B1 (stereoscopic presentation/static) and A2B2 (stereo/dynamic). Reduced spatial information results in lower performance and a presumably lower UX and spatial presence.

4.1 Apparatus and Task

The immersive table tennis simulation consists of a rear projection system, a tracking system and an application host and is housed in a university VR lab. The system is a state of the art enhancement of the first iterations [40, 41]. The projection screen (4 x 3m) is divided into four screen tiles, each worked by an Epson EHTW 8100 projector. Together the four projectors show high-resolution stereoscopic images necessary for the application. The Rendering is done using parallel rendering on several graphic cards on four PCs. The application runs on a separate PC and requires two tracked objects: Stereoscopic shutter glasses and the table tennis racket each contain several tracking targets (Figure 1).

Fig. 1. Two objects with tracking targets used for the simulation

The tracking of the glasses (standard 5 targets) is needed to compute the correct visual perspective in the scene, the racket (6 targets) is used as the main input device. The tracking is achieved using four ARTtrack1 cameras, running on a separate computer. The simulation uses four cameras to reduce marker occlusion due to the fast, wide range movements of the table tennis scenario. The software application is based on the scene graph library V3D [42] and is employing spatial audio, realistic game physics, a virtual opponent AI and animation. Overall, the simulation was received well in the past (e.g. on IEEE VR2005, CeBit 2006) and could be used by users with no prior VR experience.

The users were tasked to play a 10 minute match of table tennis against an AI opponent for each of the four presentation modality conditions. The game difficulty decreased over time in each condition.

4.2 Procedure

We recruited five participants, who were pre-selected on the basis of their respective table tennis experience. They stated their experience on a 5-point scale between 1 and 5 with "1" having no experience at all and "5" playing table tennis professionally. One participant plays professional table tennis (5), another plays semi-professionally (4), two have minor expertise (2; 3) and one participant has no prior game experience at all (1). All participants had no prior VR experience. The difficulty was manipulated using an increasing racket radius size (10cm; 15cm; 20cm; 30cm) and help level

(0%; 30%; 60%). Each participant completed all four conditions in a different sequence (due to learning effects) with starting values for racket radius size of 10cm and help level of 0%. Every 30 seconds, the values were increased, resulting in decreasing game difficulty (Table 1). During the experiment, all simulation variables (coordinates for the position of the ball, player head, racket, game score, etc.) were chronologically recorded in a log file.

After the game session, all participants filled out the AttrakDiff [18] and the User Experience Questionnaires [19] for an overall UX evaluation of the simulation.

Table 1. Experimental sequence for each condition

Time	*0s*	*30s*	*60s*	*120s*	*180s*	*240s*	*300s*	*330s*	*390s*	*450s*	*510s*	*570s*
Racket radius (cm)	10	10	10	15	15	15	20	20	20	20	20	20
Help level (percent)	0	30	60	0	30	60	0	30	60	0	30	60

4.3 Results and Discussion

The coordinates of the ball, the racket and the game score were analyzed for each condition and difficulty setting. To evaluate the performance of the players, three measures were computed from the raw data: the play-back-ratio (ratio of successfully returned serves) the points scored and the average distance of the center of the ball to the center of the racket, when the player hit the ball. Since our goal is a smooth gameplay experience with several rallies, we did not include simple hit-ratios in the analyses, but focused on play-back-ratios as indicator for the difficulty.

As hypothesized, the mode of presentation significantly impacted play-back-ratios, $F(3, 43) = 3.004$, $p < .05$. In general, our assumption holds: The more spatial cues are available, the better the performance. After analyzing assistance variables, help level was dropped since only racket radius significantly affected performance, $F(3, 6) = 10.967$, $p < .01$, $\eta^2 = .85$).

To achieve an equal difficulty level, we set the target play-back-ratio to 75%, so that an average player can play the simulation rather easily and to encourage positive emotions during gameplay due to high self-efficacy [43]. To calculate the difficulty level at $y = 0.75$, we fitted the data on the logarithmic regression function to calculate required racket radii ($R^2_{\text{mono/static}} = .97$; $R^2_{\text{mono/dynamic}} = .92$; $R^2_{\text{stereo/static}} = .80$; $R^2_{\text{stereo/dynamic}} = .74$; Figure 2).

The values for $x = f(y)$ were calculated: Mono/static (racket size = 25.1cm), mono/dynamic (racket size = 20.4cm); stereo/static (racket size = 17.9cm); stereo/dynamic (racket size = 20.7cm). The estimated values for racket radius should allow average users to achieve similar game performance metrics, based on play-back-ratio for a smooth gameplay. Of course individual skill will still be determining the performance of a single participant, whereas on average, we expect an equal difficulty distribution over all modalities.

The calculated values for racket size in the various conditions were used in a later study (N = 130) with a between-subjects design investigating the specific role of presentation mode and perspective on spatial presence, instead of UX of the system as a whole. The resulting mean values of play-back-ratio lay within a standard deviation of 0.75: Empirical values were M = 0.78 (0.17) for mono/static, M = 0.74 (0.14) for mono/dynamic, M = 0.73 (0.13) for stereo/static and M = 0.79 (0.13) for stereo/dynamic. These results suggest, that the calculated values worked well. Average users experienced similar subjective task difficulty, thus eliminating frustration/challenge of the task as influence of subjective user experience or spatial presence.

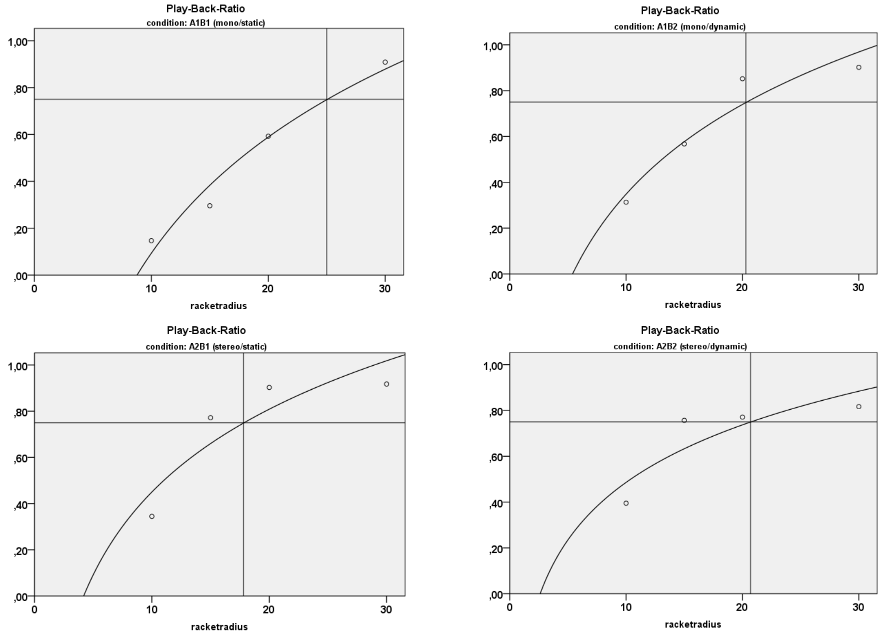

Fig. 2. Play-back-ratio with fitted logarithmic function

Results for the AttrakDiff and User Experience Questionnaires were computed using the AttrakDiff Online Resource (www.attrakdiff.de) and SPSS. With values ranging from -3 to 3, the means for hedonic (identification with the system, HQ-I; and stimulation through the system, HQ-S) and pragmatic quality (PQ) for AttrakDiff suggest a neutral assessment of the overall system ($M_{PQ} = -0.1$; $M_{HQ\text{-}I} = 0.2$; $M_{HQ\text{-}S} = 1.0$). System attractivity was also evaluated little above average ($M_{ATT} = 0.8$). This evaluation can also be supported by the UEQ data. On a range from 0 to 1, the factors attractiveness ($M_{att} = 0.61$), dependability ($M_{dep} = 0.45$), efficiency ($M_{eff} = 0.53$), and perspicuity ($M_{per} = 0.48$) indicate a neutral assessment. Novelty ($M_{nov} = 0.66$) was evaluated above average by all users, due to the fact, that they have never used a VR system before.

5 Discussion, Conclusion, and Application

In this paper we investigated difficulty levels of different modes of presentation of a virtual table tennis simulation game. Stereoscopic presentation and dynamic camera perspective were manipulated to reduce the quantity and quality of available spatial cues within the simulation. As expected, more spatial cues lead to a better overall performance and a reduced perceived game difficulty for the users. In conditions with reduced spatial cues, users performed worse than in the other conditions. For experiments investigating the effects of reduced spatial cues on the user's perception and resulting effects (such as presence or enjoyment) as well as individual user factors (such as motivation or visual spatial imagery), the diverging difficulty of different modes of presentation is a confounding variable that needs to be controlled. The difference in task difficulty was compensated by manipulating racket radius. Because the simulation was highly dynamic, we did not employ Fitts' law for assessing the task difficulty. Instead, an empirical case study with five participants with different skill levels was conducted as a within-subjects experiment. Each participant played the table tennis simulation in all experimental conditions with increasing support through assistance functions. With the use of curve fitting of the participant's game performance data, we could compute racket radii to achieve an equal difficulty level for each condition.

The findings raise several interesting questions to be addressed in future work. For example, which modalities of spatial information can also influence the performance and perceived difficulty of the task? How can differences in haptic feedback or sound be included to provide an equal distributed difficulty? The case study argued the reasons and presented a solution for the need to control task difficulty as a confounder for psychological experiments with subjective experience variables that can be implemented in future studies.

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