Immersive Virtual Reality and Gamification Within Procedurally Generated Environments to Increase Motivation During Gait Rehabilitation

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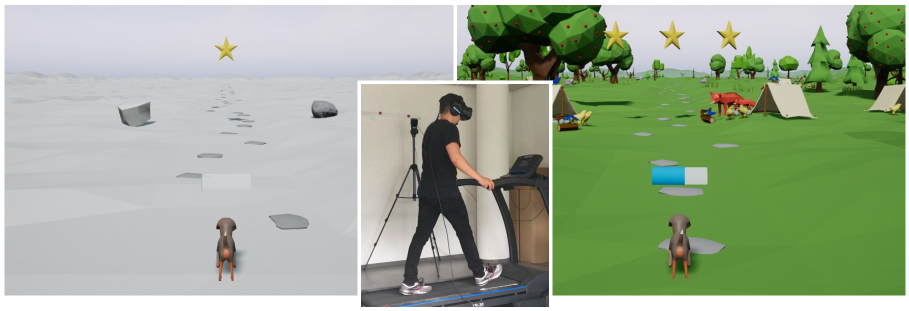

Figure 1: While the patient walks on the treadmill, the world changes from a lifeless desert to an inhabited green forest. A social companion which is represented by a small dog accompanies the patient during the training session and rewards him for reaching certain walking distances. The star and the progress bar indicate the distance to the next reward. After the patient collects a star, the reward element (e.g., a tree) grows in the virtual world and turns the lifeless desert a little more into an inhabited green forest.

ABSTRACT

Virtual Reality (VR) technology offers promising opportunities to improve traditional treadmill-based rehabilitation programs. We present an immersive VR rehabilitation system that includes a head-mounted display and motion sensors. The application is designed to promote the experience of relatedness, autonomy, and competence. The application uses procedural content generation to generate diverse landscapes. We evaluated the effect of the immersive rehabilitation system on motivation and affect. We conducted a repeated measures study with 36 healthy participants to compare the immersive program to a traditional rehabilitation program. Participants reported significant greater enjoyment, felt more competent and experienced higher decision freedom and meaningfulness in the immersive VR gait training compared to the traditional training. They experienced significantly lower physical demand, simulator sickness, and state anxiety, and felt less pressured while still perceiving a higher personal performance. We derive three design implications for future applications in gait rehabilitation: Immersive VR provides a promising augmentation for gait rehabilitation. Gamification features provide a design guideline for content creation in gait rehabilitation. Relatedness and autonomy provide critical content features in gait rehabilitation.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI; Applied computing—Health informatics

1 INTRODUCTION

Multiple sclerosis commonly induces motor deficits of the lower limbs. These deficits limit the ability to walk and to perform daily activities [24, 33]. People with multiple sclerosis frequently show reduced stride length, gait speed [35] and balance control [23]. Patients with multiple sclerosis often report mobility problems and gait disturbances as their main restrictions [2, 3, 9, 45]. Such motor deficits reduce balance control and increase the risk of falling [23]. Physical exercises reduce motor deficits in patients with multiple sclerosis [26]. Treadmill exercise is an efficient therapy to reduce motor deficits of the lower limbs [35, 37]. Treadmill training shows significant improvements in walking ability and gait variability [34, 35, 37]. However, monotone exercises tend to induce boredom and thereby reduced the motivation and compliance of patients [34].

Virtual Reality (VR) provides a promising tool to increase motivation in gait rehabilitation [34]. VR simulates a real environment and allows interaction with objects and virtual events [10, 30]. VR enables the integration of gaming techniques and direct feedback into rehabilitation [34–37]. In previous VR rehabilitation approaches, patients should, for example, collect items inside the virtual world, avoid objects placed on the ground in front of them [7, 8] or make decisions at bifurcations [35–37]. VR based treadmill training improved gait speed, endurance and the number of the patients' repetitions [34, 35, 38]. Furthermore, patients experienced higher task focus [8, 34] and expressed a more positive attitude towards training [8, 34] and some users reported reduced pain [51]. Intrinsic motivation relies on the experience of autonomy and relatedness in addition to competence [32, 40, 41]. Therefore, we propose to extend previous approaches with a particular focus on fostering autonomy, relatedness, and competence in immersive VR rehabilitation systems.

Contribution:

We based our immersive VR rehabilitation system on previous approaches that foster competence to increase motivation [7, 11, 19, 27]. However, intrinsic motivation relies on the experience of autonomy and relatedness in addition to competence [32, 40, 41]. Autonomy, relatedness, and competence operationalize needs that foster prolonged motivation [40, 41]. Therefore, we extended previous approaches by implementing game elements that foster autonomy and relatedness. We integrated game mechanics and game design elements such as an engaging storyline, a gamified reward system and a virtual social companion to increase experienced competence, decision freedom, and task meaningfulness. We used a head-mounted display (HMD) to immerse the patient in the virtual world. We conducted an ex-

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periment with 36 healthy participants to compare traditional gait rehabilitation (Non-VR) to virtual reality gait rehabilitation (VR) regarding motivational effects and physical workload. In the VR condition, participants reported increased decision freedom, increased perceived task meaningfulness, lower anxiety, lower frustration, and lower pressure. The system increased motivation while it reduced perceived physical workload, anxiety perception, pressure, and frustration. From our results, we derive three design implications for future applications in gait rehabilitation: (1) Immersive VR provides a promising augmentation for gait rehabilitation. (2) Gamification features provide a design guideline for content creation in gait rehabilitation. (3) Relatedness and autonomy provide critical content features in gait rehabilitation.

2 Related Work

Howard [22] reviewed previous virtual rehabilitation studies and summarized them under the term virtual reality rehabilitation. Massetti et al. [31] examined VR studies and described VR as a motivating and effective alternative to traditional motor rehabilitation for patients with multiple sclerosis. VR motivates patients by adding interesting tasks like exploring a world or executing everyday actions [22]. Thereby, patients get excited by experiences within the virtual world and more motivated to complete challenges [5, 6]. Therefore, motivation is an essential factor for success during the rehabilitation process.

Previous studies showed increased enjoyment and attitude of patients, using components of gamification to foster competence within VR rehabilitation systems [8, 34]. Further, patients increased their physical ability to execute a task by gamified challenges [27]. It should be noted that authors used the term VR to describe any synthetic virtual environment regardless of the interaction devices and display systems used [30]. For this reason, we distinguish, following Massetti et al. [30], immersive (HMDs) from semi-immersive (cylindric projection screens like in [11]) and non-immersive (small desktop screens with keyboard and mouse) systems.

2.1 Virtual Gait Rehabilitation

In 2017, Calabro, Naro, et al. [7] and Calabro, Russo, et al. [8] examined the role of semi-immersive large screen virtual rehabilitation systems in robotic-assisted gait training (RAGT). The results revealed an improvement of 20 % in lower limb gait and balance at the end of training. Overall, patients experienced higher positive attitude and solving ability toward their clinical problems in the on-screen group. They noted that semi-immersive flat screens are not as realistic as immersive HMDs, potentially limiting the significance of their findings [7].

Peruzzi et al. [35, 36] assessed the feasibility of immersive HMDs and non-immersive large screens for gait rehabilitation. They found that VR rehabilitation systems are feasible for patients with multiple sclerosis and improve both gait and cognitive aspects. In a further study, Peruzzi et al. [37] observed significant improvements in gait and clinical measurements for both single and dual tasks. They described the enhancements in dual tasks as a primary goal of gait rehabilitation because they result in higher autonomy in activities of daily living.

De Rooij et al. [10, 11] investigated the feasibility and effectiveness of semi-immersive cylindrical screen VR training to improve balance and gait. Their application consists of difficulty levels controlled by duration, speed, number of simultaneous tasks and amount of visual, auditive and tactile feedback. Besides an improved gait and balance after training, patients enjoyed the VR environment and increased motivation and compliance for solving challenging interventions.

Hamzeheinejad et al. [19] demonstrated an immersive VR therapy system to motivate patients during their gait rehabilitation. Their application integrates an HMD and a robotic-assisted gait device. A pre-study with healthy participants demonstrated encouraging results regarding user experience and acceptance.

Kilic et al. [27] proposed that gamification has a positive effect on coordination in gait rehabilitation. The participants walked on a treadmill and performed arm exercises. The experimental study with healthy participants revealed both improvements in gait and balance control.

These studies showed that immersive (HMD) and semi-immersive (large screen) VR rehabilitation are powerful tools for gait rehabilitation. The studies indicate the importance of enjoyment and attitude as significant factors for success during the rehabilitation process. However, these studies fostered competence to influence the participants' enjoyment and attitude. We extended these approaches by operationalizing motivation with autonomy, relatedness, and competence based on self-determination theory of Ryan and Deci [40, 41].

2.2 Theory of Motivation

Self-determination theory of Ryan and Deci [40, 41] focuses on the processes by which non-intrinsically motivated behavior can be self-determined, and the influence of the social environment on these processes. They describe motivation as *the desire to do something* and distinguish between intrinsic motivation and extrinsic motivation. Intrinsic motivation describes the behavior of people doing something because the activity is interesting, enjoyable or fun, and thereby is self-determined. Extrinsic motivation refers to an external incentive or reward and is triggered from outside. Furthermore, they distinguish between autonomous motivation and controlled motivation, where autonomy describes the own volition and the feeling of having the choice of whether to do an action or not. Intrinsic motivation represents autonomous motivation. A controlled motivation describes an activity, which includes an extrinsic reward or some pressure. In contrast, people who are not motivated have no intention or motivation to perform a task. They are not valuing the activity, not feeling competent for accomplishing it, or not interested in the result.

The satisfaction of basic psychological needs (competence, autonomy, and relatedness) is a fundamental requirement for being autonomously motivated. Competence refers to the experience of success by fulfilling challenging tasks and gaining mastery within an environment. Combined with direct and positive feedback, people feel satisfied and enjoy the task. Autonomy describes the need for decision freedom and the volition to fulfill activities, which are meaningful and in harmony with personal goals. Intrinsic motivation relies on the experience of autonomy in addition to competence [32, 40, 41]. Moreover, intrinsic motivation can decrease when feeling externally controlled [13]. Finally, relatedness describes the need to feel belongingness and connectedness with others inside the game. Relatedness is a crucial factor to accept the given task as your own so that it emerges from its self-understanding [41].

A meaningful story could satisfy the need for relatedness by including the person within the storyline and assigning a responsible role [13, 41, 43]. In summary, the satisfaction of basic psychological needs is a fundamental requirement to consider during the design process of VR rehabilitation systems. For example, an application could increase the experienced competence with positive feedback and rewards, foster relatedness by a storyline with responsibilities for the person, and support the perceived autonomy by a meaningful task.

2.3 Gamification and Serious Games

As described by Ryan and Deci [40, 41], competence, autonomy, and relatedness drive motivation. Gamification offers concepts and elements which are suitable to satisfy these basic psychological needs [43]. First introduced in the 2000s, gamification has been growing in popularity since 2010 [14]. Deterding et al. [15] define gamification as *"the use of game design elements in non-game contexts"*. Werbach and Hunter [53] describe gamification as *"The use of game elements and game design techniques in non-game contexts"*. These two definitions are broadly used and strongly focus on game design elements and their integration into gamified systems [52]. To reduce the focus on concrete elements, Werbach [52] approached a more process-oriented interpretation by defining gamification as *"the process of making activities more game-like"*. This definition enables the designer to think about making their application more game-like rather than thinking about particular game design elements. However, he labeled the definition of Deterding, Dixon, et al. [14] as the fundamental definition, but argued that the concepts of game design elements and non-game context are both contestable.

Sailer et al. [43] approved the process-oriented approach of Werbach [52], but criticized that the definition does not specify any method or game element to create user experiences characteristics of games. Instead, they proposed to define gamification as *"the process of making activities in non-game contexts more game-like by using game design elements"*. Further, Sailer et al. [43] examined the effectiveness of particular game design elements on basic psychological needs. They categorized game design elements into appropriate groups and determined the target effect on competence, autonomy, and relatedness. The first group included badges, leaderboards and performance graphs. This group positively affected competence and fostered task meaningfulness. The second group included avatars, meaningful stories, and teammates. While this group did not affect the task meaningfulness, it successfully increased the experience of relatedness. For this, Sailer et al. introduced a shared goal in the form of a story and thus conveyed the feeling of relevance. None of the game elements influenced the participants' decision freedom. Sailer et al. explained this by a relatively weak effect because the choice of an avatar did not affect the game process itself. The study showed that gamification and thereby game design elements could satisfy basic psychological needs, as long as they are well-designed and perceptible by the participants.

Games for serious purposes are classified as serious games [12, 14]. The term serious games was introduced in the 1970s [1] and used in areas such as economics, education, health, industry, military, engineering, and politics [12, 44]. Stokes [48] described serious games as *games that are designed to entertain players as they educate, train, or change behavior*. Michael [39] proposed to define serious games as *games that do not have entertainment, enjoyment or fun as their primary purpose*. Both gamification and serious games refer to the usage of game design elements [14, 15], while serious games rather characterize games for non-entertainment purposes, and gamification the incorporation of game design elements itself [18, 44]. Therefore, serious games focus on creating immersive, fully-fledged games, while gamification instead aims to affect the behavior and motivation of users by experiences similar to games [18, 44].

This leads to the question, whether the rehabilitation system presented within the current study is a gamified application or a serious game? Deterding et al. [14, 15] distinguish gamification from regular entertainment games and serious games by the intention of the system concerning the designer or user perspective. In their opinion, it is not possible to determine whether a particular system is *a gamified application* or *a game* without recourse to the designers or users perspective. Our intention from a designer perspective was to improve well-being, workload and motivation by including particular game design elements, rather than creating a whole game. From the user experience perspective, however, the game can be seen as a fully-fledged game and would, therefore, be classified as a serious game. Since in this application we took the perspective of the designer, the term gamification is used, which does not exclude a classification as a serious game in further developments.

3 Problem to Solve

Figure 2 visualizes the theoretical evaluation concept. We defined two primary goals for our VR rehabilitation approach. The first goal is to preserve or improve the physical abilities of patients (G1). In our opinion, this goal is very important, since every VR rehabilitation system should at least preserve the physical abilities of patients, in the best case increase them, but in no case worsen them. The second goal is to motivate patients during physical exercise by a virtual world (G2). We determined three subcategories (Well-Being, Workload, and Motivation) for the evaluation of our two primary goals. The first subcategory evaluates the *Overall Well-Being* (E1) by simulator sickness, user satisfaction, and anxiety sensation. The second subcategory deals with the evaluation of *Experienced Workload* (E2) by physical, mental, and temporal demand. The third subcategory comprises the evaluation of the *Perceived Motivation* (E3) after the treadmill training. This part includes the factors competence, autonomy, and relatedness.

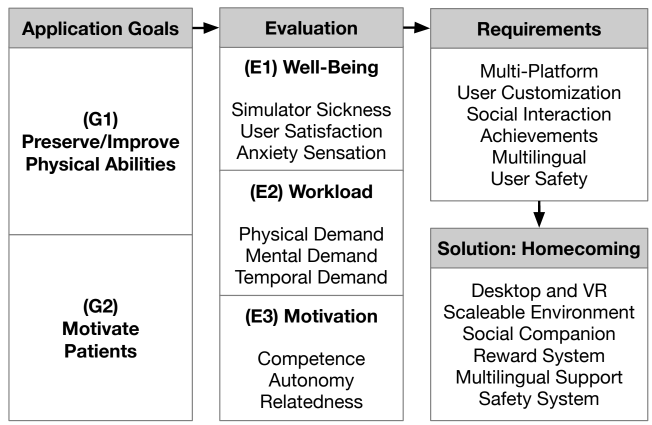

Figure 2: In the first step, we derived the evaluation categories from our application goals. We then defined the requirements and proposed our solution, named Homecoming.

We defined six requirements for our VR rehabilitation system based on these three categories.

- **Multi-Platform:** The application should work on both semi-immersive flat screens and immersive HMDs.
- **User Customization:** The application should scale according to the patient's walking ability.
- **Achievements:** The reward system should reward the patient for completing certain training goals.
- **Social Interaction:** The patient should interact with a social companion, which provides visual and auditive feedback.
- **Multilingual:** Due to the different language skills, the application should be implemented in several languages.
- **User Safety:** The application should integrate a safety system which enables the patient to see his own body and determine his position on the treadmill.

4 Solution / Conceptual Design

Our solution combines an engaging storyline with a gamified reward system and social interactions to motivate patients during their treadmill training. Our VR rehabilitation approach motivates patients to walk for longer periods while reducing perceived physical demands and effort. The entire training session is based on a storyline, which tells the story of Max and his friends. Max is a small dog and tells the patient that he and his friends lost their homes in a storm and asks the patient for support. Max explains that the patient only has to walk inside the virtual world to restore his home.

During the walking task, the patient follows Max on a straight path with stones on the ground. While the patient walks on the treadmill, the virtual world grows and becomes more beautiful. For this, the virtual world changes from an empty and lifeless desert to an inhabited green forest including flowers, bushes, trees, and animals (See Figure 1). Max rewards the patient for reaching certain walking distances and shows his happiness and excitement through positive visual and auditive feedback. During the whole training session, the patient listens to a happy and motivating piano background audio.

4.1 The Social Companion: Max

Max is a beagle, a small dog that accompanies the patient during the training. Beagles are among the most popular dogs in Germany [47]. They are happy, cute, active and perceived as peaceful and human-oriented [50]. We chose the name Max because it is a gender-neutral name and the patient decides on the gender of the dog. Max runs in front of the patient and gives positive visual and auditive feedback. Max shows informative and rewarding text messages and performs various animations such as sitting, walking, bouncing and gentle barking. Max motivates the patient to keep walking, to explore the virtual world, and to achieve the desired walking distance. We have implemented the textual dialogues of Max in several languages. The experimenter selects the target language within the configuration menu.

4.2 Reward System

The primary task of the patient is to walk in the virtual world and restore the home of Max and his friends. The gamified reward system rewards the patient at certain walking distances and visualizes the next desired walking goal by a reward. A yellow star and a reward element itself (e.g., a bush or a tree) represent such a reward. After the patient collects a star, the reward element grows in the virtual world and turns the lifeless desert a little more into an inhabited green forest. Figure 3 depicts the process of receiving a reward. In the beginning, the patient walks to the next reward (A). The progress bar indicates the target distance. After the patient reaches a certain distance to the reward, the star flies to the social companion and increases its rotation speed to visualize the timely collection (B). The social companion collects the star and rewards the patient immediately by visual and auditive feedback (C). In this example, Max tells the patient that the forest begins to grow and that the first bushes appeared. Besides the textual rewarding, Max shows his happiness and excitement by barking, jumping around, and changing its position on the straight path. After Max collects the reward, the progress bar is reset, and the reward system places the next reward in the virtual world. In (D), the next reward appeared (Trees), and the progress bar visualizes, that the patient already reached at least a quarter of the distance to the next reward.

4.3 Procedural Content Generation

The application generates the environment procedurally according to the patient's walking ability. The experimenter defines the walking distance of the patient in the configuration menu prior to the start of the training. The application creates the virtual world procedurally by randomly positioning previously created vegetation models, and increases their diversity by random rotation, scaling and density. Each reward element (e.g., bushes or trees) contains several shapes that differ from each other. Further developments could extend this procedural content generation with an algorithm that includes the generation of the vegetation itself.

4.4 Safety

The application includes a safety system (See Figure 4). Both parts show the perspective of the user. The left part shows the front view, the right part shows the bottom view. The safety system consists of two arrows that indicate whether the patient is too far forward or too far back on the treadmill (A). Further, the patient can activate the HTC Vive RGB camera image by looking downwards which shows the real world (B). The application shows the position of the patient's feet (C). In combination with the outline on the ground to visualize the running surface (D), the patient can determine the position on the treadmill. This is especially helpful in case of disorientation or repositioning on the treadmill. The application adapts the walking speed in the virtual world to the walking speed of the patients.

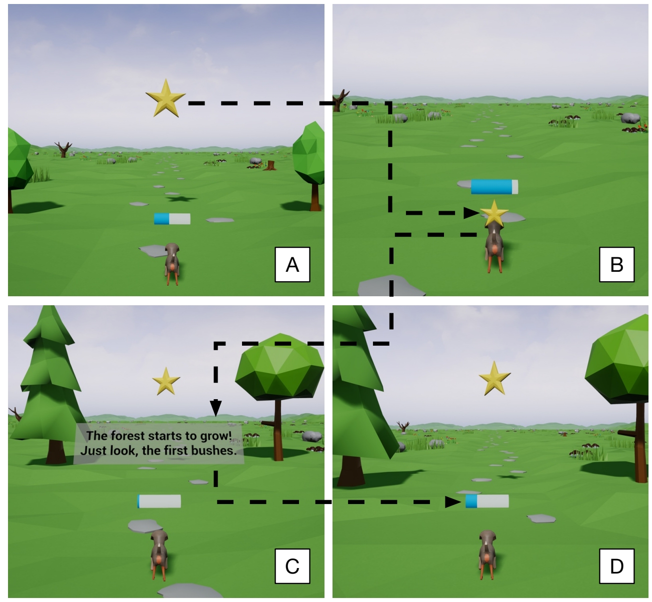

Figure 3: The process of receiving a reward consists of four steps. The patient walks toward a reward (A). When he reaches a certain distance (B), the social companion receives the star. The social companion rewards the patient immediately after the star disappears (C). The reward system already spawns the next reward on the way and the patient reduces the distance to this reward (D).

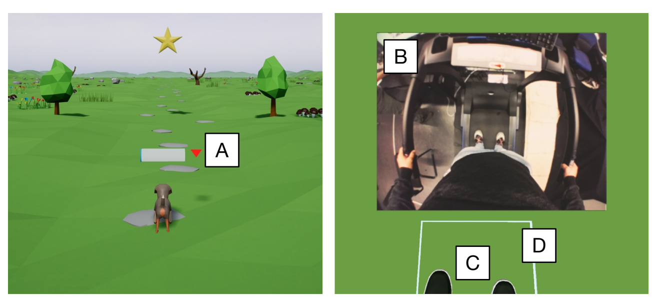

Figure 4: The safety system uses arrows to indicate whether the patient is too far forward or too far back on the treadmill (A). If the participant looks downward, the safety system displays a video stream of the world around the participant (B). If participants look downward, they see a virtual representation of their feet (C) and the outlines of the treadmill surface (D).

5 Experimental Method

The experiment followed a counterbalanced repeated measure one-factorial design with the within factor virtual reality (Non-VR vs. VR). Participants completed each condition once in balanced-randomized order.

5.1 Participants

Undergraduate students ($N = 37$; 16 women) participated in the experiment in exchange for course credit. The age of the participants ranged from 19 to 30 years ($M = 22.68$, $SD = 2.64$). All reported normal or corrected-to-normal vision and the absence of motor impairments. Participants were blind to the hypothesis of the experiment. This study received ethical approval from the institutional ethics committee. One participant was excluded due to a treadmill error. Due to technical problems, only 22 of 36 participants answered the Raw TLX.

5.2 Apparatus

We used the treadmill Cardiostrong TR30, which is an entry model and enables a speed of 0.8 km/h to 18 km/h. The treadmill provides a large running surface of 135 cm x 49 cm. We developed the application with the Unreal Engine 4.18 and a Microsoft Windows 10 based computer system which includes an i7-6700K processor, 16 GB DDR4-RAM and the Nvidia GeForce GTX 1080. The application supports both immersive head-mounted displays and semi-immersive flat screens. In the VR condition, the participant wore the VR head-mounted display HTC Vive and the appropriate HTC Vive Tracker attached to the feet for computing the movement velocity. The participant was equipped with circumaural headphones. We are going to include a large screen condition in future studies.

5.3 Measures

We used eight questionnaires in the experimental study. The Simulator Sickness Questionnaire (SSQ) [25] to measure the symptoms of simulator sickness, the Self-Assessment Manikin (SAM) [4] for affective emotional responses, the International Positive and Negative Affect Schedule - Short Form (I-PANAS-SF) [49] to assess the overall mood, the State-Trait-Anxiety Inventory German Version (STAI State G-SF) [17] of Spielberger State-Trait Anxiety Inventory (STAI) [46] for the current anxiety of the participants, the Intrinsic Motivation Inventory (IMI) [42] for intrinsic motivation of participants, a simplified form of the NASA Task Load Index (NASA-TLX) [21] called Raw TLX (RTLX) [20] to measure the experienced workload, the User Experience Questionnaire (UEQ) [29] for general user experience, and the User Satisfaction Evaluation Questionnaire (USEQ) [16] to evaluate the satisfaction of the user in this virtual rehabilitation system. The Estimates questionnaire includes the four questions *How many {minutes / meter / steps} did you walk on the treadmill?* and *How many more minutes would you have walked voluntarily?* We conducted the SSQ prior and post the VR condition (See Figure 5). The other seven questionnaires were administered to the participants after both training sessions. Finally, the participants completed the demographic questionnaire.

5.4 Procedure

Figure 5 visualizes the procedure of the experimental study. The experimenter welcomed the participants and participants gave informed consent prior to the start of the study. In the VR condition participants wore the HTC Vive head-mounted display and circumaural headphones. In the Non-VR condition, participants wore neither a head-mounted display nor headphones and were not exposed to the VR application. In each condition, participants walked on a treadmill for 7.5 min at 4 km/h. After each walking exercise, the participant completed several questionnaires mentioned in section 5.3. In the VR condition participants filled in the simulator sickness questionnaire prior and post the walking exercise. After completing both training sessions, the participants filled in a demographic questionnaire.

5.5 Statistical Analysis

We used a two-tailed paired t-tests to compare ratings between the VR and Non-VR condition. We set the a priori significant level to $p < .05$ for all statistical tests. We report Cohen's d as a measure of effect size.

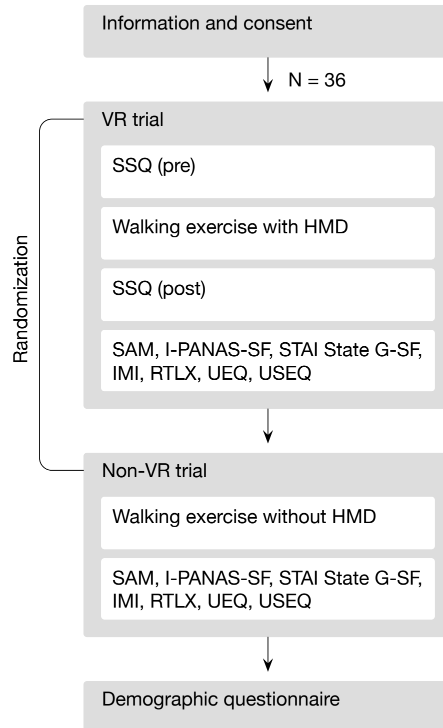

Figure 5: The experiment followed a single factor repeated measures design. Participants completed the VR trail and the non-VR trial in balanced randomized order. In both conditions, they walked on a treadmill and answered questionnaires afterward. In the VR condition participants completed the SSQ before and after VR exposure.

6 Results

Table 1 shows the mean comparisons of the SSQ scores prior and post the VR condition. Table 2 summarizes the comparisons between the VR and the Non-VR condition for all conducted scales. We visualized the most important results (IMI and RTLX, and UEQ) with diagrams in Figure 6, 7, and 8.

6.1 SSQ

We compared simulator sickness ratings in the VR condition before and after VR exposure (See table 1). The SSQ subscales *Oculomotor* ($t(35) = 3.38$, $p = .001$, $d = 0.56$), and *Total Severity* ($t(35) = 2.53$, $p = .015$, $d = 0.42$) revealed significantly lower ratings after VR exposure compared to before VR expose. We found no significant differences for the SSQ subscales *Nausea* ($t(35) = 0.21$, $p = .830$) and *Disorientation* ($t(35) = 1.37$, $p = .176$).

Table 1: Comparisons of SSQ ratings before (Pre) and after (Post) participants performed the task in the VR condition

SSQ Subscale	p	Cohen's d	Pre†	Post†
Nausea ^{a}	.830		15.63 (16.15)	15.10 (14.49)
Oculomotor ^{b}	.001	0.56	21.68 (20.59)	12.42 (16.32)
Disorientation ^{c}	.176		16.23 (27.54)	11.21 (16.57)
Total Severity ^{d}	.015	0.42	21.19 (20.87)	14.23 (15.45)

Note. † Mean (SD); Scale range from *low* to *high*: ^{a} 0 – 200, ^{b} 0 – 159, ^{c} 0 – 292, ^{d} 0 – 235;

6.2 Estimates

In the VR condition, participants were willing to continue for a significantly longer period of time than in the Non-VR condition ($t(35) = 6.42$, $p < .001$, $d = 1.07$). They did not estimate the duration of the exercise ($t(35) = -0.09$, $p = .922$), the performed steps ($t(35) = 1.27$, $p = .209$), or the distance walked ($t(21) = -0.25$, $p = .797$) differently between both conditions.

6.3 SAM, I-PANAS-SF, and STAI State G-SF

All SAM subscales revealed significant differences between the VR and the Non-VR condition. In the VR condition we identified significantly higher *Valence* ($t(35) = 9.64$, $p < .001$, $d = 1.6$), *Arousal* ($t(35) = 3.34$, $p = .001$, $d = 0.55$), and *Dominance* ($t(35) = 3.68$, $p < .001$, $d = 0.61$) compared to the Non-VR condition. The I-PANAS-SF *Positive Affect* scale revealed significantly higher scores in the VR condition compared to the Non-VR condition ($t(35) = 6.90$, $p < .001$, $d = 1.15$). The I-PANAS-SF *Negative Affect* scale revealed no significant difference between both conditions ($t(35) = -1.70$, $p = .097$). STAI State G-SF scores reveals significantly lower state anxiety ratings in the VR condition compared to the Non-VR condition ($t(35) = -3.71$, $p < .001$, $d = 0.61$).

6.4 IMI

All IMI subscales revealed significant differences between the VR and the Non-VR condition. In the VR condition we identified significantly higher *Interest* ($t(35) = 9.90$, $p < .001$, $d = 1.65$), *Competence* ($t(35) = 5.01$, $p < .001$, $d = 0.83$), *Effort* ($t(35) = 2.24$, $p = .030$, $d = 0.37$), *Choice* ($t(35) = 5.52$, $p < .001$, $d = 0.92$) and *Value* ($t(35) = 5.22$, $p < .001$, $d = 0.87$) ratings compared to the Non-VR condition. In the VR condition we identified significantly lower *Pressure* ($t(35) = -4.14$, $p < .001$, $d = 0.69$) ratings compared to the Non-VR condition.

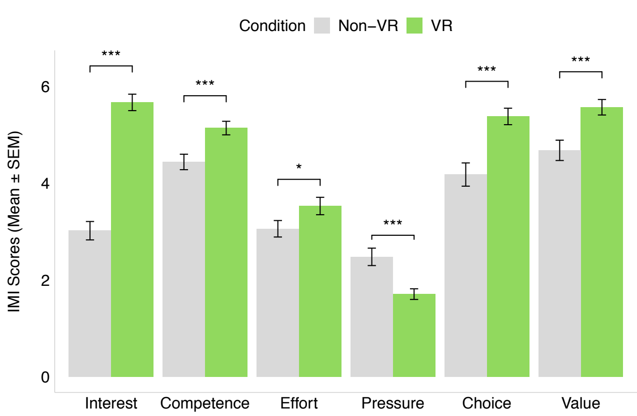

Figure 6: Score on the IMI subscales in the Non-VR and VR conditions. Participants showed a significantly higher result for Interest, Competence, Effort, Choice, and Value. Participants showed a significantly lower result for Pressure. Likert scales range from 1 (*low*) to 7 (*high*). * $p < .05$, *** $p < .001$.

6.5 Raw TLX

The RTLX subscale *Performance* ($t(21) = 2.66$, $p = .014$, $d = 0.56$) revealed significantly higher ratings in the VR condition compared to the Non-VR condition. The RTLX subscales *Physical Demand* ($t(21) = -2.85$, $p = .009$, $d = 0.60$), *Effort* ($t(21) = -2.66$, $p = .014$, $d = 0.56$), *Frustration* ($t(21) = -2.51$, $p = .020$, $d = 0.53$) revealed significantly lower ratings in the VR condition compared to the Non-VR condition. We found no significant differences for the RTLX subscales *Mental Demand* ($t(21) = 0.74$, $p = .462$) and *Temporal Demand* ($t(21) = -0.12$, $p = .904$).

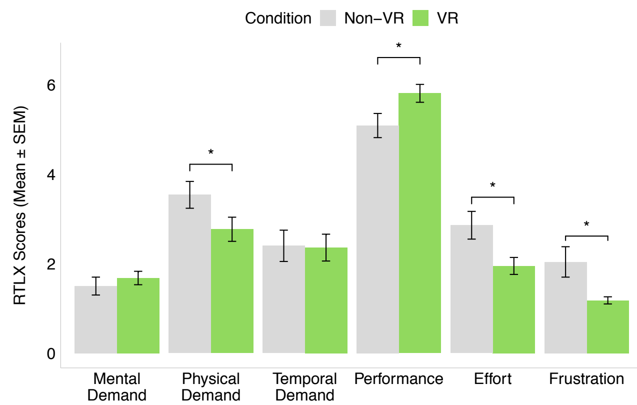

Figure 7: Score on the RTLX subscales in the Non-VR and VR conditions. Participants showed a significant increase for Performance and a significant decrease for Physical Demand, Effort, and Frustration. Likert scales range from 1 (*low*) to 7 (*high*). * $p < .05$.

6.6 UEQ and USEQ

The UEQ subscales *Attractiveness* ($t(35) = 11.1$, $p < .001$, $d = 1.85$), *Novelty* ($t(35) = 19.0$, $p < .001$, $d = 3.16$), and *Stimulation* ($t(35) = 10.7$, $p < .001$, $d = 1.79$) revealed significantly higher ratings in the VR condition compared to the Non-VR condition. The UEQ subscale *Dependability* ($t(35) = -3.56$, $p = .001$, $d = 0.59$) revealed significantly lower ratings in the VR condition compared to the Non-VR condition. We found no significant differences for the UEQ subscales *Perspicuity* ($t(35) = 0$, $p = 1.00$) and *Efficiency* ($t(35) = 0.09$, $p = .922$). We found a significantly higher USEQ total score in the VR condition compared to the Non-VR condition ($t(35) = 7.30$, $p < .001$, $d = 1.21$).

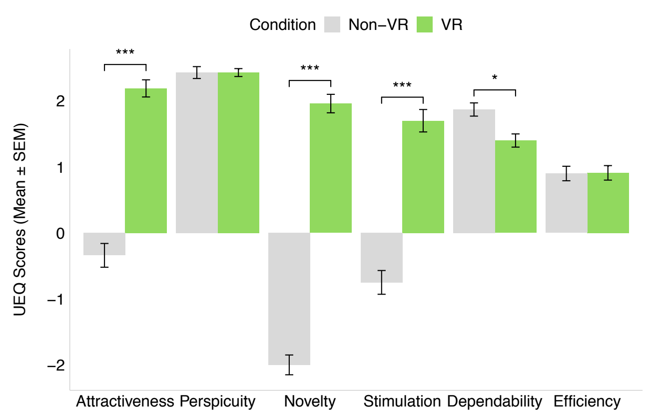

Figure 8: Score on the UEQ subscales in the Non-VR and VR conditions. Participants showed a significantly higher result for Attractiveness, Novelty, and Stimulation. Participants showed a significantly lower result for Dependability. Likert scales range from -3 (*low*) to 3 (*high*). * $p < .05$, *** $p < .001$.

Table 2: Comparisons of subjective ratings between the Non-VR and the VR condition

Measure	Subscale	p	Cohen's d	Non-VR†	VR†
Estimates	Duration [min]	.922		8.25 (3.02)	8.19 (3.42)
	Willingness to Continue [min]	***	1.07	5.77 (6.96)	13.33 (9.77)
	Performance [steps]	.209		1013 (1057)	1128 (1166)
	Distance Walked [m]	.797		761 (584)	734 (587)
SAM ^{a}	Valence	***	1.60	4.91 (1.50)	7.55 (1.13)
	Arousal	.001	0.55	3.50 (1.64)	5.02 (2.32)
	Dominance	***	0.61	5.25 (1.99)	6.75 (1.36)
I-PANAS-SF ^{b}	Positive	***	1.15	13.41 (3.63)	18.05 (3.22)
	Negative	.097		6.11 (1.96)	5.50 (0.94)
STAI State G-SF ^{c}	State Anxiety	***	0.61	30.30 (9.10)	24.36 (7.11)
IMI ^{d}	Interest	***	1.65	3.02 (1.14)	5.67 (1.07)
	Competence	***	0.83	4.44 (0.96)	5.14 (0.86)
	Effort	.030	0.37	3.06 (1.07)	3.53 (1.12)
	Pressure	***	0.69	2.48 (1.09)	1.71 (0.66)
	Choice	***	0.92	4.18 (1.49)	5.38 (1.03)
	Value	***	0.87	4.68 (1.26)	5.57 (0.97)
RTLX ^{d}	Mental Demand	.462		1.50 (0.96)	1.68 (0.71)
	Physical Demand	.009	0.60	3.54 (1.43)	2.77 (1.30)
	Temporal Demand	.904		2.40 (1.65)	2.36 (1.43)
	Performance	.014	0.56	5.09 (1.26)	5.81 (0.95)
	Effort	.014	0.56	2.86 (1.48)	1.95 (0.89)
	Frustration	.020	0.53	2.04 (1.61)	1.18 (0.39)
UEQ ^{e}	Attractiveness	***	1.85	-0.34 (1.09)	2.19 (0.79)
	Perspicuity	1.00		2.43 (0.58)	2.43 (0.37)
	Novelty	***	3.16	-2.00 (0.92)	1.96 (0.85)
	Stimulation	***	1.79	-0.75 (1.09)	1.70 (1.04)
	Dependability	.001	0.59	1.87 (0.62)	1.40 (0.63)
	Efficiency	.922		0.90 (0.66)	0.91 (0.70)
USEQ ^{f}	Total Score	***	1.21	20.63 (3.64)	25.80 (1.99)

Note. † Mean (SD); *** $p < .001$; Scales range from *low* to *high*: ^{a} 1 – 9, ^{b} 5 – 25, ^{c} 10 – 80, ^{d} 1 – 7, ^{e} -3 – 3, ^{f} 6 – 30;

7 Discussion

The goal of this study was to use VR to enhance motivation during gait rehabilitation. We developed an immersive VR rehabilitation system that includes a head-mounted display and motion trackers. We evaluated the effect of an engaging storyline with a gamified reward system on workload and motivation. We examined the usability and acceptance of this VR rehabilitation system to ensure clinical applicability. We based our immersive VR rehabilitation system on previous studies, which included tasks that foster competence (e.g., [11, 19, 27]). We used gamification [14, 15] to increase intrinsic motivation. Therefore, we fostered motivation by satisfying the needs for autonomy, relatedness, and competence [40, 41]. We conducted a study with 36 healthy participants to compare the immersive VR gait training to Non-VR traditional training. Participants reported significant improvements in well-being, motivation, and workload in the VR condition compared to traditional training.

7.1 Well-Being

We evaluated the overall well-being of participants by the factors user satisfaction, anxiety, and simulator sickness. Our results revealed higher well-being of participants in the VR condition compared to the Non-VR condition. The results showed a significantly higher user satisfaction (USEQ), attractiveness (UEQ), positive affect (I-PANAS-SF and SAM) in the VR condition compared to traditional training. In the VR condition participants reported significantly lower anxiety (STAI State G-SF), pressure (IMI), temporal demand, and frustration (RTLX). We implemented safety features to reduce anxiety during VR training. Participants preferred the VR treadmill training and considered the VR rehabilitation system as helpful for rehabilitation training (USEQ). Our application adapted the walking speed in the virtual world to the walking speed of the participants, as [8, 11, 19, 27, 37]. Preventing simulator sickness was of utmost priority in the design of VR application. The application did not induce simulator sickness. Participants reported lower simulator sickness after the VR treadmill compared to before. In particular, participants reported reduced symptoms for the items of the oculomotor subscale (blurred vision, difficulty focusing) and the less specific items general discomfort, fatigue and difficulty concentrating. Constant focusing on the head-mounted display might have reduced difficulty focusing, difficulty concentrating and blurred vision. Due to the pleasant game experience, participants might neglect general discomfort. Distraction during VR exposure might have enhanced this effect.

7.2 Motivation

In the VR condition participants experienced a significantly higher interest, and competence (IMI), higher valence, arousal, and dominance (SAM) compared to the Non-VR condition. The results are in line with previous studies and show the motivational effect of VR rehabilitation systems [7, 8, 11, 27, 34]. Intrinsic motivation relies on the experience of autonomy and relatedness in addition to competence [32, 40, 41]. Therefore, we extended previous approaches by implementing game elements that foster autonomy, relatedness, and competence. The application fostered autonomy by involving the participants within the storyline and thereby increased the experienced meaning and decision freedom. Further, patients can reduce the speed or stop at any time if they feel unable to continue. In the VR condition participants experienced a significantly higher choice and value (IMI), dominance (SAM), and significantly lower dependability (UEQ) compared to the Non-VR condition. The engaging storyline with a social companion increased relatedness: participants reported lower pressure, higher value, and choice (IMI) in the

VR condition compared to the Non-VR condition. We attribute these motivational effects to the interaction of several factors: a immersive (HMD) VR application that presents an engaging storyline with a social companion embedded into a gamified reward system.

7.3 Workload

We used the RTLX questionnaire to evaluate the perceived workload of participants. The results revealed a significantly lower physical demand and effort in the VR condition while the mental demand and temporal demand remained unchanged. Further, participants perceived a significantly higher performance. This is in line with previous findings [8, 11, 37]. Participants were willing to continue the treadmill training for a significantly longer time in the VR condition. We assume that the VR application distracted participants from unpleasant physical restrictions and perceived workload. We attribute this effect to the presence of an engaging storyline and a gamified reward system. The reward system conveys the feeling of competence to solve enjoyable tasks, and therefore increases the perceived performance and lowers the experienced effort. In comparison to other studies, which included dual tasks to increase the cognitive load [7, 11, 27, 37], we focused on the single task performance. Thus, we did not evaluate the physical impact on walking ability and gait variability [34, 35, 37]. However, our immersive VR rehabilitation application generates a significantly lower physical demand and effort while also significantly increasing the perceived performance and competence.

7.4 Design Implications for Future Applications in Gait Rehabilitation

Our results motivate the design of applications to increase motivation in gait rehabilitation. We discuss three design implications for such systems.

1. Immersive VR Provides a Promising Augmentation for Gait Rehabilitation

In previous studies, participants reported boredom during traditional gait rehabilitation training. This sensation lowered their motivation for the task [34]. Thus, our target was to involve participants in a virtual world through an engaging and gamified storyline and a social companion. We used head-mounted displays to immerse the participants in the virtual environment. The results indicated that participants experienced higher well-being and also increased their competence, autonomy, and relatedness. Participants mentioned a decreased physical demand, and less effort and frustration. In particular, we recommend immersive VR as an augmentation for traditional gait rehabilitation to increase motivation. We recommend integrating an advanced safety system to increase the objective and subjective safety of participants.

2. Gamification Features Provide a Design Guideline for Content Creation in Gait Rehabilitation

We extended concepts of previous studies that motivate patients by fostering competence. We based our approach on the self-determination theory of Ryan and Deci [40, 41], and successfully integrated game mechanics and game elements that foster autonomy, and relatedness, and competence. The results indicated increased interest, competence, attractiveness, and pleasure of participants. Thus, we assume that gamified reward systems combined with social companions increase motivation. We recommend using the concept of gamification as a design guideline and integrating game elements into the VR rehabilitation system.

3. Relatedness and Autonomy Provide Critical Content Features in Gait Rehabilitation

The third design implication deals with relatedness and autonomy. As the results showed, it is important to establish a social connection within the application. This application realizes relatedness through the engaging storyline and the social companion, who accompanies the participants during the treadmill training. The companion assigns an important role to the participants and thereby increases the social commitment, gives them the feeling of meaning, and supports belongingness. The application encourages the participants' volition to fulfill the activity. As the results indicated, the participants' interest, choice, and value increased while they did not feel influenced, dependent or controlled by others. We assume that relatedness and autonomy are fundamental requirements for VR rehabilitation systems and recommend designing an engaging storyline with social connections and interactions to foster both relatedness and autonomy.

7.5 Limitations

The study had a repeated measures design. Hence, the experience of the first condition might influence the experience of the second condition. The balanced-randomization distributes this effect equally, however, a systematic bias may remain. We conducted the study in only one session. A novelty effect for immersive VR treadmill training might confound the results. We conducted the study only with healthy participants. However, we consider motivation as a general concept. Hence, we assume that our results sufficiently generalize to the target population.

7.6 Future Work

We will evaluate the effectiveness of our approach with multiple sclerosis patients. Further, we will test the impact of system modifications. For example, we will test the impact of avatar embodiment on motivation [28]. We will test the impact of increased task variety and dual tasks [35, 36]. We plan to create various procedurally generated virtual worlds for multiple training sessions.

8 Conclusion

We presented a immersive VR rehabilitation system for gait rehabilitation. Our approach extends previous studies that foster competence to increase motivation [8, 11, 19, 27]. However, intrinsic motivation relies on the experience of autonomy and relatedness in addition to competence [32, 40, 41]. Therefore, we propose to foster the experience of autonomy and relatedness in VR rehabilitation systems. To foster prolonged motivation, competence, autonomy, and relatedness were operationalized within this study [40, 41]. We integrated game mechanics and game design elements into traditional gait rehabilitation to foster autonomy and relatedness. These elements include an engaging storyline, a gamified reward system, and a social companion.

We conducted a user study with 36 healthy participants to compare immersive VR gait training with traditional gait training. In the VR condition, participants reported increased decision freedom, increased perceived task meaningfulness, lower anxiety, lower frustration, and lower pressure. Our study supports the assumption that virtual rehabilitation significantly increases the motivation [7, 11, 27] and attitude [8] of participants during treadmill training. Our study emphasizes the importance of autonomy and relatedness. The system increased motivation while it reduced perceived physical workload, anxiety perception, pressure, and frustration. We assume that an engaging storyline with a gamified reward system, relatedness, and social commitment are key features to increase motivation in gait rehabilitation.

We derive three design implications for future applications in gait rehabilitation: (1) Immersive VR provides a promising augmentation for gait rehabilitation. (2) Gamification features provide a design guideline for content creation in gait rehabilitation. (3) Relatedness and autonomy provide critical content features in gait rehabilitation.

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