The Matrix Has You

Realizing Slow Motion in Full-Body Virtual Reality

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ABSTRACT

While we perceive time as a constant factor in the real world, it can be manipulated in media. Being quite easy for linear media, this is used for various aspects of storytelling e.g., by applying slow motion in movies or TV. Interactive media like VR however poses additional challenges, because user interaction speed is independent from media speed. While it is still possible to change the speed of the environment, for interaction it is also necessary to deal with the emerging speed mismatch, e.g., by slowing down visual feedback of user movements. In this paper, we explore the possibility of such manipulations of visual cues, with the goal of enabling the use of slow motion also in immersive interactive media like VR. We conducted a user study to investigate the impact of limiting angular velocity of a virtual character in first person view in VR. Our findings show that it is possible to use slow motion in VR while maintaining the same levels of presence, enjoyment and susceptibility to motion sickness, while users adjust to the maximum speed quickly. Moreover, our results also show an impact of slowing down user movements on their time estimations.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**;

KEYWORDS

virtual reality; slow motion; time perception; evaluation.

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1 INTRODUCTION

Nowadays, manipulation of time is commonly used as a stylistic device in traditional linear media like movies and television, and to a certain degree also in games, as for replay scenes. The purpose of such manipulations ranges from storytelling aspects (often by imitating common human temporal illusions), to more analytic functions like slow motion replay in sports coverage. Speeding up or slowing down time is easy to implement in such media, given the fact that the events are not subject to user interactions, but unfolding linearly in front of the user who is merely a spectator. In interactive media, however, using time manipulation is much more difficult, as such a manipulation needs to target not only the media time, but also perceived time of the user, as the user's interaction speed does not necessarily change with a speed change in media. This is less of a problem with weakly-immersive media like games played on a traditional PC screen, because interactions occur indirectly, with feedback occurring separated from user input. However, in fully immersive scenarios like VR, where real-world body movements are often represented in the virtual world normally in real-time, time manipulation (e.g., by slowing down auditory and visual events in the environment) inevitably leads to a conflict between the close-coupled feedback which represents users real movements, and the desirable effect of time manipulation, to the point where aspects like realism or the level of immersion might be influenced negatively.

In this paper, we focus on the question of how time in interactive virtual realities still can be manipulated (e.g., for storytelling purposes or as an element of game play), in a way which not only aims to alter the actual time perception of the user, but also preserves or improves the user's level of presence and enjoyment. To address this challenges, we focus on methods to cover the perceptional mismatch between the user's visual sense and the proprioceptive sense, which allows humans to know their posture and movement in space without relying on their visual sense. By using several visual redirection techniques, we build on previous work (e.g., [Azmandian et al. 2016]), which exploits limits of the visual human sense in the spatial domain to enable interactions with real-world objects. Based on this work, our goal is to expand this approach into the temporal domain.

For this, we built a system that is able to manipulate two cues which are important for time perception. The first ones are environmental cues. These can be the visual speed of objects, or auditory cues, like playback speed and pitch. These cues are independent of the user and interactions, and their manipulation is well-known from linear media and also easily recognizable for the user. On top of this, we developed different cues for manipulating the users body and limb movement speed in VR as second indicator for slow motion. Both concepts were systematically evaluatedn in a user study with 16 participants.

Our results show that the presented approach and algorithms for visual redirection is an appropriate method for applying slow motion to user movements. While increasing enjoyment, no decrease of presence could be observed. In addition, our results show that

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manipulating the perceived movements significantly influenced user's time estimation, while manipulating only environmental cues did not show any effect. Besides this, we provide insights regarding more general aspects like simulator sickness and the visual perception of a redirected body in VR.

2 RELATED WORK

Time perception is a complex process, having no physical representation, but taking place solely in the human brain. Humans have senses for visual or auditory information, but no dedicated sensory organ for time. Our perception of time is most of all influenced by an internal imaginary clock that creates a sense of time out of a variety of other senses. Therefore, the perceived time may vary, e.g., depending on a task, since we have to count the "ticks", which is harder when being more distracted. These features may influence our time perception retrospectively, but not in the present. There is no situation in the real world where we perceive slow motion. Instead, it can be assumed that popular representations of slow motion are learned e.g., from depictions in media. Following out of this, there also exists no baseline of realism for manipulating time.

2.1 Human Time Perception

The perception of time is based on intervals, while it is hard to define what the concept of *now* really is. The perceived reality is a sampled interpretation of our visual, auditory and other senses. While the single senses are processed using different temporal resolutions, our brain needs to sample this information to a unified perception [Brockman 2009].

Slow motion itself is an imaginary, mostly learned concept, something never experienced in the real world. The only baseline arises out of linear media like movies. There, slow motion usually leads to visual aspects like increased motion blur and slower movements.

There are, however, some well-known aspects of basic time perception – mostly out of the domain of psychology and physiology. Humans may retrospectively estimate time as being shorter or longer than it really was. These differences in time estimation can arise through emotional states [Angrilli et al. 1997] (e.g., like awe [Rudd et al. 2012] or fear [Fayolle et al. 2014]), or even by space (e.g the Kappa effect [Cohen et al. 1953]).

2.2 Time Perception related to Gaming and Virtual Reality

Wood et al. [Wood et al. 2007] collected quantitative as well as qualitative data of 280 gamers through an online survey. They found that the perception of time is often lost while playing. This circumstance is most of all influenced by the complexity, missions, multi-player interaction and plot of the game. The loss of time was perceived as both, positive (relax and escape from reality) and negative (e.g., feeling of wasted time).

Tobin et al. [Tobin et al. 2010] compared retrospective and prospective time estimates while playing. They could confirm that prospective time estimates are longer than retrospective ones. Comparing different durations, they observed, that 35 minute and 58 minute retrospective estimates were significantly lower than 12 minute estimates. They also provide information indicating that gamers might have problems with time estimations while playing, resulting in inaccuracies of estimations.

There is also work on time perception in the context of VR. Bruder et al. [Bruder and Steinicke 2014] compared time perception while walking in VR and in the real world. Participants were able to estimate the time very accurately in the real world. There were only slight changes compared to the VR condition.

Schatzschneider and Bruder [Schatzschneider et al. 2016] analyzed the impact of a natural and unnatural movement of the virtual sun on time estimations. They compared immersive VR using an Oculus Rift, to a non-immersive setup using monitors. In addition, the participants were either involved in a cognitive task, or not. While not involved, participants overestimated duration, while slightly underestimated duration in conditions, where cognitive tasks had to be solved. Participants estimated duration as a little longer if no movement of the sun was displayed. Changing the speed of the sun did not significantly influence time perception.

2.3 Redirecting Movements in Virtual Reality

Since the real-world visual sense is fully overridden due to the use of VR glasses, it has been proven possible to also override the real-world body pose, orientation or movement by divergent visual information to a certain degree, thus rendering the proprioceptive sense less important [Azmandian et al. 2016; Kohli 2010]. Though, such techniques have a maximum threshold of manipulation, before users are able to perceive the manipulation.

3 SLOW MOTION IN INTERACTIVE VR

To enable the use of slow motion, e.g., as an additional tool for storytelling, different aspects need to be considered. As there exist no known direct means of altering time perception for humans, a direct manipulation of time also in VR seems impossible at a first glance. Furthermore, on a more basic level, humans even lack the experience of a manipulated temporal flow in reality at all (as time is experienced as linear and constant), meaning there is also no real reference for quantifying the result of attempts to manipulate time perception.

However, it is possible to manipulate various aspects of stimuli which are presumably used by the human brain to determine how time is passing, e.g., the speed of certain environmental changes over time, like movement or sound frequency. For both of those stimuli, humans have learned over the course of their life which relative speed is to be considered natural or "real-time". Our basic assumption for this work is that with increasing immersion and presence, the manipulation of such aspects thus leads to an altered perception of time, which in turn can be exploited for enabling slow motion in VR.

The main challenge with this approach however lies in the (at the first sight) contradicting requirements to maintain high levels of presence and immersion, while also manipulating parameters which are contributing to presence and immersion themselves. This especially applies to the mapping of bodily movements in the real world onto a virtual body in VR. One might assume that the more precise this mapping occurs, the higher levels of presence and immersion can be reached and maintained. However, for enabling slow motion, this mapping needs to be modified, as the human movement speed outside of the VR cannot be altered or limited without applying mechanical limiting devices. In contrast, it is however fairly easy to modify the position or maximum velocity of virtual limbs, a fact which we exploit for implementing redirection strategies.

Since this work is to the best of our knowledge the first to address the topic of active time manipulation in VR, we established several hypotheses, touching basics as well as practical issues, which are described in the following sections.

3.1 Relative Perception of Time

As it is difficult to get a hold on the absolute time perception of a user, in this work we focus on determining differences in relative time perception as an indicator of slow motion perception. Specifically, we aim to influence the relation between the perceived absolute time that passed compared to the actual absolute time that passed for a given scenario. This dimensionless ratio is further on called the *time quotient*. We hypothesize that this relation is being influenced by manipulating the *playback speed* of the virtual scene (with a speed of 1.0 being real-time), both considering the environment as well as interactions and movements, with the latter being a stronger influence factor.

3.2 User Interaction Behaviour

As there is no reference in the real world for experiencing a change in time flow, it is hard to guess how users react when dealing with such an effect. Furthermore, the actual implementation of this effect may also influence the reaction. We hypothesize that when visually restricting the movement speed in the virtual space, the user will also adapt to this change rather quickly in the real world by slowing down his movements accordingly. By sensibly designing the actual redirection of movements and choosing the right parameters for this mechanism, this should also be possible to achieve without a loss of control or realism.

3.3 Presence, Enjoyment and Simulator Sickness

Besides the actual effects listed above, which directly influence the feasibility of VR slow motion as a means of enhancing interactive storytelling, we also focus on more generic parameters of VR experiences like presence, enjoyment and simulator sickness. For slow motion to be a usable tool in VR, it is desirable that, by carefully designing the slow motion metaphors and redirection, those parameters at least stay at the same levels despite the obvious deviation between real world and virtual world. If slow motion is perceived as an appropriate additional means of storytelling, at least the values for enjoyment may even increase.

4 IMPLEMENTATION

To test our assumptions, we developed two different visual redirection techniques to enable slow motion in virtual reality, which are described in the following section. Both have in common that they slow down the movements of the user's virtual character and its limbs by a given amount, however using slightly different approaches when doing so. The approaches can be compared to a low pass filter applied on the angular velocity of the user's joints connected by a kinematic chain, a graph like system connecting the human joints by bones.

All of those joints have a defined rotation in 3D space, which is represented as quaternions in our system. Due to the kinematic chain, rotation of a joint leads to changes in position of all descendant joints. The way how exactly the velocity of the real human body joints is transferred to the virtual characters' joints greatly affects the type of slow motion effect that can be achieved.

4.1 Developing Slow Motion Movements

The idea behind our implementation was to use an algorithm that does not only slow down the user by just delaying movements, since such an approach could be interpreted as some kind of malfunction or lag. We therefore decided to design the approach in a way which is always reacting to the user's movements without any delay. A first idea was to compute the current direction and velocity of movement and keep the direction while decreasing the velocity if it is reaching the maximum. The problem of such an approach is that the virtual pose keeps separating from the real one and the arising mismatch between real and virtual pose accumulates over time, without ever synchronizing again.

We therefore decided to design our low pass approach to adapt to the current pose while only decreasing the velocity if necessary. This way, there is still a smooth virtual experience without delay. If a user adapts to the maximal angular velocity there is even no difference between real and virtual movements.

In addition to the described simple low pass, we implemented a second low pass approach where the maximal angular velocity is no longer a constant factor, but depending on the current velocity. The faster a user moves, the lower the maximal velocity. This approach should force the user to move slower, since moving too fast would lead to very slow virtual movements. This approach is further on called *restricted low pass*. An additional feature of the restricted low pass is, that while not moving, the virtual character stops moving as well. In the simple low pass condition, the virtual character moves at maximum velocity as long as the virtual and real poses match.

The last factor we tested was the whether users would like to get visually informed about their real pose. Therefore, we included a third condition that slowed the movements down by the simple low pass, but additionally showed a transparent body that always followed the real-world pose instantly.

4.2 Simple Low Pass

The first approach is implemented by applying a low pass filter on the angular velocity between a joint's angle of the tracked user $Q(t)$ and the similar joint's angle of the virtual character $Q(c)$ (which still is the one of the last frame). Using this kind of representation, the virtual body moves as fast as possible, with the current pose of the user as a reference. The virtual pose is slowly adapting the real one if the user moves too fast. The used equations are as follows:

$$\Delta Q(t) = (Q(t)^{-1} \cdot Q(c)) \cdot \Delta t \tag{1}$$

$$Q_t(c) = (\Delta Q(t) \cdot Q_{t-1}(c)) \tag{2}$$

In equation 1, we calculate the angular velocity per second ($\Delta Q(t)$) which is interpolated according to the maximal allowed angular velocity (see section *Threshold Estimation*). Equation 2 then applies the interpolated rotation to the character joint's last orientation. The rotation of a bone is directly influenced by the prior bone defined by a kinematic chain, a graph which defines the connection (bones) of skeletal joints in a hierarchy. We start our low pass at the center of the body and process each branch of the kinematic chain's graph until the leafs considering the prior rotations. The index j stands for the current joint, while $j-1$ is the previous joint in the kinematic chain.

$$Q_t(u_j) = (Q_{t-1}(u_{j-1})^{-1} \cdot Q_t(u_{j-1})) \cdot Q_t(u_j) \tag{3}$$

4.3 Restricted Low Pass

The second approach is similar to the previous approach and is called a *restricted low pass*. While all calculations are done according to the regular low pass, an additional restriction regarding the angular velocity is applied. The calculated $\Delta Q(u)$ is no longer depending only on the maximum allowed velocity, but also on the current velocity of the user. The current velocity of a bone is divided by the threshold and applied to a non-linear function, which maps the quotient to a scale factor, which is 1 for movements slower than the threshold and slowly decreases to 0 when moving faster. Using this approach, the user should be able to control the virtual angular velocity better by actually forcing slower motions. While it is possible to see the virtual character move while not moving in reality using the simple low pass condition, the user has to move the respective bone to change the visual representation of posture with this approach. As long as the user's angular velocity is below the defined maximum, the character moves in real-time. When the user moves faster, the virtual character actually moves slower.

4.4 Low Pass with Forecast

The last feature we tested was showing the participant the adapted pose based on the slowed down movements, but the real pose as well, illustrated by a semi-transparent second body (see figure 1). When visually slowing down movements, the virtual body no longer follows the real movements which could lead to confusions or a loss of the feeling of body ownership and therefore to a decrease of presence. We therefore decided to use a third slow motion condition to get insights about whether users want to get feedback of their real-world movements. Since the virtual pose always adapted to the real pose with the maximal angular velocity, the transparent body which followed the movements in real-time can also be interpreted as forecast of virtual movements.

4.5 Pilot Test and Threshold Estimation

We conducted pilot tests with two initial participants to estimate thresholds for the maximal angular velocities for slow motion in VR. They performed the same test as described in the *study* section under real-time conditions. The measured mean angular velocities were used to determine the velocity thresholds, which were calculated as the mean angular velocity multiplied by 0.4 (the same time scale as the visual and auditory environmental cues). The threshold was determined for upper-body parts (around 60°/s) and lower-body parts (around 45°/s) separately.

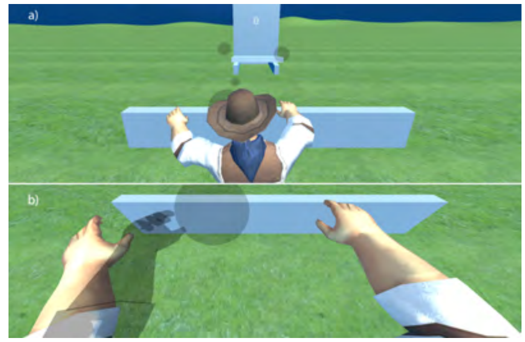

Figure 1: a) Overview of the scene. b) First person view of the transparent forecast metaphor.

5 STUDY DESIGN

Overall we used the three slow motion conditions: *simple low pass*, *restricted low pass* and *low pass with forecast* (each played with playback speed 0.4). Additionally, we tested a real-time condition without slowing down environmental cues nor the body movements. As a second ground truth, we also tested a condition where the virtual speed was in slow motion (playback speed 0.4) but without changing the character's movements. In this condition, the participants experienced slow motion only by environmental cues and were able to move as fast as they wanted.

In typical gaming scenarios, it is unlikely to experience slow motion at all times. Since one aim of the presented evaluation was on the playing experience, we tested each of the slow motion conditions two times, one with constant slow motion and one alternating real-time and slow motion multiple times during the tests.

We therefore tested eight conditions in total (the three slow motion conditions two times, plus the two ground truths). The sequence of conditions was determined by a latin square to compensate for learning effects in the analysis.

5.1 Method

We measured two experience related scores, presence and enjoyment, using the E^2I questionnaire [Lin et al. 2002] without memory task items after each condition. Since we slowed down movements, we also used the SSQ [Kennedy et al. 1993] questionnaire to test if simulator sickness is increased by our redirection approaches.

To analyze the movements of the participants, we also logged the angular velocity over time per joint. This data was used to get insights on how participants adapt their movements to the slow motion considering the different conditions.

To gain insights about the perceived control over the virtual body and realism, we asked participants to use a scale from *1 (not at all)* to *7 (absolutely)* to answer the following questions: *I was in control over my virtual body*, *I could predict the movements of the virtual character*, *The experience was realistic*, and *I would like to have such an experience in VR*. In addition, the participants should give an estimation of how long (in seconds) they had been playing. Both the questions and the estimation were asked for after each condition.

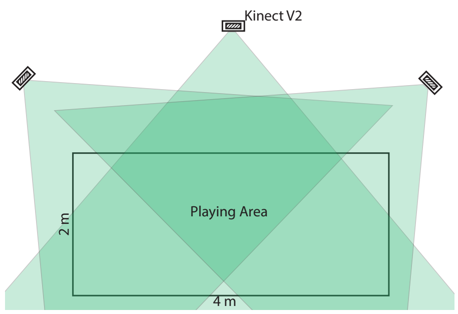

Figure 2: Top view of the playing area including Kinect positions.

After playing all conditions, an additional free text questionnaire was used to get qualitative insights on how the slow motion felt and what participants liked or disliked.

5.2 Participants

16 participants took part in our study (5 female; age 22 - 36 (mean 27)). Each participant was compensated with 5 Euro. We also asked each participant to describe their prior experience on VR on a five point Likert scale (from *1 none* to *5 very experienced*). Three participants had no prior VR experience, four stated the maximum of 5 (mean 3.7, standard deviation 1.4).

5.3 Setup

For tracking the movements, we used the FusionKit [Rietzler et al. 2016], a software designed for the fusion of multiple Kinect V2 sensors to enlarge the tracking space and optimize the accuracy compared to a single Kinect setup. The fused skeletal data was streamed via UDP to a mobile Unity3D application. A Unity3D application converted the skeletal data to its own coordinate system and transforms them to match a virtual character's bone angles. The virtual camera was applied to the head of the character, to allow a first person experience. We used a multi-Kinect setup with three Kinects placed in front of the user (see figure 2). Since the task did not involve turning around, the frontal tracking was sufficient. For the HMD hardware, we used a GearVR and a Samsung Galaxy S6, which was connected via WiFi to a master computer which handled the fusion of the Kinect data. We initially measured the delay between the FusionKit server and time of retrieval on the Smartphone, which was in mean below 3ms with a maximum of 10ms. The application was running at around 50 - 60 fps.

5.4 Task

We developed a game, where users had to hit bubbles that were flying towards the user within a limited area. The trajectories of the flying bubbles was chosen randomly within the area. Since the users could hit the bubbles with the whole body and the active playing area was large enough to force the user to walk within the tracking space, the task involved movements of all body parts as well as relocation of the user. We provided visual and auditory feedback about the playback speed. Visual feedback of the virtual playback speed was provided by the speed of the bubbles and the speed of falling raindrops. Auditory feedback included the sound of the rainfall, as well as the bursting sound when hitting a bubble, which were played slower and with less pitch during slow motion. The visual and auditory design of the scene was kept simple to leave the focus on the task and motions. We also wanted to include as less distracting factors as possible to reduce possible perceptual side effects. The scene (without effects) is shown in figure 1.

At the start of each condition, a training phase of 10 seconds was included, to let the participants get used to the current condition. The task started after the training phase.

While the participants were told to be able to influence the time of playing by hitting the targets, the duration was always limited to 70 seconds for all conditions. This time is given in real-time and not depending on the playback speed. This procedure was chosen to allow for a comparison between the perceived absolute time of playing and actual absolute one. Since the participants should not be influenced regarding their time estimation, they were not informed about any duration, including the duration of the training phase.

As stated above, a total of eight conditions was tested (listed here with the playback speed v and the type of movement redirection approach that was applied):

- *Control real-time*: Real-time (v = 1.0), no movement redirection
- *Control slow motion*: Permanent slow motion (v = 0.4), no movement redirection
- *Permanent low pass*: Permanent slow motion (v = 0.4), simple low pass movement redirection
- *Permanent forecast*: Permanent slow motion (v = 0.4), simple low pass movement redirection, w/ forecast
- *Permanent restricted low-pass*: slow motion (v = 0.4), restricted low-pass movement redirection
- *Alternating low pass*: Alternating slow motion (v = 0.4 ⊕ 1.0), simple low pass movement redirection
- *Alternating forecast*: Alternating slow motion (v = 0.4 ⊕ 1.0), simple low pass movement redirection, w/ forecast
- *Alternating restricted low-pass*: Alternating slow motion (v = 0.4 ⊕ 1.0), restricted low pass movement redirection

5.5 Procedure

Each participant was welcomed and informed about the topic of the study – the simulation of slow motion in VR. After this introduction, the participants signed a declaration of consent and a demographic questionnaire. The participants then played each condition in the order determined by a latin square. After each condition, the participants filled in the three questionnaires (E^2I, the SSQ and our own questionnaire). After the last condition, the participants filled in the final questionnaire, including free text questions. Each session lasted for about 45 minutes.

6 RESULTS

The presentation of the results is split in three categories. The first is about time perception, containing the results about time estimations. The second one contains the results of the recorded movements. The last category handles the results of the playing experience related items and questionnaires.

6.1 Impact on Time Perception

In the first part of our analysis we concentrate on how time perception and estimation was influenced by slow motion in general. These results were gained from the estimations given by the participants during the trials. All shown results are based on the *permanent* conditions, since the effect of alternating the playback speed is not predictable.

Comparing the Control Conditions: To be able to quantify the influence of environmental visual and auditory cues on the relation between estimated and real-time of playing, we first compared the two control conditions without any modifications of user movements, but only altered speed of environmental cues. We divided the estimated time by the real-time of playing (time quotient). Therefore, the estimate of 1.0 indicates a correct estimation, while e.g., 0.5 is an estimate of half the real-time of playing. Using the Wilcoxon signed-rank test for dependent variables we compared the medians of all of the participant's accuracy of time estimations. There was no significant difference between the two control conditions (p = .82).

Time Quotient in Redirected Slow Motion Conditions: We then ran the same comparison for the redirected, permanent slow motion conditions to both control conditions respectively, first using a Friedman *Two-Way Analysis of Variance by Ranks for dependent variables*. Here the difference was significant on the 5% level (see also figure 3). Since there was a significant difference, we also compared each slow motion condition with each control condition adjusting significance values by the Bonferroni correction. We could find significant ($p < .05$) differences between the low pass (*Median* 0.84) and the real-time control condition (*Median* 1.09) and between control condition 2 (*Median* 1.07) and all permanent redirected slow motion conditions.

In slow motion conditions including visual redirection, the participants judged the absolute time of playing about 25% less than in the real-time condition. This effect is likely caused by slowing down the movements since the comparison of the control groups showed that only slowing down visual and auditory cues did not have any significant effect. As shown in figure 3, there was a large standard deviation regarding the time estimations with *SD*=0.53 in the simple low pass condition, and *SD*=0.91 in the restricted low pass condition. Since even the real-time control condition had a large standard deviation of *SD*=0.67, we assume that it was difficult for participants to estimate the absolute duration in general at least during our tests.

Absolute Perceived Playback Speed: We also analyzed the relation of perceived playback speed to actual playback speed. When comparing perceived speed of the slow motion control condition to the redirected slow motion conditions, we found no significant differences ($p > .05$). This indicates that slowing down motions does not influence the perception of playback speed (see figure 3). When comparing slow motion conditions to the real-time conditions the results turned out as expected, since the slow motion effects could not be overlooked. Moreover, the participants were also able to

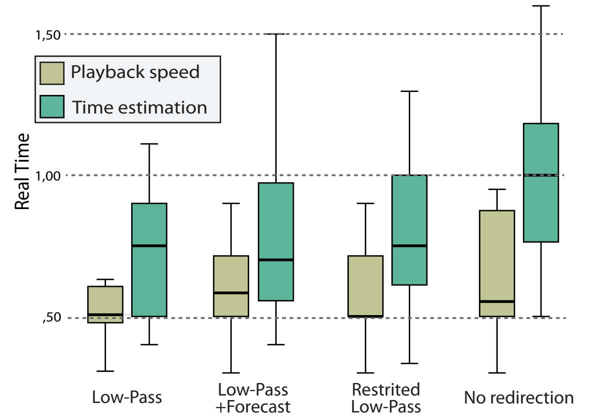

Figure 3: Box plots of the time quotient and perceived playback speed of the *permanent* conditions as well as the slow motion control condition (no redirection), each divided by the participants real-time control condition.

estimate the absolute playback speed very well (real-time: 0.95 instead of 1.0, mean slow motion: ~0.47 instead of 0.4) – an extent of absolute precision we found to be interesting in itself.

6.2 Movement

We also analyzed the movement data as logged during the trials, to gain insights on if and how users adjusted their body movements during the experiments.

Overall Adaptation of Movement Speed: We hypothesized that the participants would adapt their movement speed to the visually sensed maximum. We therefore analyzed the angular velocities over time of the fastest moving joint (which was in our tests the right elbow) since we assumed that this joint would mirror adaptions of speed in the best way. We compared the medians using an ANOVA and Tukey post-hoc tests. Interestingly, there was no significant difference between the simple and the restricted low pass condition (Means: 57°/s vs 62°/s, *SD*: 41 vs 42, $p > .05$). Considering the visual angular threshold of 60°/s for the wrist joints, users adapted their movement speed very precisely to the maximum.

In the real-time condition, the mean velocity was around 127°/s (*SD* = 175), while the slow motion control condition's mean was at around 125°/s (*SD* = 152). So there were no remarkable difference regarding the velocity of movements when only slowing down the playback speed without redirecting the movements.

Speed Group Distribution: To get further insights on how the participants moved in slow motion conditions, we normalized the angular velocities to five discrete groups. The categorization was done per participant considering the mean velocity and its standard deviation in the real-time condition. The first category was defined as *rest* which had the only constant threshold of 5°/s. *Slow movements* were defined as movements faster than rest and slower than *regular movements*, which started by the mean velocity minus half a standard deviation. *Fast movements* were defined as movements faster than the mean velocity plus half a standard deviation. Very fast movements, which we most of all considered to be *reactionary*

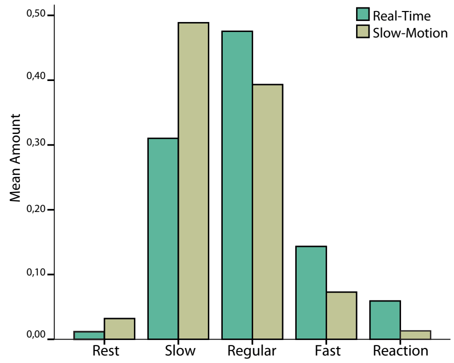

Figure 4: Distribution of the movement styles in real-time and slow motion.

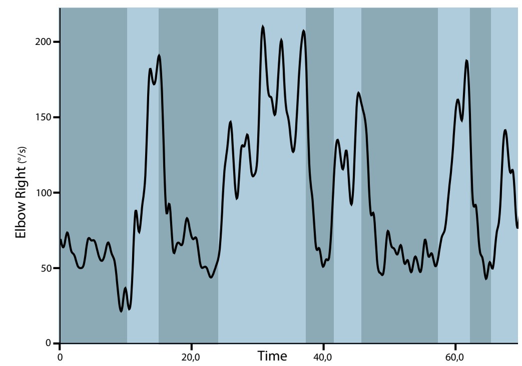

Figure 5: Average movement speed over time in the low pass alternating condition with time changes. (darker areas: slow motion)

actions, were defined as movements faster than the mean plus two times the standard deviation. The results (see figure 4) show, that the amount of slow movements in the slow motion conditions strongly increased, while most of all reactionary and fast actions were reduced. There was also little more resting in slow motion conditions, which could arise from the reduced speed of bubbles in the respective conditions. Since only little more resting periods could be measured, we assume that participants did not just move fast until the position they desired and rested, but truly adapted their velocity.

Adaptation rate: We also analyzed the times until a participant adapted to slow motion or real-time when alternated. Since there is no such definition of adaption, we defined a participant to have adapted to the condition at the time, when the mean velocity of the following 1.5 seconds was less or equal to the mean velocity of the same slow motion approach in the respective non-alternating conditions plus a tolerance of 5%. We excluded transitions, where a user was already moving slow before the time changed. The adaption time from real-time to slow motion was fastest using the restricted low pass (around 0.29s), followed by the restricted forecast condition (0.39ms). Using the simple low pass approach, the adaption took around 0.51ms. Though the reaction times differed using restrictions or the visual forecast, they did have a significant influence on the adaption time ($p < .05$ using Wilcoxon signed rank test). The adaption time from slow motion to real-time was equal for the restrictive and the simple low pass (around 0.5s), while it took significantly longer in the forecast condition (around 1s, $p < .05$ using Wilcoxon signed rank test). This leads to the conclusion that adaption of movement speed is a fast process, with the participants being faster when adapting to slow motion than to real-time velocities. An example of mean velocities sampled to 0.5 second steps is shown in figure 5.

6.3 Experience

After each condition, the participants filled the E^{2}I questionnaire and an own one containing items about the visually perceived movements (control, realism, predictability). The participants' answers were compared using the Friedman Two-Way Analysis of Variance by Ranks.

Realism: There was a significant difference ($p < 0.05$) regarding the judged degree of realism between all conditions. We therefore compared the three slow motion conditions to the real-time control condition, where no difference could be found ($p = .863$). The restricted slow motion movements were perceived as realistic as the ones in real-time. The only significant change could be found for the *alternating simple low pass w/ forecast* condition, which proved to be perceived as significantly more realistic.

Control: Regarding the perceived control of movements, there was no significant change between control conditions and all slow motion conditions. The only significant change of perceived control could be observed in the restricted low pass condition, where the participants perceived a loss of control. Box plots of the results are shown in figure 6.

Predictability: Further, we analyzed the participants' answers to the question if the movements were predictable using the Friedman analysis. No difference could be observed between the conditions.

We observed that with the restricted low pass condition, which "forced" a user to move slowly, by decreasing the visual velocity when the real velocity increased over a threshold, answers turned out to be more controversial than within the other conditions. The standard deviation shows that there were participants which preferred this kind of redirection, while others rated it worst in all scores. We therefore took a closer look on correlations between how a user moved and how he rated realism and control of the virtual body in this condition. Though not significant, there were negative correlations regarding the strength of acceleration and the felt control ($p = .062$, $\rho = -.478$), predictability ($p = .118$, $\rho = -.406$) and realism ($p = .096$, $\rho = -.430$). Similar tendencies could be observed for the velocity. We thus assume that this condition only was enjoyable for participants fully accepting the slow motion by adapting their real-world movement speed.

Presence: Comparing all conditions using the Friedman Two-Way Analysis of Variance by Ranks, we could not find any effects regarding the felt presence (see also figure 7). The presence was slightly decreasing when slow motion was presented permanently

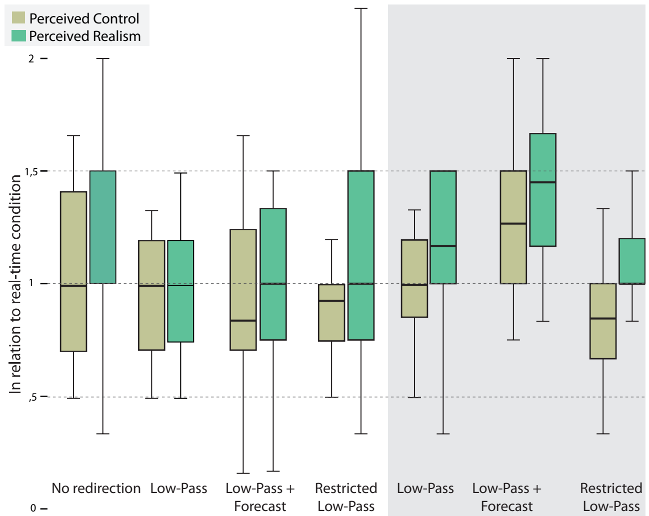

Figure 6: Boxplots of the perceived realism and control of movements relative to the control condition (the three conditions on the right are the alternating conditions).

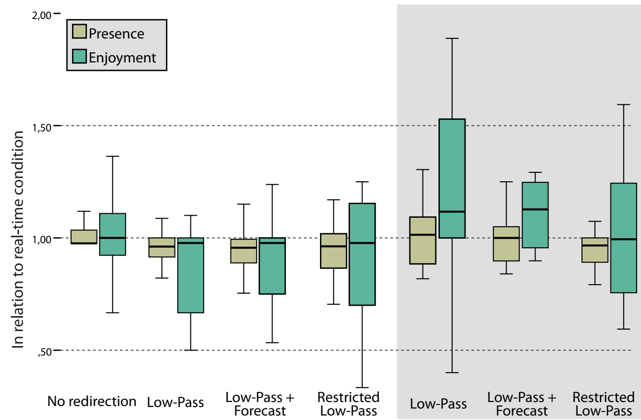

Figure 7: Box plots of presence and enjoyment scores relative to the control condition (the three conditions on the right are the alternating conditions).

during the whole test, while it even increased slightly for one condition when slow motion and real-time alternated.

Enjoyment: Regarding the enjoyment score, we found significant differences between the control group and the alternating conditions. Most of all, the difference between real-time and the alternating simple low pass with forecast (p = .013) and between real-time and alternating low pass (p = .028) showed that slow motion can have a positive effect on enjoyment in VR (see also figure 7). The same effect could also be observed when comparing the control conditions, whereas here the only significant increase of presence was found for the simple low-pass condition. Comparing the two control conditions, the resulting enjoyment scores did not show significant differences.

Simulator Sickness: We also analyzed the simulator sickness questionnaire (SSQ). None except one of the participant did suffer simulator sickness at all (scores below 5 – negligible). One had minimal symptoms for each condition. There was no difference between the conditions.

6.4 Overall analysis

We tried to gain further insights by combining data from the different questionnaires and the logged movements.

Relation of Presence, Control, Enjoyment and Realism: First, we searched for correlations using Spearman's rank correlation coefficient. Presence was strongly correlated to a feeling of control (p = .000, ρ = .646) and the perceived realism of movements (p = .000, ρ= .623). Enjoyment was most of all affected by the perceived realism of movements (p = .000, ρ = .740). This allows the assumption that perceived realism influences enjoyment in slow motion conditions.

Relation of Control, Predictability and User Adaptation: Combining the analyzed movement features with the questionnaires lead to more insights in how the user's adaption to the time conditions influenced the different scores. Though not significant, there was a remarkable negative correlation between acceleration in slow motion conditions and the felt control (p=.070, ρ=.-272) and predictability (p=.071, ρ=-.271) of movements. The amount of slow motions had a significant influence on enjoyment (p=.007, ρ=.398) – enjoyment was higher when participants adapted their movement speed. An equal effect could be observed for presence, though not significant on the 5% level (p=.076, ρ=.267).

User Acceptance: After each condition, the participants were asked if they would like to have such effects in VR applications on a 7 point Likert scale. Though there was no significant difference, a slight tendency towards the simple low pass with forecast could be observed (Mean: 5.4). The slow motion control condition (without affecting the movement) was less appreciated (Mean: 4.5). In a final questionnaire, we asked the participants if they liked slow motion in general. 87% of the participants affirmed this.

6.5 Participant's comments

In the final questionnaire, we also asked the participants to describe the different slow motion styles they could distinguish and how they perceived them. None of the participants could distinguish between the low pass and restricted low pass, though they rated both differently in the questionnaires. One participant requested a tutorial or a longer training phase. Many participants reported, that they liked the visual representation of a slowed down movement, but stated that it was too slow. One wished to have no restrictions of body movements at all. Some participants complained about the task which was either not demanding or not spectacular enough. The most frequent desire was the use of guns and to dodge bullets in a shooting scenario. One participant stated the desire for more visual feedback of slow motion like motion blur.

6.6 Interpretation and Discussion

In the first part of this paper, we stated several hypotheses regarding time perception, movements as well as on user experience. With the analysis of the gathered data, we are able to answer or at least partially answer the questions.

Regarding the influence of environmental slow motion effects on the time perception, the comparison of the two control condition showed no remarkable or significant difference. We therefore assume that such features do not influence time perception. Our results thus match Schatzschneider's and Bruder's results, who could also find no difference in time perception while changing the speed of a virtual sun.

We also analyzed the influence of slow motion movement redirection on time estimations. Due to our within subject design, we could only acquire prospective time estimates, since the participants would know to be asked for a time estimation after the first trial. Our results show, that there is a significant decrease of perceived duration in slow motion conditions – an effect that could only be observed when movements were visually slowed down. Changing the playback speed without affecting movements did not have any effect on time estimation. There were very high standard deviations regarding all estimates, however the perceived duration were significantly decreased by around 25% compared to the real-time (and 23% compared to the slow motion condition without influencing movements). This is a strong hint towards the potential of influencing time perception in VR by temporally scaling movements.

We also assumed that the perceived playback speed would be influenced by both, the environmental and the movement features. While both conditions significantly differed compared to the real-time condition (which is obvious), there was no difference between slow motion with and without redirection. The users could estimate the playback speed for each condition remarkably precisely (estimated: 0.46, applied: 0.4).

Regarding the user's motions, we could observe that the participants adapted their angular velocity very closely to the defined threshold of $60°/s$ (mean over all slow motion conditions: $59°/s$). In addition, the measured time until the participants changed their angular velocity to the maximum, which was by around 0.3s. Those facts support the hypothesis that users adapt quickly to speed changes by restricting their movement speed. Participants on the other hand did not change their behavior when only playback speed was decreased.

The analysis of the questionnaire items about the perceived control and realism of movements showed that there is no difference between real-time and slow motion conditions. The comparison of realism even emphasized an increase when alternating times. We assume that this is caused by the desire of getting involved into the virtual world and that users are willing to accept unrealistic features as realistic, if they are reasonable (like the slowed down movements in slow motion).

We also compared the perceived presence between the different conditions and could not find any differences, independent of the applied redirection technique. For enjoyment, there was a significant increase when slow motion and real-time speed were alternating. In slow motion only conditions, the enjoyment was slightly but not significantly lower than during real-time only conditions. The results of the questionnaire items proved that participants liked the respective slow motion style, as well as 87% of participants stating they would like to have such slow motion effects in VR, which is also supporting the idea of using slow motion as a stylistic device in VR applications.

The negative correlations between the amount of slow movements and the felt presence and enjoyment (though not significant) led us to the assumption, that enjoyment and presence seem to be dependent on how the users adapt their speed. While the restricted low pass condition was designed to force the user to adopt angular velocities, it was perceived controversial. Some participants felt much more control and realism of the movements as well as an increased enjoyment and presence, while other users stated the opposite. Since we did not include any kind of tutorial on how to move in slow motion, we assume that this controversial was caused by the less intuitive phenomena of moving slower, when actually moving faster. While the participants who adapted their movements accordingly by decreasing velocity and acceleration felt significantly more enjoyment, there was also a non-significant tendency towards an increase of felt control, realism and predictability of movements when adapting. In addition, there was no participant who distinguished the simple low pass and the restrictive low pass conditions in the final questionnaire. We therefore assume that this approach – although performed worse than the others – could be promising when users get used to it.

The analysis of the SSQ did not show any changes between the conditions, while there was only one user at all suffering slight effects of simulator sickness during the participation.

6.7 Limitations

Though we gained a lot of insights in how users perceive slow motion in VR during different treatments, many more questions arise by the results, like the influence of the velocity thresholds. The chosen thresholds of scaling down the movements to 0.4 times the mean real-time velocity seemed to be too low for many participants. We assume that choosing higher thresholds could improve enjoyment as well as other presented results. On the other side, the extreme threshold shows, that the concept of visually slow down movements by redirecting can also be applied using extreme values.

The 16 participants were enough to get first insights on many of our hypotheses, but are not enough to finally validate or reject all of them. The list of different influence factors is much too long to be investigated probably in one study.

For the results regarding time estimation, we could only compare prospective data, due to the within subject design. In future work, this could also be done on retrospective estimations by reducing the tested conditions.

The design of the task was done without any disturbing or influencing visual or auditory cues, which on one side should make the experiments more controllable and the results more reliable, but on the other side, we assume that many effects (most of all the increase in enjoyment), would be much more impressive using a more appealing scenario and design of the virtual scene.

7 IMPLICATIONS

A large majority of the participants would like to have slow motion in virtual reality given a suitable use case. According to their preferences, slow motion should also be represented by manipulating the virtual character's movements. The results of our questionnaires support this finding. While enjoyment was increased, interestingly, the potential mismatch between the real and virtual pose did not decrease presence. Participants also did not report any loss of control over the virtual body when redirected, it was even increased in the *forecast* condition. Our item on the judgement of realism was an interesting one. Speaking of realism when actually manipulating time and even the own body movements is hard to define. Our participants rated realism as very high, and even higher when manipulating movements (in the *forecast* condition). We therefore argue, that movements should be affected by slow motion, but there should be a visual hint about the real pose.

In our *restricted low pass* condition, we forced the users to adapt to the maximal velocity. Here the results are ambiguous. Some participants rated this restriction most realistic, having the greatest experience of realism, while others rated it worst of all and reported a loss of control over the virtual body. As our results showed a negative correlation between velocity and enjoyment, we assume, that this kind of slow motion representation was the less intuitive one. Participants who adjusted their movements had a very good experience, while those who did not struggled with this condition. We therefore suggest providing some kind of tutorial that explains how the underlying mechanisms work to improve the experience.

Moreover, the applied maximal angular velocity of 60°/s was too low for some participants, we suggest testing other threshold values to improve the experience depending on the application.

8 CONCLUSION AND FUTURE WORK

In this paper we described the results of a study on simulating slow motion in virtual reality using full-body tracking. We compared three different conditions slowing down the movements of the virtual character to a defined maximum by visual redirections to two control conditions without redirection. Our results show, that it is possible to slow down body movements by redirection without decreasing presence or increasing simulator sickness. When slow motion and real-time alternates, which would be the case in common gaming scenarios, the participants even perceived the movements as more realistic and controllable compared to the two control conditions. Restricting body movements also proved to enhance the enjoyment and the participants stated to be fond of such effects in VR gaming. By measuring the angular velocities during the tests, we could show that the users adapt their real movement speed close to the visually perceived maximum within a short time, which helps in increasing presence and enjoyment.

In addition, we found that the restriction of body movements influences time estimations. Participants estimated the playing time to be 25% less in slow motion with redirection while it remained unchanged without.

We assume that our results can be applied to other virtual reality formats using three-dimensional tracking (like e.g., controllers or upper-body only situations), since the underlying principles are the same. The presented results therefore cover a wide area of scenarios and applications, since such an approach could also be applied to simulate other features, like e.g., the restriction of water or different gravitation.

We also were able to identify many possible influence factors that could be investigated in the future, like the influence of different thresholds on presence, enjoyment and time perception or the introduction of additional visual features, similar to the tested visual forecast, like stronger motion blur.

Overall, we conclude that VR seems to be suitable for including slow motion effects for storytelling purposes when done the right way. Our results strongly indicate that effects of slow motion should be applied to both environmental cues and the visual representation of character movements to get a persistent experience. Users adapt their own velocity to visually presented restrictions. When doing so presence not only remains untouched but may also even increase though the visual movements do no longer perfectly match the real ones. Our results further indicate that both movements – the real ones and the adapted ones – should be visualized to increase presence. Forcing a user to slow down movements negatively influenced presence and seems therefore not to be a suitable approach.

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