Who turned the clock? Effects of Manipulated Zeitgebers, Cognitive Load and Immersion on Time Estimation

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Abstract—Current virtual reality (VR) technologies have enormous potential to allow humans to experience computer-generated immersive virtual environments (IVEs). Many of these IVEs support near-natural audiovisual stimuli similar to the stimuli generated in our physical world. However, decades of VR research have been devoted to exploring and understand differences between perception and action in such IVEs compared to real-world perception and action. Although, significant differences have been revealed for spatiotemporal perception between IVEs and the physical world such as distance underestimation, there is still a scarcity of knowledge about the reasons for such perceptual discrepancies, in particular regarding the perception of temporal durations in IVEs.

In this article, we explore the effects of manipulated zeitgebers, cognitive load and immersion on time estimation as yet unexplored factors of spatiotemporal perception in IVEs. We present an experiment in which we analyze human sensitivity to temporal durations while experiencing an immersive head-mounted display (HMD) environment. We found that manipulations of external zeitgebers caused by a natural or unnatural movement of the virtual sun had a significant effect on time judgments. Moreover, using the dual-task paradigm the results show that increased spatial and verbal cognitive load resulted in a significant shortening of judged time as well as an interaction with the external zeitgebers. Finally, we discuss the implications for the design of near-natural computer-generated virtual worlds.

Index Terms—Time perception, cognitive load, virtual environments

1 Introduction

Virtual reality (VR) technologies allow users to experience virtual three-dimensional (3D) worlds in a similar way as the real world. With the combination of tracking and immersive stereoscopic display systems, such as head-mounted displays (HMDs), users can explore immersive virtual environments (IVEs) as if they were moving with their body in a corresponding existing real-world environment [10]. These technical possibilities are leveraged in different application domains to create user experiences in artificial or realistic virtual scenes from an embodied egocentric perspective. Traditional application fields include training applications or immersive walk-throughs through architectural designs or urban planning environments [13, 14]. Recently, one could observe enormous interest from the interactive games and entertainment market in these technologies, which coincides with a growing market of low-cost consumer hardware such as the Oculus Rift[1] or Samsung GearVR[2] HMDs.

When developing a computer-generated 3D world, developers have the freedom to implement *time* in virtual environments (VEs) in different ways, for example, by implementing a natural day-night cycle inspired by the Earth spinning around the sun; but they can also ignore sun movements or implement a varied time lapse of the sun. There are generally four common possibilities of how the passage of time and the movement of the virtual sun could be realized in IVEs:

1. Time of day progression and movement of the virtual sun are implemented *realistically* replicating real-world behavior, e. g., by using the dedicated server's or user's local time of day and position on the Earth.
2. Time of day progression and virtual sun movement are *amplified or compressed*, for instance, to allow users to experience a full virtual day in just a few minutes or hours or even more than 24 hours.
3. There is *no continuous movement* of the sun, and hence the time of day does not change in the VE, e. g., due to convenience reasons or as part of the storytelling.
4. Moreover, the passage of time might be altered as part of a non-linear narrative or story that is told in the VE, e. g., by advancing time after events or by *jumping* back or forth in time.

In the context of time perception, the sun is the most natural *zeitgeber*[3]. The term zeitgeber describes environmental cues that entrain the human circadian rhythms and synchronizes our biological rhythms to the Earth's 24-hour day-night cycle and 12-month cycle. Such cues provide humans with an absolute estimate of the time of day as well as a relative estimate about the progression of time [4, 31, 34]. Hence, discrepancies between the virtual sun and the actual time of day in the real world have the potential to cause non-veridical estimates of time while immersed in a VE. To our knowledge, no previous literature evaluated if and how such zeitgebers affect time perception in VR, even though anecdotal evidence suggests that there might be differences in time perception between HMD environments and the real world [13, 36].

Indeed, virtual worlds with realistic virtual suns have been used for years in non-immersive display setups, most dominantly in video or computer games [13]. However, experiments revealed that players in such virtual game worlds often misperceive the time duration while they are playing [40, 43]. It is still an open question if such discrepancies are caused by the mechanics or the cognitive and motor challenges of the game, which may all contribute to an improved gaming experience (*flow theory*) [18], or whether there is also an impact of subtle factors such as non-veridical movements of the sun.

In this article, we present a perceptual experiment on time estimation, in which we evaluated the effects of a veridical or manipulated movement of the sun as external zeitgeber as well as effects of cognitive load on time estimation in an immersive and non-immersive VE. Therefore, we scaled the movement of the sun over the sky with time

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[1] https://www.oculus.com/en-us/rift/
[2] http://www.samsung.com/global/microsite/gearvr/
[3] The term zeitgeber originates from German and means "time-giver".

gains describing the difference between the virtual and the real progression of time. To test effects of cognitive load, we compared conditions with spatial and verbal cognitive tasks and a baseline condition without a cognitive task. While, as far as we know, this is the first reported experiment evaluating these factors individually with respect to time estimation in an IVE, we also compared their mutual effects. In particular, we were interested in the question whether high spatial cognitive load might reduce the effects of spatial zeitgebers related to the sun, or whether verbal and spatial cognitive load might dominate such subtle spatial zeitgebers.

To summarize, our article provides the following contributions by analyzing the

- effects of non-veridical external zeitgebers on time estimation in IVEs and differences to non-immersive setups,
- effects of verbal and spatial cognitive tasks and interactions with spatial zeitgebers on time estimation, and
- implications for the development of immersive virtual worlds with accurate time estimation in VR.

The remainder of this article is structured as follows. Section 2 discusses related work in the scope of the article. Section 3 describes the experiment in which we evaluate time estimation in IVEs. The results are presented in Section 4 and discussed in Section 5. Section 6 concludes the article.

2 Background and Related Work

In this section, we provide an overview of related work on time perception, external zeitgebers and cognitive resources. Furthermore, we discuss their possible effects on the estimation of temporal durations when they are presented in a non-veridical way in IVEs.

Time Perception

According to Immelmann [28] human time perception is usually divided into at least two categories: (i) *daytime perception* and (ii) *short time perception*. *Daytime perception* is usually attributed to the circadian system, a neuronal structure, devoted to regulating daytime-dependent bodily rhythms. Its output neurons fire approximately every 24 hours, marking the end of a day [45]. It plays a regulatory role in the bodily day-night rhythm and can be influenced by the amount and color of light entering the eyes of the observer [1]. Researchers have successfully tried to treat various symptoms related to problems with the circadian system, such as jet lag, insomnia and winter depression, utilizing the light sensitivity of the system [4, 31, 34, 42]. Engineers and designers were able to synchronize the circadian system by exploiting the sensitivity of the circadian rhythm to light entering the eyes. For instance, Cole [17] developed a night cap with built-in LEDs that flash peaks of light into a user's eyes when they are asleep in order to synchronize the circadian rhythm with a specified time zone. Cajochen et al. [16] found that the light emission produced by LED displays has an impact on the circadian rhythm and therefore on the emission of melatonin and serotonin into the bloodstream. They compared the exposure of participants to LED screens and non-LED screens and received different results on several measures, indicating that not just the total light input, but also the color of light is used as input to the circadian system.

Short-time perception on the other hand, does not seem to have a specific neuronal correlate in the brain like the circadian system, but appears to be derived from general cognitive processes [28]. Therefore, the usage of working memory plays an important role in human perception of time. Furthermore, Katsuura et al. [29] found that the color of light displayed to humans influences their short-time perception as well. They exposed participants to monochromatic blue and red light while having to rate the duration of very short intervals of time. They observed a speedup of temporal estimation in the condition with red light. The results suggest an interaction effect between the position of the sun in the sky and short-time perception, e. g., more natural red light in the morning and evening and more blue light during the day. In the last years, different temporal illusions have been discovered, which are applicable to manipulate the human perception of time in a laboratory setup [21]. Also, immersion by means of VR display and tracking technologies might by itself have an effect on time estimation. A preliminary evaluation of time perception in an HMD setup suggested that participants observed short time intervals as longer with an HMD than in a real-world baseline condition [13].

Studies exploring the influence of light patterns in videos or simulations have suggested additional influences on time perception, such as emotions produced by movies [20]. However, in the evaluation of time perception introduced in this article, we decided to focus on the objectively measurable environmental impact factors on time perception, i. e., we ignored other factors related to excitement or arousal.

External Zeitgebers

Zeitgebers are cues that help to locate oneself in time (of day) or to mark the passing of time, i. e., the speed of time [3]. The literature depicts zeitgebers mostly as input variables to the circadian system [27]. In order to categorize these cues that people rely on to orient themselves in time, we apply the term zeitgeber to non-circadian-rhythm related topics as well. We further divide zeitgebers into subcategories.

- *Absolute zeitgebers* are those that tell the time of day, like the position of the sun in the sky.
- *Relative zeitgebers* indicate the speed at which time is passing.

Relative zeitgebers are important for humans because the perception of the speed of time can deviate from the actual passing of time significantly [22, 32]. Humans often exploit combinations of absolute and relative zeitgebers to extract information about time and duration. For instance, hearing or seeing the ticking of an analog clock is one typical example: While hearing ticks would by itself provide a relative zeitgeber, seeing the position of the hands on the clock would provide an absolute zeitgeber. Also, absolute zeitgebers can be interpreted as relative zeitgebers and vice versa, when observing the absolute zeitgebers over time, e. g., when looking at a clock at two distinct moments in time.

Another differentiation may be drawn along the origin of the zeitgeber [23].

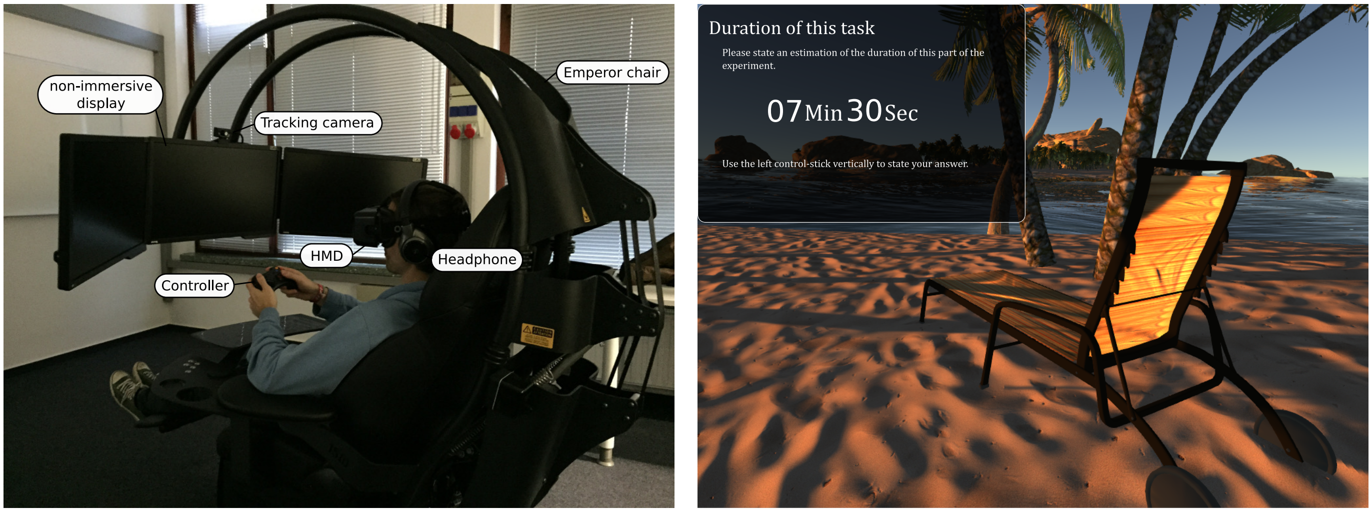
- *Natural zeitgebers* are those produced by nature, like the sun, shadows, speed of the stars moving and similar phenomena.
- *Artificial zeitgebers* are those that are created artificially by humans, like clocks.
- Additionally, *social zeitgebers* are those that are derived from social contact with other individuals.

Regarding the last, there is evidence that the circadian system is disrupted in depressive individuals, leading to the conclusion that social zeitgebers play indeed a role in human time keeping [25].

Finally, we differentiate between external and internal zeitgebers:

- *External (or exogenous) zeitgebers* are those cues in the external world that an organism relies on to estimate time.
- In contrast, an *internal (or endogenous) zeitgeber* is something inside the organism, like the circadian system or even a cognitive strategy like counting seconds for example [34].

The sun is the most prominent example of an external and natural zeitgeber providing absolute as well as relative information about the time. Humans adapt to the daily change of lighting produced by the sun [35]. While the sun's position by itself is a zeitgeber, it produces *secondary* zeitgebers such as shadows on the ground; e. g., sun clocks exploit this property. Since the sun is certainly the most important natural source of zeitgebers, we decided to focus on the sun and its movement in this article.



(a) (b)

Fig. 1. Experimental setup: (a) annotated photo of a user wearing an Oculus Rift DK2 HMD and holding a Speedlink Torid controller while seated in an MVE Lab Emperor chair, and (b) visual stimulus consisting of a virtual island which participants experienced while lying on a virtual sun lounger. The inset shows the input mask which participants used to judge the elapsed time after trials in the experiment.

Cognitive Resources

The human working memory draws from finite cognitive resources, for which several theoretical models have been proposed, which usually distinguish at least between *verbal* and *spatial* cognitive resources [24]. A well-known theoretic model of cognition and working memory was proposed by Baddeley and Hitch [6], which considers manipulation and storage of visual and spatial information in a speech-based loop. According to this model, general attention and access to both verbal and spatial working memory are handled by a central executive. This model has been revised and expanded [5], and experiments suggest a further division of the visuospatial sketchpad into separate pools for visual and spatial tasks [19].

As described above, time perception partially relies on external zeitgebers, which may be presented verbally, such as numbers on a digital watch, or spatially, such as hands on an analog watch or the movement of the sun, shadows etc. Since the analysis of such zeitgebers uses verbal as well as spatial working memory, and thus competes with other tasks in VEs for finite cognitive resources, it is reasonable to assume that tasks with a high cognitive load may affect temporal judgments [9, 39]. Indeed, previous work has indicated that time judgments are shortened during phases of high cognitive load [2, 15, 26, 33]. This main effect of cognitive load on temporal judgments is well documented in the real world and has also been considered for non-immersive displays [40, 43]. However, in this article, we are particularly interested in the yet unexplored interaction effect with manipulated natural spatial zeitgebers in immersive VEs. In this scope, we assume that a high spatial cognitive load will diminish the effects of these external zeitgebers on temporal judgments.

3 Experiment

As discussed above, external zeitgebers and cognitive load in IVEs have the potential to interact with each other concerning their effects on the estimation of temporal durations. In this section, we describe the experiment in which we analyzed such mutual influences by studying movements of the virtual sun, which we amplified and compressed by means of *time gains*, and different concurrent spatial and verbal cognitive tasks. In addition, we compared time estimation between an immersive and a non-immersive display setup to investigate effects of immersion on time estimation.

3.1 Participants

We recruited 21 participants (8 female and 13 male, ages $18-42$, $M = 26.5$) for our experiment. The participants were students or members of the department of informatics at our university. The student participants obtained class credit for their participation. All of our participants had normal or corrected-to-normal vision. Three participants wore glasses and four participants wore contact lenses during the experiment. None of our participants reported a disorder of equilibrium or binocular vision disorders. Ten participants had previously used HMDs. The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was three hours. During the experiment, participants wore the HMD for approximately two hours with the remaining hour being spent for questionnaires and for the experiment trials in the non-immersive display condition. Participants were allowed to take breaks at any time between trials. During the breaks, we asked them to rest their eyes without taking off the HMD in the immersive display conditions.

3.2 Material

We performed the experiment in one of our laboratory rooms, which was sealed off during the experiment. As illustrated in Figure 1(a), participants wore an Oculus Rift DK2 HMD for the stimulus presentation, which provides a resolution of 960×1080 pixels per eye with a refresh rate of 75 Hz and an approximately 100 degrees diagonal field of view. We tracked its position and orientation with the inherent optical-inertial tracking system of the Oculus Rift DK2.

The visual stimulus consisted of a virtual tropical island with sand, palm trees and ocean water as illustrated in Figure 1(b). For rendering, system control and logging we used an Intel computer with 4.0 GHz Core i7 processor, 16 GB of main memory and an Nvidia Quadro K5200 graphics card. The stimuli were rendered with the Unity 3D 5.0.3 engine. During the experiment, participants were seated in an MWE Lab Emperor chair, which provides a comfortable pose similar to the virtual sun lounger that we showed to participants in the VE (see Figure 1(a)). Participants could naturally look around in the VE, but they were instructed not to stand up from the chair. As illustrated in Figure 1(b) and Figure 3, the VE that was shown to the participants during the experiment consisted of a virtual morning with a rising sun. We set the virtual local time of day to 7 am and approximated a sunny morning to ensure that there was from the start sufficient light avail-

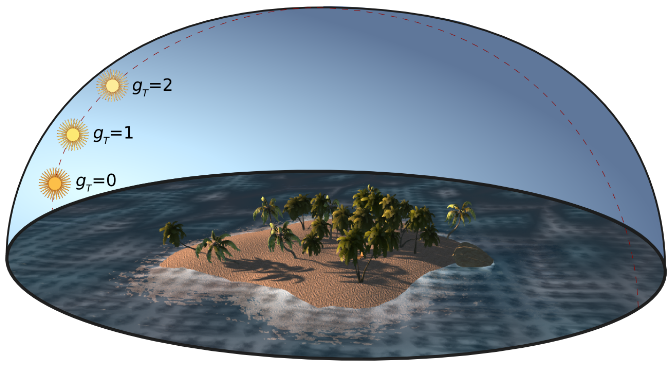


Fig. 2. Illustration of the virtual island from a bird's eye perspective and movement of the sun in the virtual world scaled by the three time gains $g_t \in \{0,1,2\}$.

able for the different tasks in the experiment.[4] To simulate the virtual movement of the sun at different speeds, we implemented a realistic sun model in Unity 3D. In particular, a directional light was moved around the virtual hemisphere and the ambient lighting was manipulated using keyframe animations to simulate a natural change in color from red to blue after sunrise. A procedural skybox drew a white circle, dependent on the rotation of the directional light in the scene with sunshafts as a post-effect enabled (see Figure 2). Shadows from the palm trees in the virtual scene with self-shadowing and soft shadows provided additional cues about the position and movement of the sun over the sky. The virtual sun was located at a randomized angle ± 40 degrees relative to their body's forward facing direction, which ensured that participants were not always looking straight into the sun, but the sun was visible in the periphery from their pose on the sun lounger.

We decided to provide a comfortable pose and limited movements in this experimental setup based on previous tests, which suggested that participants would not suffer from strong simulator sickness symptoms over longer times of the experiment [38]. In order to maintain the participants' sense of presence in the VE no communication between experimenter and participant was performed during the experiment. Task instructions were presented via slides in the VE during the experiment. Participants performed the cognitive tasks via button presses on a Speedlink Torid controller. Participants wore fully-enclosed Sennheiser RS 180 wireless headphones during the experiment to reduce their auditive perception of real-world ambient noise. The participants received auditive feedback in the form of a clicking sound when they pressed a button on the Speedlink controller.

In order to explore the influence of immersive display technology on time estimation, we also considered a non-immersive display setup with a window-on-a-world metaphor as baseline condition. As in the similar experiments in non-immersive setups [40, 43], this condition used monoscopic display without head-tracking. Participants saw the VE displayed on a BenQ XL2411T 24 inch LCD computer screen with a resolution of 1920×1080 pixels at 120 Hz mounted in front of them in the Emperor chair without stereoscopic display or head tracking.

3.3 Methods

In order to test the influences of cognitive load on another task, dual-task studies can be used, which are a widely accepted method to understand influences of cognitive tasks on other tasks in user interfaces [44]. The dual-task method requires users to perform a secondary task while performing a primary task to determine the costs involved in performing the concurrent task [8], such as performing an additional cognitive task while keeping time. If the primary task performance deviates from a session without the secondary task, it can be concluded that this task requires resources from the same pool as the secondary task. In the case of this study, the primary task involved the estimation of a time interval, while the secondary task involved spatial, verbal or waiting tasks.

In preliminary iterations of this experimental design we observed strong interpersonal differences in time estimates, so we decided on a within-subjects design for this experiment. In the immersive display setup, we tested three cognitive conditions (i. e., (i) verbal task, (ii) spatial task, and (iii) no task), and three virtual sun movement speeds, i. e., (i) no movement, (ii) natural movement, and (iii) twice the natural speed formalized as gains $g_t \in \{0,1,2\}$ respectively, which are multiplied with the actual speed of the sun (see Figure 2).

In addition, we also tested the three cognitive conditions in the non-immersive display setup. However, in this condition we did not manipulate natural zeitgebers and used the natural movement speed of the sun, i. e., $g_t = 1$. This non-immersive display condition was always completed before the immersive conditions and served as a baseline condition, which also allowed us to verify if participants understood the task. All other (i. e., cognitive and gain) conditions were randomized.

Before the experiment, participants filled out an informed consent form and received detailed instructions on how to perform the cognitive tasks. Furthermore, they filled out the Kennedy-Lane simulator sickness questionnaire (SSQ) [30] immediately before and after the experiment, further the Slater-Usoh-Steed (SUS) presence questionnaire [41] after the experiment, as well as a demographic questionnaire. Every participant practiced each of the cognitive conditions once at the beginning of the experiment. These trials were excluded from the analysis.

We used a prospective design for time estimation experiments [11], which means that participants were aware from the start that they would be required to judge the elapsed time afterward. During each trial, the VE was displayed to the participants for exactly ten minutes, i. e., 600 seconds. However, we ensured that they were not aware of the identical durations of the trials by explaining to them that in such experiments usually all trial durations are randomized and can differ largely. We found in pre-tests with actually varied trial durations that users had significant difficulties in consciously differentiating trial durations of ten minutes plus or minus several minutes, so we decided on this simplified design for this experiment, which proved to be suitable. The only context information that participants might have utilized as to how long a trial took was the previously communicated expected duration of the experiment of about three hours in total. However, participants were not aware of how many trials would be tested before the experiment. After each trial, they were asked to judge the elapsed time by specifying minutes and seconds using the Speedlink controller (see inset in Figure 1(b)).

To analyze the impact of cognitive load on time estimation in the presence of the manipulated external zeitgebers, we chose two tasks, which have shown that they can induce high verbal or spatial cognitive load (see next section for more details). Participants registered their responses on the cognitive tasks (detailed below) by pressing buttons on the Speedlink controller. Participants were instructed to perform the cognitive tasks to the best of their ability. We logged all responses in the experiment and classified them as true positives, true negatives, false positives, and false negatives depending on the cognitive task.

Verbal Working Memory Task

As illustrated in Figure 4(a), the verbal working memory task was a letter *two-back* comparison task [24] designed to be comparable to related work in [12]. In every trial, participants were shown a continuous stream of letters that were flashed on a virtual sign in the VE. The sign was always displayed in front of the participants at a distance of two meters, which ensured always good readability (see Figure 3(b)). Participants were instructed to respond by pressing the button on the Speedlink controller if (and only if) a presented letter was the same as the one that came up two stimuli back in the sequence. This task has a high verbal working memory load since it requires continuous on-line monitoring and maintenance of the presented letter until two

[4] Sun position and world coordinates of the participant were chosen to reflect the appearance of the sun in central Europe at that time, starting with the virtual sun at an elevation of approximately 15.75 degrees.

(a) (b) (c)

Fig. 3. Experimental tasks: (a) scenario without additional cognitive task (baseline), (b) two-back letter verbal working memory task, and (c) one-back mental rotation spatial working memory task.

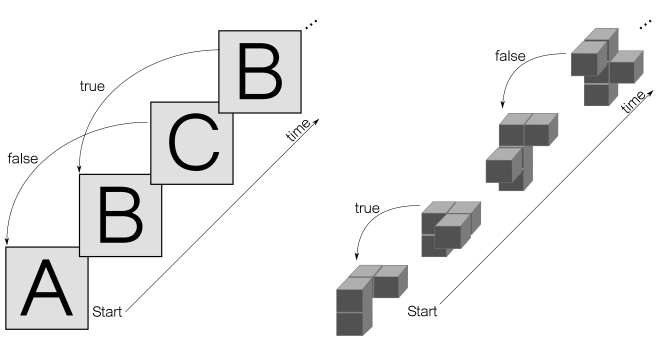
consecutive letters appeared. The letters appeared continuously at the same position in front of the participants to reduce the required spatial memory resources. The display duration for every letter was set to 0.5 seconds with a randomized inter-stimulus interval of 1.1-1.5 seconds (cf. [7]), thereby allowing for 322 logged responses for each trial.

Spatial Working Memory Task

As illustrated in Figure 4(b), the spatial working memory task consisted of a *one-back* mental rotation task, similar to that of Shepard and Metzler [37]. Participants had to first memorize and then mentally rotate a three-dimensional object constructed from a number of cubes (see Figure 3(c)). The forms of the 30 predefined objects ranged from fairly simple to slightly complex. Participants had 1500 ms to memorize the object, followed by a retain-phase with a pseudo-random duration between 1100 ms and 1500 ms, in which no object was shown. After the retain-phase, a new object was displayed and the participant had 3500 ms to decide whether the displayed object was a rotated version of the one they were holding in memory. The objects and their colors were taken from the original Shepard-Metzler test, but we altered the colors of the objects to make the decision phases more distinguishable from the memorizing phases. The objects and their presentation were randomized. The spatial memory task is demanding, but since this spatial task is very hard to verbalize it is not considered to require much verbal working memory [37]. The task allowed for 95 logged responses for each trial.

Hypotheses

Based on the literature review we expect that it will be possible to elicit changes in time estimation with manipulated spatial external



(a) (b)

Fig. 4. Illustration of true and false responses in cognitive working memory tasks: (a) two-back letter verbal working memory task, and (b) one-back mental rotation spatial working memory task.

zeitgebers related to the movement of the virtual sun, as well as effect changes based on cognitive load and immersion. Hence, we test the following hypotheses:

- H1 Mean temporal judgments differ between the three time gain conditions in the IVE.
- H2 Mean temporal judgments are shorter after participants performed spatial or verbal tasks than without cognitive task.
- H3 Spatial cognitive load has a larger effect on temporal judgments based on spatial zeitgebers than verbal cognitive load.
- H4 Mean temporal judgments differ between the immersive and non-immersive conditions.

4 Results

We analyzed the results with repeated-measure ANOVAs and TukeyHSD multiple comparisons at the 5% significance level. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated.

4.1 Time Estimation

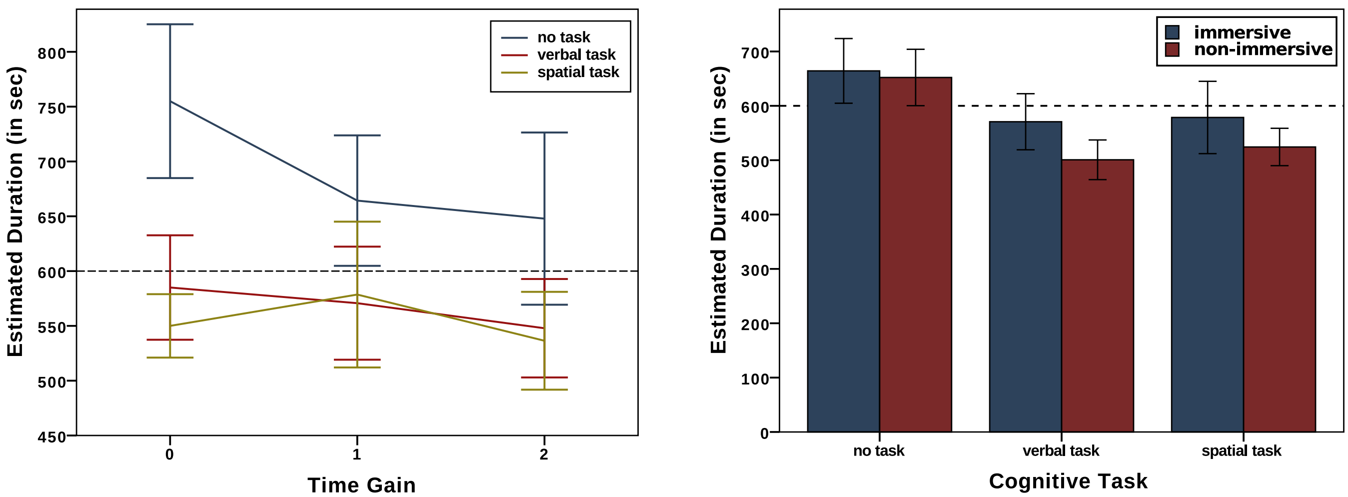
We analyzed the effects of the different factors (cognitive tasks and gains) on time estimation in the experiment by comparing the estimated durations in the conditions while participants were immersed in the VE. Furthermore, we compared the results with the baseline and non-immersive condition without manipulation of the sun.

Figure 5(a) shows the pooled estimated durations for the tested time gains and cognitive tasks while participants were immersed in the VE. The vertical bars show the standard error of the mean. The colored lines show the results for the verbal task, spatial task, or condition without cognitive task.

Cognitive Tasks

We found that participants tend to overestimate time durations in the immersive condition without any additional cognitive tasks, but tend to slightly underestimate time duration in conditions with additional cognitive tasks. This finding is in line with previous research on non-immersive environments [40, 43]. On average participants estimated a 600 sec time duration as 561.43 sec ($SD = 185.26$ sec) with and 689.05 sec ($SD = 306.14$ sec) without concurrent cognitive task. This corresponds to a 6.43% underestimation and a 14.84% overestimation, respectively.

We found a significant main effect of cognitive task condition on the estimated durations ($F(1.08, 21.60) = 5.40$, $p < .03$, $\eta_p^2 = .21$). Post-hoc tests revealed that participants judged the durations as significantly shorter ($p = .048$) if they were required to perform a concurrent verbal task compared to the situation in which no additional task was required. We found a similar result for time estimation and spatial tasks.



(a) (b)

Fig. 5. Results of the experiment: (a) Pooled estimated durations for the time gains and cognitive tasks in the immersive condition. The x-axis shows the time gains and the y-axis shows the estimated duration. (b) Pooled estimated durations for the comparison between the immersive and non-immersive conditions for the different cognitive tasks with time gain $g_t = 1$.

Post-hoc tests revealed that participants judged the durations as significantly shorter ($p = .015$) if they were required to perform a concurrent spatial task compared to the situation in which no additional task was required. We could not find any significant difference between time judgments with concurrent verbal or spatial tasks.

Time Gains

We found no significant main effect but a trend of time gains on the estimated durations ($F(2,40) = 1.85$, $p = .17$, $\eta_p^2 = .08$) as well as a trend for an interaction effect between time gain and cognitive task on the estimated durations ($F(2.67, 53.48) = 1.35$, $p = .27$, $\eta_p^2 = .06$). Hence, we analyzed the effects of time gain on estimated durations separately for the different cognitive tasks. Here, we found a significant main effect of time gain on the estimated durations in the condition without cognitive task ($F(2,40) = 5.34$, $p < .01$, $\eta_p^2 = .21$). Post-hoc tests showed that participants judged the durations as significantly longer if no movement of the sun was displayed (corresponds to $g_t = 0$) compared to the situation in which the sun moved with realistic speed, i. e., $g_t = 1$, ($p < .02$) or with amplified speed, i. e., $g_t = 2$, ($p < .02$). In contrast, we found no significant main effect of time gain on the estimated durations in the conditions with verbal task ($F(2,40) = .33$, $p = .72$, $\eta_p^2 = .02$) or spatial task ($F(1.28, 25.58) = .47$, $p = .54$, $\eta_p^2 = .02$).

Immersion

Figure 5(b) shows the differences in estimated durations for the different cognitive tasks with time gains of $g_t = 1$ between the condition in the immersive and non-immersive display setup.[5] The vertical bars show the standard error of the mean.

We found that participants estimated the time duration in the immersive condition for all cognitive tasks conditions longer in comparison to the non-immersive condition. On average participants estimated the 600 seconds time duration 1.86% longer without cognitive tasks, 13.98% longer with verbal tasks, and 10.35% longer with spatial tasks in the immersive condition compared to the non-immersive condition.

Furthermore, we found that time estimates in the non-immersive display condition significantly differed from veridical for the verbal task ($p = .013$) and spatial task ($p = .039$), but not without cognitive task ($p = .327$). In the immersive display condition we found no significant difference from veridical in time estimates for the verbal task ($p = .577$), spatial task ($p = .751$) nor without cognitive task ($p = .293$). Moreover, we found no significant difference but a trend between the estimated durations in the real and virtual world in the condition with verbal task ($p = .17$), spatial task ($p = .37$), and without cognitive task ($p = .71$).

4.2 Task Performance

We analyzed the effects of the different time gains on verbal and spatial task performance in the experiment and compared the results with the baseline condition in the non-immersive setup.

Verbal Task

Figure 6(a) shows the differences in task performance for the immersive conditions with different time gains and the non-immersive baseline condition with realistic sun movements (i. e., $g_t = 1$). The responses are categorized as correct responses (true positives and true negatives) as well as incorrect responses (false positives and false negatives). The results are plotted as percentages for a total of 322 logged responses.

We found no significant main effect in verbal task performance, i. e., true positives ($F(2,40) = .99$, $p = .38$, $\eta_p^2 = .05$), true negatives ($F(2,40) = .45$, $p = .64$, $\eta_p^2 = .02$), false positives ($F(2,40) = .09$, $p = .91$, $\eta_p^2 = .01$), and false negatives ($F(2,40) = .06$, $p = .94$, $\eta_p^2 = .001$), between the different time gains while participants were immersed in the VE. Comparing the verbal task performance between the immersive and non-immersive conditions for time gain $g_t = 1$ we found a significant difference for true positives ($t(20) = 3.70$, $p = .001$), but not for true negatives ($t(20) = .36$, $p = .72$), false positives ($t(20) = 1.14$, $p = .27$), or false negatives ($t(20) = 1.75$, $p = .10$), i. e., participants made more errors in the non-immersive than in the immersive setup. On average, 88.70% of the participants' responses were correct for tasks with a time gain $g_t = 0$, as well as 88.91% with a time gain $g_t = 1$, and 88.75% with a time gain $g_t = 2$. For the non-immersive condition with a time gain $g_t = 1$, participants' responses were correct in 86.40% of the trials. Overall, the error rates are comparably low, indicating high performance and focus of participants on this task.

[5] As explained above, we focused on time gains of $g_t = 1$ to simulate a realistic real-world behavior of the sun displayed with a window-on-a-world metaphor.

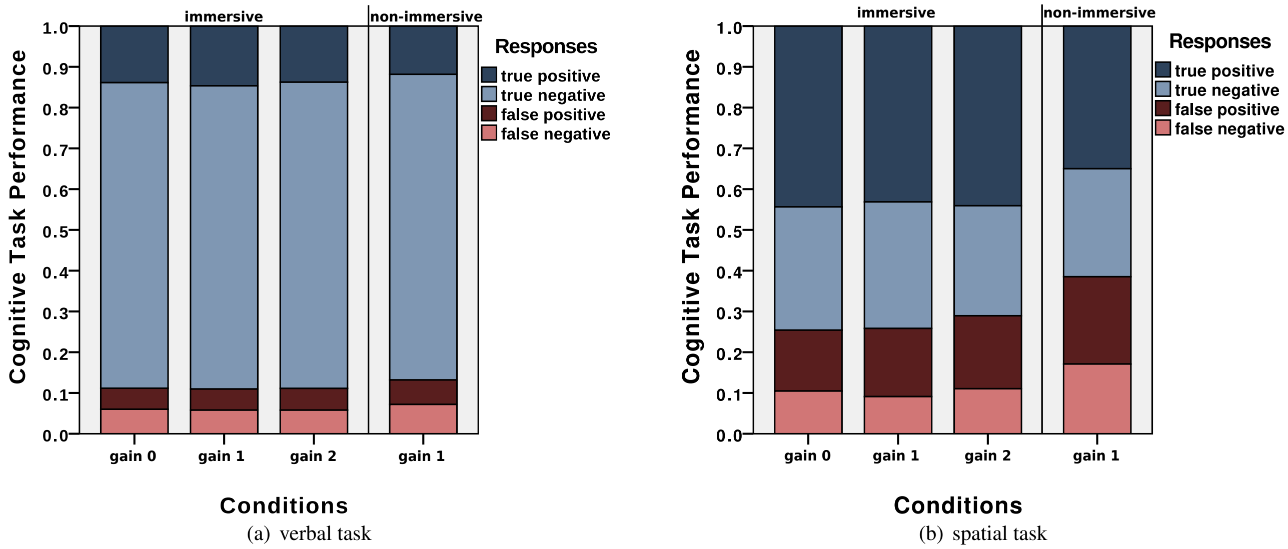


Fig. 6. Pooled distribution of cognitive task performance in terms of true or false positive or negative responses during the experiment for (a) the verbal cognitive task and (b) the spatial cognitive task.

Spatial Task

Figure 6(b) shows the differences in task performance between the immersive and non-immersive conditions for the spatial task. The results are plotted as percentages for a total of 95 logged responses.

We found no significant main effect in spatial task performance, i. e., true positives ($F(2,40) = .27$, $p = .76$, $\eta_p^2 = .01$), true negatives ($F(1.38,35.75) = 1.71$, $p = .20$, $\eta_p^2 = .08$), false positives ($F(2,40) = 1.45$, $p = .25$, $\eta_p^2 = .07$), and false negatives ($F(2,40) = .96$, $p = .39$, $\eta_p^2 = .05$), between the different time gains while participants were immersed in the VE. Comparing the verbal task performance between the immersive and non-immersive conditions for time gain $g_t = 1$ we found a significant difference for true positives ($t(20) = 3.36$, $p < .01$) and for false negatives ($t(20) = 4.475$, $p < .001$), but not for true negatives ($t(20) = 1.27$, $p = .22$) or false positives ($t(20) = 1.83$, $p = .08$), i. e., participants made more errors in the non-immersive than in the immersive setup. On average, 74.19% of the participants' responses were correct for tasks with a time gain $g_t = 0$, as well as 73.73% with a time gain $g_t = 1$, and 70.63% with a time gain $g_t = 2$. For the non-immersive condition with a time gain $g_t = 1$, participants' responses were correct in 61.45% of the trials.

These results are in line with those of the verbal task, although overall the error rates are higher than for the verbal task; but still considerably low. Considering the challenging mental rotation task, the results still indicate high performance and focus of attention of participants on this task.

4.3 Questionnaires

We measured a mean SSQ-score of 7.84 ($SD = 1.81$) before the experiment, and a mean SSQ-score of 13.71 ($SD = 3.38$) after the experiment [30]. The results indicate a typical increase in simulator sickness when wearing an HMD over the time of the experiment. However, none of the participants complained about serious symptoms or discomfort during the experiment.

The mean SUS-score for the sense of feeling present in the VE in the immersive display conditions was 5.15 ($SD = .91$), which indicates a high sense of presence [41].

5 Discussion

In the experiment, we found a significant main effect of time gains on time estimates when no cognitive task was present, which indicates that time judgments were affected by manipulated zeitgebers related to the speed at which the virtual sun moved over the sky in the IVE, which supports our hypothesis H1. Furthermore, our results revealed a comparably low effect size and main differences between time gains of $g_t = 0$ and $g_t = 1$. Increasing the speed of the sun to twice its natural speed did not result in a significant change in time estimates. Hence, it appears that time estimation is improved in the presence of a dynamically moving sun while it is degraded in static virtual scenes. This is an important implication for implementing near-natural IVEs since it suggests that humans extract time information from the representation and movements of a virtual sun. And furthermore, the results show that manipulating such natural zeitgebers can influence the estimation of time durations. While the present experiment focused on zeitgebers related to the virtual sun, i. e., the position of the sun in the sky affecting the direction and movement of shadows and natural lighting, we believe that it would be possible to gain similar effects with different visual zeitgebers or via other sensory modalities as well, such as repeating or progressing noises in the environment or the temperature rise and fall that is induced by the sun [38].

In contrast, our results show that time estimation was not significantly affected by time gains if participants were engaged in a verbal or spatial cognitive task. In line with the literature on time perception in non-immersive display setups (see Section 2), our results show that both cognitive tasks resulted in shorter estimated times supporting our hypothesis H2, which also approximated more the actual durations in our experiment compared to the condition without cognitive task. However, one cannot assume that users of VR are constantly involved into complex cognitive tasks, and ignore external natural zeitgebers such as the sun.

The results do not support our hypothesis H3 that the effect of time gains on time estimation would be more reduced by the spatial cognitive task and less by the verbal task; spatial as well as verbal tasks effectively dominated these external zeitgebers. Our results showed a trend in the difference between time estimation in the immersive and non-immersive VE in line with hypothesis H4 though the analysis did not reveal any significance, assuming a small effect size of immersion. For the spatial as well as verbal tasks we found a significant effect on performance regarding the true positives for the immersive and non-immersive conditions for time gain $g_t = 1$. Participants made more errors in the non-immersive than in the immersive setup, in particular, in the spatial tasks, which might be due to the missing motion parallax in the non-immersive condition or due to lack of more immersive stimuli, leading to lower presence in the VE.

Very few research experiments addressed this question so far and it is an interesting direction for future work to investigate these trends between the real and virtual world with focused experiments. In particular, it is interesting to compare such observed trends between very long or very short time intervals [13].

6 Conclusion and Future Work

In this article, we explored the effects of manipulated zeitgebers, cognitive load and immersion on time estimation as yet unexplored factors of spatiotemporal perception in VEs. We presented an experiment in which we analyzed human sensitivity to temporal durations while experiencing an immersive HMD as well as non-immersive VE. We found that manipulations of external zeitgebers caused by a natural or unnatural movement of the virtual sun in the sky had a significant effect on time judgments. Moreover, we found that increased spatial and verbal cognitive load with a dual-task method resulted in a significant shortening of judged time as well as an interaction with the external zeitgebers. We discuss the implications and provide some guidelines for near-natural temporal stimuli in computer-generated virtual worlds.

In the future, we plan to investigate alternative manipulation approaches for zeitgebers such as virtual sand clocks or watches incorporating also multimodal information such as audio stimuli representing ticking of a clock. In this scope, we plan to evaluate the effects of physical heat from the virtual sun on time estimation and adaptation of the circadian system. Furthermore, we want to consider more dynamic and ecological reliable scenarios, for instance, in which users actively move through the IVE, while still ensuring that external zeitgebers are constantly visible.

With the increasing availability and the enormous interest of the consumer market in VR technology, it is clear that more and more people will use VR technology in the future, and it is important to understand how time is perceived in VR. This research provides a first step towards understanding time perception and manipulation in IVEs, and we believe that this topic has great potential to stimulate new research directions, in particular when numerous users will use VR technology for long periods of time [38].

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