From Clocks to Pendulums: A Study on the Influence of External Moving Objects on Time Perception in Virtual Environments

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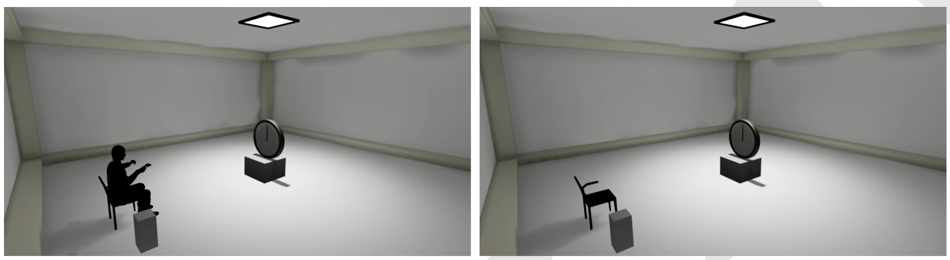

Figure 1: Participants observed objects, like a clock, for 30s each. In study 1, they watched a scene video on a monitor as if present. In study 2, they used a VR headset. Left: embodied avatar; Right: scene without avatar.

ABSTRACT

This paper investigates the relationship between perceived object motion and the experience of time in virtual environments. We developed an application to measure how the motion properties of virtual objects and the degree of immersion and embodiment may affect the time experience. A first study (n = 145) was conducted remotely using an online video survey, while a second study (n = 60) was conducted under laboratory conditions in virtual reality (VR). Participants in both studies experienced seven different virtual objects in a randomized order and then answered questions about time experience. The VR study added an "embodiment" condition in which participants were either represented by a virtual full body or lacked any form of virtual body representation. In both studies, time was judged to pass faster when viewing oscillating motion in immersive and non-immersive settings and independently of the presence or absence of a virtual body. This trend was strongest when virtual pendulums were displayed. Both studies also found a significant inverse correlation between the passage of time and boredom. Our results support the development of applications that manipulate the perception of time in virtual environments for therapeutic use, for instance, for disorders such as depression, autism, and schizophrenia. Disturbances in the perception of time are known to be associated with these disorders.

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CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Empirical studies in HCI**; **Mixed / augmented reality**; *HCI theory, concepts and models*; Displays and imagers.

KEYWORDS

virtual reality, mixed reality, extended reality, time perception, embodiment, virtual time, virtual zeitgeber

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1 INTRODUCTION

The factors and effects that influence our perception of space and time have long been the subject of psychological research. In particular, time perception has been the subject of extensive research because it plays a crucial role in our daily lives. The ability to accurately perceive and estimate the duration of events is essential for both physical and mental well-being. However, several factors can influence our perception of time, including attentional processes, emotional states, and environmental stimuli. For example, the presence or absence of environmental stimuli, such as clocks or sunsets, can affect our ability to accurately estimate the duration of events. Events could be anything in our daily life we perceive as a contiguous unit, such as waiting for a doctor's appointment to happen, which is also already an estimate-able event, as well as the examination by the doctor. The variability, density, synchronicity and predictability of events also play an important role in how we perceive them. These external environmental stimuli that help synchronize our inner clock and regulate our sense of time and are also known as internal or external zeitgebers [26, 42]. When we use such zeitgebers in a virtual environment, we can accordingly speak of virtual zeitgebers. External virtual zeitgebers, such as clocks, fans, or pendulums, are easy to manipulate and control, making them an ideal tool for studying the influence of environmental stimuli on time perception. In recent years, virtual reality (VR) technology has emerged as a promising tool for investigating the influence of these factors on time perception. By simulating real-world environments, VR provides a unique platform for studying the complex interplay between environmental stimuli and cognitive processes that contribute to our perception of time. In addition, VR can also be used as a therapeutic tool to improve time perception in patients with temporal distortions, such as those with depression or anxiety [55, 56]. In a recent study, participants were asked to view virtual zeitgebers in a VR environment and then report on their subjective experience of time. The results showed that exposure to virtual zeitgebers can significantly affect participants' perception of time. For example, the speed of a virtual sun influenced time estimates when no cognitive task was present [42]. The speed and frequency of a simulated movement through a virtual tunnel, showed not only an influence on time experience but also a link between judged speed of time and vection [25]. In the studies presented here, we specifically investigated the use of external virtual zeitgebers and validated whether they are able to influence observers' subjective perception of time. Participants used a virtual environment in a non-immersive display setting (monitor) in Study 1 and in an immersive display setting (hmd) in Study 2. In both studies, they observed various virtual external zeitgebers, such as a clock, a fan, or a pendulum. After exposure, they were asked to report their subjective experience of time. The aim of these studies was to evaluate the effects of these virtual zeitgebers on participants' judgements about their perception of time. The results suggest that virtual zeitgebers could be used in the design of VR-based interventions to regulate and normalize patients' perception of time. Further research is needed to investigate the efficacy of VR-based interventions in the clinical setting and to determine the most appropriate virtual stimuli to optimize therapeutic outcomes.

2 RELATED WORK

2.1 Time Perception

Physical time is understood as the time given and measured using clocks in the real world. *Psychological time* is often described as being subjective, referring to experienced temporal dimensions of duration, speed, and the order of perceived events [58]. According to Schatzschneider et al., Landeck et al. and Unruh et al. [26, 42, 53], time judgements could be manipulated in different virtual environments, and as of now we want to refer to *virtual time* in this context. In a virtual world, *Physical Time* drives the simulation update intervals. Changes to the position, animation and logic of objects are based on the time elapsed between two updates (also known as *Delta Time*). This measured *Delta Time* can be artificially increased or decreased by a certain factor, the *Time Dilation Factor*, typically resulting in faster or slower object motion. Consequently, the *Virtual Time* can either be equal to the *Physical Time*, or it can be manipulated in VR to potentially affect the *Psychological Time*, for example, by making the object fall slower than usual. There are many factors that can influence *Psychological Time*. Here we refer to the *passage of time* as the speed at which time subjectively passes when perceiving events and *duration estimation* when estimating time frames retrospectively. How we subjectively experience temporal moments can be extremely variable. An influencing factor is attention, where splitting the focus between a task and time can lead to a subjective acceleration or deceleration of time. This has been described in psychology with the 'attentional gate model' (AGM) [59], which "...holds that a person may divide attentional resources between attending to external events and attending to time. An 'optimal experience' is one in which attention is placed solely on the task, and time appears to pass much faster. This creates a state characterized by a loss of the sense of time and self, and deep concentration on the task at hand [57]. This altered time perception is a mental state known as 'flow', coined by Csikszentmihalyi [9]. For example, participants in a VR video-game study who experienced higher levels of flow not only performed better in the game, but also estimated time passing more quickly [40]. The estimation of time is a fundamental feature of interpreting 'cause and effect', meaning that it is imperative to our own feelings of agency [13], the idea that we as individuals are able to interact with the world and maintain the feeling that it is we who are causing an effect. Both the feelings of agency and the estimation of time are altered in pathological mental conditions, such as depression, autism, and schizophrenia [2, 24, 32]. How time passes has been the subject of much research, particularly on how one can modulate the subjective experience. Promising results have been found by applying modern technological advancements from the realm of gaming and virtual environments. For example, Kuehn et al. [24] were able to modulate the subjective time experience as a therapeutic approach. Patients suffering under depression reported a trend for rumination to decrease after playing an infinite runner game named "Boson X". In addition to the mediation of perceived time through attention, psychological research has already identified factors and effects that influence our relativity of space-time perception. Two prominent and well-known effects are exemplary for the relativity of space-time perception, the 'tau effect' [3, 14] and the 'kappa effect' [1, 8]. Longer time intervals appear to take place over larger spatial distances (tau) and a longer temporal interval could be made to appear shorter by decreasing the spatial distance between successive flashes and vice versa (kappa). Brown et al. [5] examined the effects of motion stimuli on time perception. In a series of experiments, measured either by judgments or with reproduction tasks, faster speeds lengthened perceived time more than slower speeds, and intervals with more changes were judged as longer than intervals with fewer changes. We extended these findings and tested how different appearances and motion characteristics of external virtual zeitgebers manipulate observers' attention and temporal experience, and how this influences judgments between a non-VR and a VR setup.

2.2 Time Perception in VR

Virtual Reality (VR) can be used to create controlled environments that allow the investigation of responses to many questions in a less dangerous environment. LaViaola [28] defined VR as "...an approach that uses displays, tracking, and other technologies to immerse the user in a virtual environment." This virtual environment can be seen from a first-person perspective through a display device that is under the user‘s real-time control. When users are more convinced they are inside the virtual environment, it is traditionally called the 'sense of presence' [6, 29, 49]. Presence is also often extended to the concept of a place illusion. This refers to the virtual place, and consequently, the plausibility of events occurring in this virtual environment is often referred to as a 'plausibility illusion' [41, 47]. Schneider et al. [44, 45] already demonstrated that by immersing patients inside a virtual environment (VE), time perception can be passively influenced by the VR headset as a distraction itself. Malpica et al. [31] provided evidence that larger visual changes shorten perceived time (monitor vs. VR). Schatzschneider et al. [42] showed that subjective time perception could be scaled inside a VE and manipulated by virtual "zeitgebers". "Zeitgebers are cues that help to locate oneself in time or to mark the passing of time. i.e., the speed of time" [42]. This concept was extended in work by Landeck et al. [26]. Traditionally, zeitgebers are external cues that provide timing information to the internal biological clock of an organism. They play a critical role in regulating circadian rhythms and synchronizing the physiology and behavior of an organism with its environment. Schatzschneider et al. [42] extended and applied the term to non-circadian-rythm related topics and summarized different categorizations of zeitgebers, internal, referring to the traditional usage of the term, and external, to refer to stimuli in the external world where organisms rely on to experience time. They also divided the zeitgebers into further subcategories: Absolute zeitgebers, which indicate the time of day, such as the position of the sun in the sky, and relative zeitgebers, which indicate the speed at which time is passing. Landeck et al. [25] were the first to test the vection on retrospective time experience in a VR simulation. Faster speeds led to significantly higher passage of time ratings, for example, they confirmed that the corresponding velocity of the virtual tunnel and the amount of tunnel sections enhanced virtual time.

2.3 Contributions

To summarize the presented research, time research in virtual reality is already well advanced, but we are, to the best of our knowledge, the first to investigate space-time relativity in VR with different external virtual zeitgebers. In contrast to previous investigations of virtual waiting room scenarios, the trial length is set to 30 seconds to counteract emphasized focus on time and boredom. We investigate their properties such as the type of motion, the number of spatial dimensions in which the motion takes place, and the number of visible moving parts. These play an important role in how boring the scenario is to watch, but also in how fast time is perceived to pass and how much observers actively think about time.

3 HYPOTHESES

In line with previous work and according to our main motivation, the following hypotheses were developed:

(H1) External virtual zeitgebers associated with more visible changes will be perceived longer than zeitgebers with fewer changes.

(H2) Oscillatory motion behavior of an external virtual zeitgeber will lead to higher passage of time ratings in comparison to zeitgebers with linear motion behavior.

(H3) There will be a linear relationship between boredom ratings and passage of time ratings.

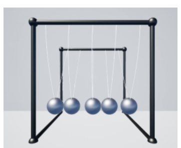
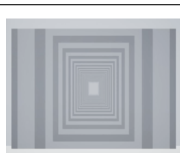
(H4) External virtual zeitgebers associated with movements involving more dimensions will be perceived faster than zeitgebers with fewer dimensions.

(H5) For participants who are embodied in a full-body virtual representation, time experience will be changed when watching external virtual zeitgebers compared to participants who were not embodied.

4 APPARATUS

The Unreal Engine 4.27 [11] was used to develop the virtual reality application for the two studies presented. It was used to create the external virtual zeitgebers, the experimental parameters, the virtual user and the virtual environment. The seven different zeitgebers were placed $3m$ in front of the participant while the participant was seated. The average speeds of the moving parts of the zeitgebers were measured with virtual probes attached, and we tried to ensure comparability by using similar accelerations and speeds. The selected zeitgebers represented different types of motion, from zeitgebers with rotary motion (clock, fan) to zeitgebers with irregular or oscillating motion (newton pendulum, orbital pendulum, torch) or simple linear motion (starfield, tunnel). The zeitgebers were chosen because of their different types of motion, because of the different number of dimensions in the (virtual) space where the motion takes place, because of the different number of visible moving parts and their occurrence in the related literature. The selection criteria are summarized in Table 1. The maximum velocity was measured to be $90cm/s$. In addition, simple materials, gray and silver, were chosen for all zeitgebers to control as much as possible the confounding effect of color as a distractor. From the beginning, the participant was placed exactly in the center of the virtual space. A visual representation of the virtual environment can be seen in Figure 1. Benchmarks were used to ensure a consistent frame rate that matched the frame rates of the target devices. When the trial end was reached, the display faded out and the in vivo questionnaires appeared. The application recorded the responses to the questionnaires and automatically saved them after each trial. This application was used to evaluate the study parameters. It was also used to record the videos played to the participants in the remote online study.

Table 1: The selected zeitgebers

Zeitgeber	Motion Type	Movement description and argument for selection
	Rotary	The clock arm is rotating around the center at a constant speed continuously, and the movement takes place in 2 dimensions. A clock is a well-known object that is associated with time and represents a rotary motion type. A summary of several studies has shown that altered time perception can be effectively induced by manipulated (sped-up or slowed-down) external clocks [50]. According to Brown [5], and Kaneko et al. [20], faster speeds and intervals with more changes were able to influence time perception. Since the speed is set to be comparable at 90 cm/s and the interval changes are low, we expect it to have a medium effect.
	Rotary	The 4 fan blades are rotating around the center in a constant speed continuously and the movement takes place in 2 dimensions. The fan represents a rotary moving object, but not associated with time directly, as the clock. Four blades rotating instead of one clock arm, and according to Brown [5], intervals with more visible changes were perceived to be longer than intervals with fewer changes.
	Oscillating	The Newton pendulum consists of 5 visible moving parts (spheres) and swings back and forth from left to right. The movement takes place in two dimensions and it represents an external zeitgeber with an oscillating motion type. Kaneko et al. [20] investigated motion properties in space, time and frequencies. We believe that expectations from the real world play an important role at the processing stage. Regular or linear motion patterns seem to be easier to replicate and are less distinguishable from reality, e.g., virtual clocks.
	Oscillating	The Orbit pendulum consists of 5 circles with different attachment points. The inner circle is attached to the inner sphere in the center and is oscillating around it. Every next circle is attached to the previous circle and is oscillating on its own. The visible moving parts are the 5 circles where spheres of different sizes are attached. These parts move in 3 dimensions and around the center. The orbit pendulum was added to enrich the collection with an oscillating zeitgeber that moves in 3 dimensions.
	Linear	The starfield consists of continuously moving bright spheres towards the observer. This setup is often used for vection (visually induced self-motion) experiments [52]. It is also of interest in various psychological studies [18]. In addition, Kanai et al. [19] showed that the temporal frequency of a stimulus could serve as the "clock" for perceived duration. They tested this with expanding grating stimuli, which is represented by the starfield and the tunnel zeitgeber.
	Irregular	The torch is often related to as relaxing and warming, but its movement is also described as complex and irregular. This makes it an ideal candidate to test it against the zeitgebers of linear, oscillating and rotary motion type. The torch consists of a particle system and this continuously emits a particle count in a fixed range of time. Blood pressure values were compared before and after viewing the simulated fire with and without sound. The results showed a consistent decrease in blood pressure. The prediction that fire would be captivating and elicit a relaxation response because of its visual flicker was partially confirmed by the reductions in blood pressure in the fire-without-sound situation [10].
	Linear	The tunnel is similar to the starfield zeitgeber. It consists of the properties: tunnel segments ratio and amount. It is continuously moving towards the observer. It is described as a journey through a virtual tunnel, and an impact on time experience was shown by Landeck et al. [25]. Kanai et al. [19] explored expanding grating stimuli influences on time perception and the tunnel could be classified as expanding stimuli.

5 STUDY 1: REMOTE ONLINE STUDY

5.1 Design

Online access to the study was achieved through a participant recruitment system where students and external users could view the list and sign up. The desktop study consisted of 12 pages. On the 12 pages there were buttons, text inputs or visual analog scales to answer. There was an automatic video playback embedded in the condition pages after which it disappeared, and questions for time-duration judgments, passage of time, time thinking and boredom appeared. This was tested on several browser and monitor configurations to ensure comparability.

5.2 Procedure

Participants were recruited through an online university participant portal. On the welcome page, participants were greeted and consent to the privacy policy was mandatory to proceed to the next page. Participants were then asked general demographic questions about gender, age, education, and vision. On the following page, information was provided about the videos and participants were asked to remove all distractions and not listen to music. The instruction was to focus on the videos and not to develop counting strategies. Since the subjects watched several videos, we decided to tell them in advance that their experience of time, not their ability to count, was being assessed. The first condition started on the following page. A page with a button was loaded, and once the button was clicked, the video was played. After the video had played, four questions were displayed (time estimate, time passage, time thinking and boredom). All 7 conditions were displayed in random order. After the survey was completed, the final page was loaded and participants were thanked and given the opportunity to leave a comment.

5.3 Software and Hardware

The online study was designed with LimeSurvey version 4.5.0 [43] . Custom functionality was put in using HTML and javascript code. An explicit start button for the video playback ensured that all participants were ready to focus from the beginning on. The results were exported from LimeSurvey hosted at the university and analyzed using JASP v.0.14 [16] and the programming language R.

5.4 Participants

We had 147 respondents in total. Two had to be excluded due to extreme outliers: the highest time estimate was 340 seconds for a 30-second video. Final sample of N = 145 with an average age of 21.2 years (117 females and 28 males).

5.5 Measures

5.5.1 Duration Estimation, Passage of Time, Time Thinking and Boredom. We implemented the Subjective Time, Self, and Space (STSS) questionnaire [17] to assess the effects of the virtual tunnel, perceived on a computer monitor, on time experience and bodily perception. Two items from the STSS were adapted to assess the experience of the passage of time: 1) “Intuitively, without thinking about it, how long did the trial last?,”2) “How fast did time pass for you?” (based on Tobin et al. [51]). In addition the item was asked: 3) “How often did you think about time?”, and 4) "How bored have you been?". Except for the first question, all other questions were answered using a vertical streak on a horizontal line, a visual analog scale (VAS) that ranged from 0 to 100.

5.6 Statistical Analysis

We conducted repeated-measures ANOVAs to test which effects the perceived objects had on the estimation of duration, the subjective passage of time, time thinking and boredom ratings. Time-duration estimations, passage of time, time thinking and boredom ratings were analyzed using the interval measurement scale [17, 34]. Normality was tested with the Shapiro-Wilk test. The assumption of sphericity was checked using the Mauchly test, and sphericity corrections were made with the Greenhouse-Geisser correction when necessary. We used JASP v.0.16.4 [16] for the analyzes. We conducted Spearman’s correlations between the four dependent variables of duration estimation, passage of time, time thinking and boredom for each perceived object.

5.7 Results

5.7.1 Duration Estimation. For this dependent variable variance homogeneity, but not normality, were assumed. Although the Anova is quite robust to violations of normality, we still performed it with log transformed duration estimates. It revealed that there was a statistically significant difference between at least two groups ($F(4.84, 696.97) = 5.517, p < 0.001$). In a post-hoc analysis, with respect to the dependent variable of duration estimation (judgement in seconds), the duration of the trial length was significantly judged shorter for the clock in comparison to the fan, the torch and both pendulums ($p < .001$). The tunnel was judged significantly shorter in comparison to the fan, the newton pendulum and the torch. The starfield was judged significantly shorter in comparison to the newton pendulum.

5.7.2 Passage Of Time. For this dependent variable variance homogeneity could not be, but normality, could be assumed. It revealed that there was a statistically significant difference between at least two groups ($F(5.49, 790.83) = 23.795, p < 0.001$). In a post-hoc analysis, participants rated significantly higher passage of time for the clock zeitgeber compared to the fan, starfield, tunnel and torch zeitgeber ($p < .001$). The newton pendulum was rated significantly higher in comparison to fan, starfield, tunnel and torch ($p < .001$). The orbit pendulum was rated significantly higher in comparison to the fan, starfield, tunnel and torch ($p < .001$). The torch was rated significantly higher in comparison to the fan.

5.7.3 Time Thinking. This dependent variable, which is violating the sphericity assumption, but not normality, revealed that there was a statistically significant difference ($F(5.42, 780.98) = 21.554, p < 0.001$). For the dependent variable of time thinking, the clock was significantly rated highest ($p < .001$). The fan was rated significantly higher in terms of time-thinking ratings compared to both pendulums. The orbit pendulum was rated significantly higher in how much participants thought about time in comparison to the torch, starfield and the tunnel zeitgeber.

5.7.4 Boredom. The dependent variable of the boredom ratings is violating the sphericity assumption but not the normality assumption. It revealed a significant difference between the zeitgebers, ($F(5.38, 774.34) = 27.876, p < 0.001$). The fan was rated significantly with the highest boredom ratings, in comparison to all other zeitgebers ($p < .001$). The newton pendulum was significantly rated with less boredom compared to the fan, the starfield, the tunnel, and the torch zeitgeber ($p < .001$). The orbit pendulum was rated significantly lower in boredom compared to all other zeitgebers except the other pendulum ($p < .001$).

5.7.5 Correlations. The Spearman correlation is more reliable in this case because some of the data is not normally distributed. You can also perform a Pearson correlation on non-normally distributed data, but it is not as reliable as a non-parametric test, which does not assume a normal distribution. Summarized, we found a strong inverse correlation with high significance ($r = -0.72, p < 0.01$) between Boredom and Time Passing ratings in this study.

5.8 Limitations

We gave clear instructions on how to use the browser in full-screen mode after the demographic questionnaire and previous assessments of fatigue and boredom. We instructed participants at the outset not to use mobile devices, to keep all distracting elements away from the computer screen, and to focus on the virtual objects as best they could. Potential distractions could not be completely ruled out and remain as a limitation for this study design. The size of the screens and the distances the participants sat in front of their screens could not be recorded. Since there was a high amount of female participants in this study, in contrast to the male participants, this should be mentioned as an additional limitation.

6 STUDY 2: VR STUDY

6.1 Design

Additional parameters were supported for the VR simulation: a virtual full-body representation and a virtual chair. Participants were asked to leave their controllers with their hands on the armrest after the initial calibration and acclimatization phase. The application was responsible for calibrating the user, setting up the condition parameters, and starting and stopping the experimental logic where the external virtual zeitgebers were placed sequentially in random order. A physical chair was present in the experimental room to provide a haptic experience corresponding to the virtual chair. It served to provide additional haptic feedback, which was expected to increase presence even in the absence of a virtual avatar. A virtual headphone was present on a shelf next to the participant in the virtual room. Putting on the virtual headphones was used as a familiarization task and served another purpose: to get haptic feedback on the ears through the VR headset's headphones and to be able to hear white background noise to avoid unwanted external noise influences. The virtual chair and the virtual room served as a frame of reference to the user's position and orientation and to provide a contrast to the moving zeitgebers. This, along with the participant's seated position, was expected to reduce discomfort from visually induced motion sickness [7] and increase focus on the external virtual zeitgebers.

6.2 Procedure

Participants were informed about the details of the study and asked to sign an informed consent form. They were given a demographic questionnaire and a questionnaire to assess their current well-being. The participants were then asked to complete the Virtual Reality Sickness Questionnaire (VRSQ). The experimenter explained the basics of the experiment, as well as the VR devices. Participants were seated at a chair and asked to perform a t-pose for the avatar calibration and then to do the following tasks, reporting any problems aloud: 1) move their head to visually explore the virtual environment, 2) move their hands, 3) touch the virtual chair with their hands. They were then asked to pick up the virtual headphones and attach them to their virtual body. In addition, a mirror was shown only during the initial familiarization phase. This familiarized the subjects with the virtual environment and showed them how to answer the questions that appeared at the end of each trial. See Table 1 for the set of zeitgebers that were displayed. The trials were randomised at the beginning of the series for 100 participants using a pseudo-randomizer [12] to avoid any unintended influence of a particular combination. Each of the seven virtual zeitgebers was displayed for 30 seconds and followed by in vivo questions on time judgement, time passing, thinking about time and boredom. Participants were asked to complete the VRSQ again after the experimental session and to complete the Igroup Presence Questionnaire (IPQ) and the Virtual Embodiment Questionnaire (VEQ) for the first time. This completed the study and the participants were dismissed.

6.3 Software and Hardware

Participants experienced the VR environment with the HTC Vive Pro head-mounted display (HMD) with a resolution of 1440 × 1600 pixels per eye and an 90 Hz refresh rate. The field of view was 110°. Two controllers were employed to respond to presented questions following a trial. The PC specifications were as follows: Intel i7-9700K processor, 32 GB RAM, GeForce RTX 2080Ti.

6.4 Participants

Sixty participants with an average age of 21 years were recruited (44 females and 16 males). The vast majority were students from the University, recruited via an online platform. According to the changes in the regulations during the COVID-19 pandemic, participants completed a verbal checklist of symptoms and presented a negative antigen test or vaccination certificate the day of the trial. Each participant was given ten Euros for their participation. This study was approved by the local Ethics Committee of the Institute.

6.5 Measures

6.5.1 VRSQ. The Virtual Reality Sickness Questionnaire (VRSQ) [23] was used to assess simulator sickness before and after the experiment. This is a shortened version of the Simulator Sickness Questionnaire (SSQ) [21]. It has been adapted for use in VR. It includes the 2 subscales "Oculomotor" and "Disorientation" from which the "Total" score is calculated. The aim was to check whether the VR environment negatively affected participants and could bias the results.

6.5.2 VEQ. To measure the experience of owning a virtual body in the virtual environment can be assessed using the traditional Illusion of body ownership questionnaire (IVBO) [22, 33, 48]. A further development of the original IVBO and the Alpha-IVBO [38] was the VEQ [36, 37]. The VEQ comes with the subscales "Ownership", "Agency" and "Change". Every sub-scale consists of four corresponding items, that were rated along a seven-point likert scale. Participants had to answer the VEQ at the end of the experiment. Since the VEQ items mainly consist of questions asking about the virtual body, participants experienced, we decided to alter the VEQ only in the "non-embodied" group [54]. Since questions regarding your virtual body, if not virtual body was present, could be confusing for participants. We were mainly interested if an illusion of owning a virtual body additionally contributed to the experience of time, sense of being there, place illusion, or presence.

6.5.3 IPQ. We also evaluated the feeling of presence, or how present participants really felt being inside the virtual environment, with the Igroup Presence Questionnaire (IPQ). Presence and embodiment correlate with each other and therefore it seemed to be important for us to be able to validate the ratings for the embodied group [35, 46]. Especially the comparison between the groups "embodied" and "not-embodied" could provide interesting insights. The IPQ's subscales: (1) "General Presence", (2) "Spatial Presence", (3) "Involvement" and (4) "Experienced Realism". Also a seven-point Likert scale was used for the item assessment.

6.6 Statistical Analysis

We conducted repeated-measures ANOVAs, as for study 1 but with an additional between factor: embodiment, to test which effects the perceived objects and a virtual body representation had on the estimation of duration, passage of time, time thinking and boredom ratings. Time-duration estimations, passage of time, time thinking and boredom ratings were analyzed similar to study 1. The additional VEQ, IPQ and VRSQ ratings were analyzed using the interval measurement scale [4, 53]. To compare the VEQ, IPQ and VRSQ scores and it's subscales between the embodiment conditions, the items were analyzed using a dependent t-test where normality and homogeneity of variance could be assumed. Normality was tested with the Shapiro-Wilk test and homogeneity of variance with the Levene test. If a normal distribution could not be assumed, a Wilcoxon signed rank test was performed. If the assumption of homogeneity of variance was violated, a Welch (or Satterthwaite) approximation was used. We used JASP v.0.16.4 [16] and the programming language R using RStudio [39] as a development environment for the analyzes.

6.7 Results

6.7.1 Duration Estimation. For this dependent variable variance homogeneity, but not normality, were assumed. Although the Anova is quite robust to violations of normality, we still performed it with log transformed duration estimates. We used the transformed time estimates in the following tests. Sphericity was violated, therefore we decided to use the Greenhouse-Geisser correction. With respect to the dependent variable of duration estimation (judgement in seconds), we found a significant main effect for the displayed zeitgeber,that means, the duration of the trial length was significantly judged differently among the zeitgebers watched ($p < .001$). There was no significant interaction between the zeitgebers and the between subjects factor embodiment. In a post-hoc analysis, for the clock zeitgeber in comparison to all other zeitgebers, the trial length was judged significantly longer by participants ($p < .001$).

6.7.2 Passage of Time. With respect to the dependent variable of passage of time, the ratings were significantly different between the zeitgebers watched ($p < .001$). There was no significant interaction between the zeitgebers and the between subjects factor embodiment. In a post-hoc analysis, the clock in comparison to the orbit pendulum was significantly rated slower ($p < .001$), the fan was significantly rated slower in comparison to both pendulums (newton, orbit)($p < .001$). And the fan was also significantly different from the torch and the starfield zeitgeber ($p = 0.007, p = 0.037$). The newton pendulum was significantly rated slower than the orbit pendulum ($p = 0.028$). The orbit pendulum was significantly rated faster in comparison to the starfield, tunnel and torch zeitgeber ($p < .001, p = 0.002, p < .001$)

6.7.3 Time Thinking. With respect to the dependent variable of time thinking, the ratings were significantly different between the zeitgebers watched ($p < .001$). There was no significant interaction between the zeitgebers and the between subjects factor embodiment. In a post-hoc analysis, the clock in comparison to all other zeitgebers was significantly rated highest ($p < .001$). The fan was significantly rated higher in comparison to the orbit pendulum ($p < .001$). The newton pendulum was rated significantly higher than the orbit pendulum ($p = 0.012$). Finally, the orbit pendulum was significantly rated lower in comparison to the torch and tunnel zeitgeber ($p = 0.015, p = 0.022$).

6.7.4 Boredom. With respect to the dependent variable of boredom, the ratings were significantly different between the zeitgebers watched ($p < .001$). In a post-hoc analysis, the clock was significantly rated higher than the orbit pendulum ($p < .001$). For the fan zeitgeber, was rated significantly higher in boredom ratings than the orbit pendulum and the starfield ($p < .001$). The fan was also significantly rated higher in comparison to the newton pendulum and the torch zeitgeber ($p = 0.031, p = 0.004$). The newton pendulum was rated significantly higher in comparison to the orbit pendulum ($p < .001$). The orbit pendulum was significantly rated lower in comparison to the torch and the tunnel zeitgeber($p = 0.004, p < .001$).

6.7.5 VRSQ. The VRSQ "Total", "Oculomotor", and "Disorientation" scores were not normally distributed. The "Total" and the "Oculomotor" scores did not differ significantly between before and after the VR exposure. The "Disorientation" scores were significantly higher after the VR exposure in comparison to the scores assessed before ($Z = -2.895, p = 0.003$).

6.7.6 VEQ. Our manipulation check question, from Unruh et al. [54], item asking for: "I had the feeling of owning a virtual body", differed significantly between the embodied conditions ($p = 0.002$). The manipulation check, the "Change" and the "Control" item do not indicate a normal distribution. Of these, the "Control" scale differed significantly between the embodiment conditions ($p < .001$).

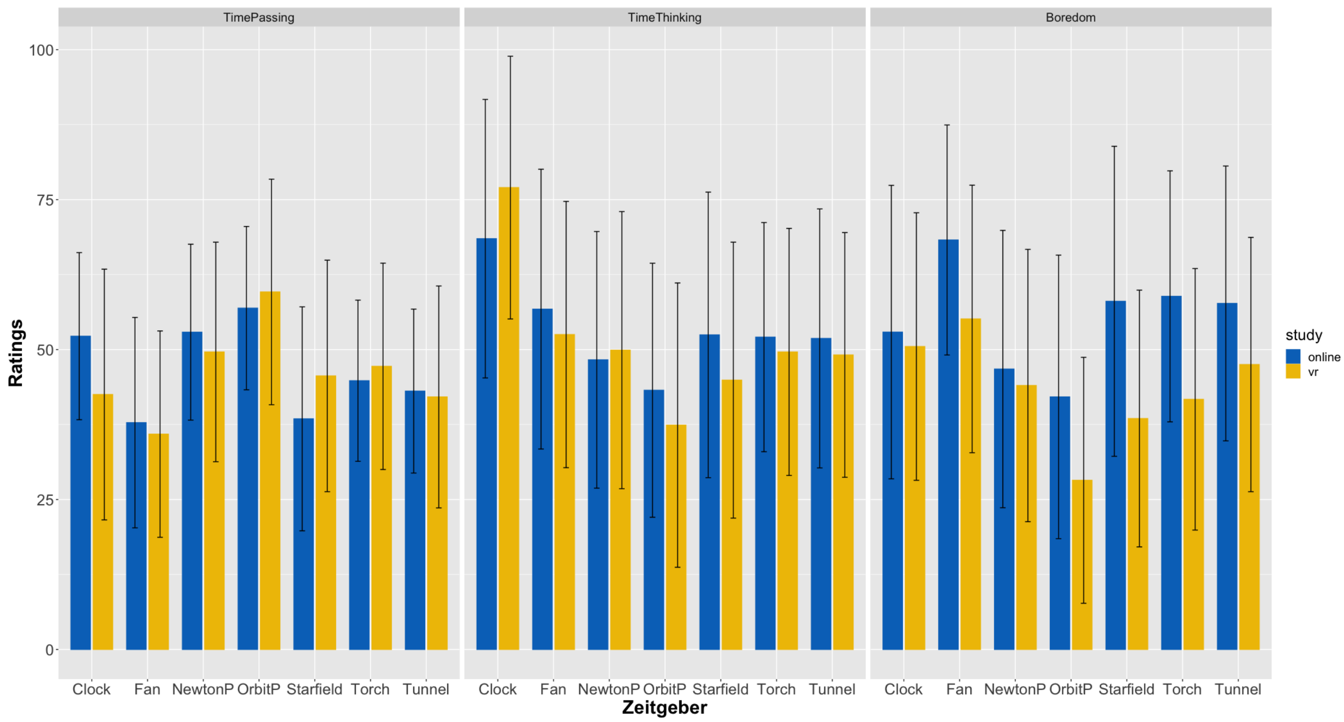


Figure 2: Overview of the STSS mean values for study 1 (remote online) and study 2 (VR). With error bars. The terms newton pendulum and orbit pendulum are abbreviated as follows: NewtonP, OrbitP.

Table 2: VR specific results of pre- and post-questionnaires for study 2 (IPQ, VRSQ, VEQ) between embodiment conditions.

	no virtual avatar	virtual avatar	p-value	effect size (Cohen's d)
General Presence (IPQ)	4.93	5.2	0.432	0.204
Spatial Presence (IPQ)	4.33	4.56	0.283	0.280
Involvement (IPQ)	4.16	4.19	0.86	0.328
Realism (IPQ)	3.23	3.48	0.208	0.169
Ownership (VEQ)	3.342	4.517	0.002	0.818
Change (VEQ)	1.95	2.208	0.38	0.228
Agency (Control) (VEQ)	3.508	5.717	< .001	1.63

Table 3: Correlations overview table for study 2 and all zeitgebers and measures. Abbreviations: time estimates (TE) in seconds, time passing(TP), time thinking (TT) and boredom (B). Significance legend: *: <0.5, †: <0.01, ‡: <0.001.

	clock				fan				newton pendulum			
	TE	TP	TT	B	TE	TP	TT	B	TE	TP	TT	B
TE	–	0.17	0.34†	−0.14	–	−0.44‡	0.37†	0.29*	–	−0.08	0.38†	0.24
TP	0.17	–	−.001	−0.76‡	−0.44‡	–	−0.48‡	−0.64‡	−0.08	–	−0.3*	−0.46‡
TT	0.34†	−.001	–	0.13	−0.37†	−0.48‡	–	−0.53‡	0.38†	−0.3*	–	0.39†
B	−0.14	−0.76‡	0.13	–	0.29*	−0.64‡	0.53‡	–	0.24	−0.46‡	0.39†	–

	orbit pendulum				starfield			
	TE	TP	TT	B	TE	TP	TT	B
TE	–	−0.08	0.15	−0.19	–	−0.05	0.43‡	0.23
TP	−0.08	–	−0.36†	−0.45‡	−0.05	–	−0.36†	0.43‡
TT	0.15	−0.36†	–	0.46‡	0.43‡	−0.36†	–	0.49‡
B	−0.19	−0.45‡	0.46‡	–	0.23	−0.43‡	0.49‡	–

	torch				tunnel			
	TE	TP	TT	B	TE	TP	TT	B
TE	–	0.02	0.28*	0.19	–	−0.32‡	−0.45‡	0.2
TP	0.02	–	−0.47‡	−0.57‡	−0.32‡	–	−0.53‡	−0.51‡
TT	0.27*	−0.47‡	–	0.39†	0.45‡	−0.53‡	–	0.5‡
B	0.19	−0.57‡	0.39†	–	0.2	−0.51‡	0.5‡	–

6.7.7 IPQ. For the general presence score and the subscales spatial presence, involvement and realism, normality and homogeneity of variance could be assumed. No significant differences were measured between the embodiment representations.

6.7.8 Correlations. As for study 1, a strong inverse correlation with high significance, $p < 0.01$, between the passage of time and boredom ratings could be found. Medium significant correlations were found between time duration judgments and time thinking ratings, but not for the orbit zeitgeber. Another medium significant inverse correlation between passage of time and time thinking ratings was found, but not for the clock zeitgeber. A strong and significant correlation was also found between time thinking and boredom ratings, but again not for the clock zeitgeber (Table 3).

6.8 Limitations

In the VR study, the virtual environment was enriched by a virtual chair, which was not present in the online study. Also, with the embodiment condition, since there was a lack of an active task, this could have influenced boredom. We did not compare it to a real example with a real fan or a real clock. As with study 1, the sample size consisted of a high proportion of female participants, and this is important to address as a limitation of this study.

7 DISCUSSION

We explored motion properties of external virtual zeitgebers in two studies, the first study being a remote online study and the second study conducted as laboratory study in VR. In comparison to the work of Schatzschneider et al. [42], we did not elaborate on a parallel task or activity and wanted to test the raw influence of external virtual zeitgebers motion on the perception of time. Similar to the work by Landeck et al. [25], relatively short trial lengths were chosen, but we focused rather on the characteristics of motion perceived as external motion, whereas the tunnel was designed to elicit a feeling of self-motion through the virtual environment where in contrast to that the physical body stayed in place. These findings could complement each other and enrich knowledge in the domain of virtual time perception or time perception in virtual environments. Zeitgebers with more changes were not judged to be longer than zeitgebers with fewer changes. Therefore, H1 was not supported. The clock was the zeitgeber, where retrospectively estimated timespans were highest compared to all other zeitgebers, but the clock incorporated a regular, rotary single movement in 2D space. Therefore, zeitgebers incorporating more visible changes, like the torch or pendulums, produced retrospectively smaller time estimates. Another reason for this could be based on prior knowledge and the association of a clock, that is traditionally well known as an explicit and artificial zeitgeber. Counting or watching the clock arms is often negatively associated with waiting scenarios [15, 30, 53]. To compare the means of the remote online study results with the VR study results, we see tendencies that estimated time spans were generally shorter for all zeitgebers in VR, except for the clock zeitgeber. Watching the pendulum's swing led to higher passage of time ratings by observers, and therefore we can accept H2. In both studies, the pendulum zeitgebers with their oscillatory motion type led to higher passage of time ratings in contrast to the zeitgebers that incorporate a rotary or linear movement type, except for the clock zeitgeber. These could be driven by internal updates, top-down, and derived expectations when observing movement in the relativity of space and time. A linear and regular movement needs less internal updates and could cost less cognitive resources in comparison to a non-linear and irregular movement. According to this conclusion, our suggested model of motion properties seemed to be suitable for predicting this. The pendulum zeitgebers should be well suited for speeding up observer's passage of time. The clock zeitgeber seemed to play a special role, that is perceived differently on a monitor in comparison to in a VR simulation. The association with time could have played an important role and is shown in the higher time thinking ratings for both studies and this is interesting for further research to investigate. Both studies show that passage of time ratings are strongly related to boredom ratings, and we can accept H3. Attention and interest, already hypothesized to be a major contributor and included in presented models such as the AGM, shows a strong influence on how participants focus on time and influence their subjectively perceived passage of time. Time passing was highest for the pendulum zeitgebers. We could suggest that oscillating motion is more complex to watch, leads to a faster-perceived passage of time, and is, on the other hand, less boring. Probably the more interesting the object is to observe, the more attention is drawn to the object and the less boring the object is perceived. The higher interest might come from the "more interesting" or more complex motion patterns to observe. We believe that both contribute to faster reported time passages. Boredom impairs attention, and attention is needed accordingly to focus on multiple moving objects in space and time. The zeitgeber with the highest average rating for the passage of time in both studies was the orbit pendulum. It also differed significantly from all other zeitgebers and especially from the other pendulum zeitgeber. Since the orbit pendulum moves in three dimensions, we can accept H4. We believe that expectations of the real-world counterpart play an additional important role in the processing stage. The plausibility and congruence theory has recently been discussed by Latoschik et al. [27], and we believe that it may also play a role in this context in terms of processing and cognitive resource load. A virtual pendulum will be more and more difficult to implement plausibly compared to a virtual clock and will consume more cognitive resources for perception during cognitive processing. On the other hand, when more resources are needed to process observations, time seems to pass more quickly. Small simulation differences between Virtual Reality and Reality could lead to a higher cognitive load for longer processing of observations, but it seems to also increase interest and reduce boredom. In contrast to previous work from Lugrin et al., Unruh et al. and Unruh et al. [30, 53, 54], we were unable to show any significant influence of the between-subjects factor embodiment on any of the time related dependent variables for the VR study. Indeed, our scenario was very different and was not about waiting time. Therefore, our findings do not support H5. The focus and interest towards the zeitgebers seemed to be more prominent than the self-representation. Furthermore, after the initial familiarization phase, there was no explicit interaction, in addition to watching the zeitgebers and interacting and confirming the in vivo questions from the STSS questionnaire. Embodiment did not appear to affect time perception in this scenario, so we can conclude that the use of external virtual zeitgebers works with or without avatar embodiment. Nonetheless, we suggest further work on the potential influence of avatar-based zeitgebers.

8 CONCLUSION

External virtual zeitgebers appeared to be able to manipulate the time experience of observers in immersive and non-immersive settings and independently of the presence or absence of a virtual body. In both studies, the time was judged faster when viewing objects with oscillating motion (i.e. with virtual pendulums). Both studies also confirm a significant inverse correlation between the passage of time and boredom. Further research is needed to confirm these results for longer trial lengths and different zeitgeber settings (position and context). Our future work will explore the possible usage of virtual pendulums and their velocity variations to regulate time perception in persons suffering from depression, who often report feeling stuck in time.

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