Tick-tock: Revisiting the Influence of Zeitgebers and Cognitive Load on Time Judgments during and after VR Immersion

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ABSTRACT

Prior research has explored the impact of virtual reality (VR) on human time perception without definitive conclusions. To enhance understanding, we replicated a seminal study, refining it and introducing novel variables. Building upon the original study, we investigated the influence of virtual sun speed and cognitive workload on time perception in a VR environment. Our experiment involved 70 participants estimating time intervals under varying cognitive demands. In addition to assessing time perception during immersion, we examined post-VR time estimations. Contrary to the original study, virtual sun movements did not affect time judgments in VR. However, cognitive workload had a consistent effect, which is consistent with previous findings. Notably, VR immersion affected post-VR time perception of short intervals, a previously overlooked aspect. We contribute to the field by deepening the understanding of time perception dynamics during and after VR experiences and refining earlier findings through replication.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; **Empirical studies in HCI**.

KEYWORDS

Time perception, virtual reality, user study, replication.

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1 INTRODUCTION

The perception of time is an integral part of human life. Individuals rely heavily on various external timekeepers, such as clocks or light-dark cycles, but must also rely on their ability to estimate the passage of time without a physical clock [2]. Interestingly, although there are several studies comparing time perception in virtual environments (VE) [34, 36], the impact of virtual reality (VR) on the experience of time has not yet been fully understood. However, the continued use of VR for training in safety-critical tasks, including remote piloting [23], surgical planning and navigation [11], and emergency medicine [35], requires an understanding of time perception during the use of such applications. Furthermore, as the use of VR becomes more prevalent in both industry and personal life[1], it is critical also to examine its after-effects to understand the impact of VR on everyday activities. Although there is little research on post-VR time perception, previous studies suggest that some of VR's negative after-effects could potentially lead to harmful situations. For example, VR in a semi-autonomous car may impair manual driving ability after immersion in a virtual environment due to VR-induced cybersickness [39, 40]. In terms of time perception, there is evidence that an altered perception of time may be experienced after exposure to certain types of media, such as 2D video games [24, 29]. Determining whether VR also causes an after-effect of distorted time perception may assist researchers and practitioners in designing interventions or structuring tasks to account for altered time perception during the transition from VR to the real world.

To this end, we conduct a partial replication study in which we closely replicate a study by Schatzschneider et al. [34]. The original work investigated the influence of virtual sun movement and cognitive workload (verbal working memory and spatial working memory) on time perception in VR. In addition to verifying the effect of sun movement on time perception in VR, we refine and extend the replicated study by including new elements, namely (1) a different type of cognitive load (visual search and short-term memory task) and (2) measurements of time estimation *after VR*. In the present study, participants are situated on a beach while the sun moves across the horizon at varying speeds. Participants either perform a workload task or remain idle (baseline), ending the task after 10 minutes for the in-VR time production task. Immediately following the VR session, they are asked to report when they think 10 seconds and 180 seconds have passed.

In the original study, Schatzschneider et al. [34] found that, in the absence of cognitive workload, participants overestimated[2] time with a static sun compared to conditions with a dynamic sun. Contrary to that, we find no significant effect of the virtual sun on the perception of time *in VR* (or *after VR*). Regarding the effect of cognitive workload on time perception in VR, our results are consistent with the original study, which shows that people tend to underestimate elapsed time when presented with a task that requires cognitive load. Beyond that, we show that being immersed

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[1] https://www.statista.com/forecasts/1337175/vr-hardware-b2c-market-revenue-worldwide-by-segment

[2] Overestimation of time means thinking something took longer than it actually did. Underestimation of time means thinking something took less time than it actually did.

in VR affects time perception briefly *after VR*, independent of sun speed or in-VR workload.

Our work makes several important contributions to the research of time perception in VR. Firstly, we provide new insights into post-VR time perception, highlighting the potential impact of VR's after-effects on users' decision-making and safety awareness. Secondly, we expand the understanding of time perception *in* and *after* VR by considering variations in cognitive workload. Here, we strengthen the original study's findings on the relationship between cognitive workload and time perception in VR. At the same time, our study challenges the findings of the replicated study on the effects of sun behaviour on time perception in VR, suggesting that the sun as an external zeitgeber is not strong enough to alter time perception in VR (or after VR). Using a different research design and a larger sample size improves our study's robustness, strengthening the empirical basis of the field.

2 BACKGROUND & RELATED WORK

2.1 Time Perception

Depending on various factors and circumstances, individuals perceive the duration of events differently. Although humans do not possess a sensory organ or system comparable to a physical clock that can be directly observed or measured, several models attempt to explain how humans perceive time. For instance, chronobiological models describe the influence of endogenous factors on the "master clock", the area in the human brain that generates circadian rhythms and sends time-of-day information to other regions of the body [7, 37]. In addition to the internal synchronization of time within the human body, various exogenous factors also play an essential role; however, light is considered to be the dominant zeitgeber (i.e., environmental time cue) for the human clock [30]. Overall, time perception can be influenced by various factors [15], including substances [1], rewards [12], emotions [32], flow [18], and immersion [33].

2.2 Time Perception in VR

VR's impact on time perception has been widely studied. Evidence suggests that VR can affect temporal perception, but whether individuals tend to underestimate or overestimate the time spent in VR depends on several factors. Below, we present a review of existing research in the field that investigates the impact of various factors, including user-related factors (e.g., users' movement and enjoyment), zeitgebers within virtual environments (e.g., light intensity), and the VR medium itself.

2.2.1 User-related Factors. One significant factor influencing time perception is movement and the perception of movement. For example, Bruder and Steinicke [6] have found that people tended to overestimate the duration of their virtual walks slightly. Bansal et al. [4] have shown that synchronizing individuals' movements with the speed of events in a virtual environment results in a subsequent underestimation of time. Likewise, Rietzler et al. [28] have demonstrated that simulating user movements in slow motion in VR leads people to underestimate the duration of time. Thus, to avoid mediators, experiments that investigate other factors should avoid moving scenarios.

Subjective variables, such as enjoyment and embodiment, have also been shown to affect time perception in VR. For example, to assess the relation between inactivity, boredom, and time perception, Igarzábal et al. [19] have replicated an experiment conducted by Witowska et al. [45] in an actual waiting room in VR. Contrary to the expectation that VR technology would be less boring and lead to a faster subjective passage of time, individuals perceived time as passing more slowly in the VR waiting room than in the actual waiting room. At the same time, Read et al. [27] have discovered that whether or not people enjoy a VR experience does not affect their perception of time. Embodiment has been linked to time perception with time passing slower in low embodiment conditions — independent of activity [42]. Contrarily, Landeck et al. [21] did not find an effect of embodiment on time perception. Based on these findings and the original study's approach, we maintained a neutral and relaxing VR environment to avoid introducing mediators. Consistent with the initial design, we opted not to include an avatar or virtual body to prevent adding potential confounders.

2.2.2 Zeitgebers in VR. The influence of zeitgebers on time perception in VR, the area of research closest to the current work, has been the subject of a handful of studies. Liao et al. [22] have researched the influence of visual (three levels of brightness) and auditory (three frequencies of ticking sounds) zeitgebers and cognitive load on the duration of a prospective time estimation task[3]. They found that individuals tended to overestimate time in dim and bright light conditions when presented with a cognitive task. However, they underestimated time without cognitive load in the same light conditions. They have also found that the sound of a ticking clock led to underestimating time in VR. Landeck et al. [21] have investigated perceived object motion (the same concept as a pendulum clock) focusing on embodiment. Time was perceived to pass more quickly when participants observed oscillating motion in both immersive and non-immersive environments. The research shows that zeitgebers can potentially influence time perception — a fact on which we base our experiment.

In the study replicated here, Schatzschneider et al. [34] have sought to determine whether the behaviour of a visual zeitgeber in VR (i.e., no movement, natural, and double the natural movement of the virtual sun) and different types of cognitive load (i.e., no workload and spatial and verbal working memory tasks) affect time perception. In the absence of cognitive load, the participants perceived the duration to be significantly longer when the virtual sun was static compared to the moving sun. However, judgments were not significantly influenced by the imposed cognitive load in the presence of the manipulated zeitgeber. Similar to other studies [3], the introduced workload shortened the judged interval.

The study of Schatzschneider et al. [34] has sparked several replications and extensions, including this work. For instance, Fischer et al. [13] have conducted a replication study across diverse environments while maintaining consistent task parameters. The differences in sun speed were not statistically significant. While they did not analyze the workload, Sabat et al. [31] have found a significant effect of cognitive workload on perceived durations, but not on the sun's speed. Notably, they shortened the duration per

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[3] Estimation of duration towards a future event.

trial from 10 minutes to 6 minutes. However, these replication studies have only investigated time perception during VR immersion. As evidence suggests that VR can alter time perception [36] and potentially lead to a distorted sense of time post-VR, our replication also examines time perception after immersion.

2.2.3 VR. The above-reviewed studies suggest that changes in time perception are often due to factors manipulated in a virtual environment rather than the VR itself. However, some studies show that immersive VR may result in a time compression effect (underestimation) due to increased attention and emotional arousal induced by novel and engaging stimuli, as well as the potential dissociative effect of immersive experiences from the real world or one's body [43]. For instance, in a study by Schneider et al. [36], patients diagnosed with cancer underwent chemotherapy with and without VR distraction. The patients significantly underestimated the time spent in VR, making the chemotherapy sessions a more tolerable procedure. In turn, Bogon et al. [5] have discovered that VR only affects users' expectations regarding the duration of specific physical processes, such as water flowing more slowly in VR, but does not influence their perception of time overall.

2.3 After-effects of VR

Research into the after-effects of virtual reality (VR) has predominantly focused on cognitive performance and the occurrence of cybersickness. Notable findings include deteriorated reaction times and choice reaction task performance, as shown by Mittelstaedt et al. [25], and slower decision times observed by Szpak et al. [40]. Cybersickness may persist for up to 40 minutes following exposure [40]. However, Varmaghani et al. [44] suggest that cybersickness does not necessarily impede cognitive processing. Visual processes are also affected, with observed changes in accommodation. This is likely due to the decoupling of accommodation and vergence in HMDs, although vergence remains unaffected [40]. Notably, Bansal et al. [4] explored time perception following VR exposure, confronting participants with a motor reproduction task (reproduction of a motion with the exact timing as shown earlier with a controller or the eye). Results revealed a significant underestimation of probe intervals by approximately 15% in trials of extended duration with VR manipulation, an effect not observed in control VR or non-VR conditions. In conclusion, the evidence indicates that VR significantly impacts humans after immersion, including their perception of time (as demonstrated by the motor reproduction task). However, there is a lack of data regarding prospective time estimation.

2.4 Summary

The verification of the sun's effect on time perception in the 10-minute condition of Schatzschneider et al.'s study is still pending. Furthermore, investigating alternative types of workloads would enhance the findings regarding the impact of workload on time perception. This would provide practitioners valuable insights into which tasks to use or avoid when managing time in VR. Finally, exploring whether time perception is distorted after VR, similar to games or other media, is essential to inform applications and interfaces to consider a potentially altered time perception by introducing interfaces that exploit or circumvent the effect.

3 STUDY

Based on the related work, our study addresses the following research question:

RQ1: How do different *speeds of the virtual sun* and *levels of short-term visual search cognitive workload* affect temporal productions made *in VR*?

To answer this research question, we partially replicate the study by Schatzschneider et al. [34], following the understanding of a conceptual replication (and not a direct replication; "test the same theoretical process as an existing study, but that uses methods that vary in some way from the previous study" [8]). More specifically, we recreate the virtual environment design as accurately as possible, including sun size, movement and elevation speed, and VR immersion time. Thus, we replicate the original conditions of sun movement (i.e., static, normal, and double the normal speed) and the original workload condition (i.e., "no workload"). We expand the original task to examine the effect of different workload levels (low and high) on time perception. In addition, our study's task relies on visual search and short-term memory instead of verbal and spatial memory. This study uses time interval productions instead of temporal estimates due to the susceptibility of the latter to cognitive biases, such as whole number response bias [46]. Time production methods can reduce the tendency for participants to report estimated intervals in rounded numbers [46].

In addition to providing more insight into the topic, our study contributes to the understanding of altered time perception *after* experiencing an immersive virtual environment. Previous research suggests that playing video games may lead to an altered perception of time [9]. It has been shown that individuals experience a loss of time after playing video games based on the evaluation of their short interval estimates, while the opposite is true for longer intervals [24]. We investigate the perception of 10- and 180-second intervals to examine whether VR, the sun's movement speed in VR, and workload in VR have short- and long-term effects on time perception after VR. Thus, our second research question is as follows:

RQ2: Do different *speeds of the virtual sun* and *levels of cognitive workload* or *VR itself* alter time perception *after experiencing VR*?

3.1 Methods

The study employed a mixed factorial design. The between-subjects variable was the movement speed of the virtual sun, categorized into three levels: *static**, *normal**, and *double the normal speed**. The within-subjects variable was represented by cognitive workload, which consisted of three levels (i.e., *no workload**, *low workload*, and *high workload*; "*" indicates conditions that were also present in the replicated study).

3.2 Sample

The call for participation was sent through the university mailing list of active students and advertised on various student Facebook groups of the university. Seventy individuals (28 self-identified as female and 42 as male) volunteered to participate in the experiment. The age range of the participants was 19 to 62 years old ($M = 26.29$, $SD = 6.5$). Most participants previously experienced VR (yes/no question; 71.4% answered yes). All had normal or corrected to normal vision.

Figure 1: VR application designed for the current study. The cognitive workload task was displayed on the blackboard.

Before the experiment, participants were randomly divided into three groups corresponding to different virtual sun conditions: the static sun group ($n_{static} = 23$), the normal speed group ($n_{normal} = 24$), and the double normal speed group ($n_{double} = 23$). This complete randomization was performed using a computer-generated sequence to ensure a fair and unbiased distribution across experimental conditions. In the analysis, the virtual sun condition served as a between-subjects factor, with each participant experiencing only one state of the virtual sun.

Next, participants were assigned to a series of workload conditions (no workload, low workload, and high workload). To account for potential sequence effects, a complete counterbalancing strategy was used for the workload conditions [14]. There were six possible sequences for the three workload conditions, and each participant was randomly assigned to one of these sequences. Thus, all participants were exposed to each cognitive workload condition, which served as the within-participant variable.

Participants received no compensation. The experiment was conducted according to the ethical regulations of the local university and the national research body.

3.3 Procedure

Participants who agreed to participate in the study were informed of the purpose and procedures of the study. They were instructed to remove any personal items that could aid in time detection. The participants were requested to fill out a demographic questionnaire. A baseline measurement of the short and long time intervals (see Subsection 3.5.1) was performed. Further, the participants were given instructions for the primary and secondary tasks. They received training on the non-temporal task in VR (see Subsection 3.5.2), practising both low and high difficulty levels until they demonstrated understanding.

The training was followed by three experimental blocks with a varying level of workload. Each block consisted of a 600s VR session and post-VR time productions of 10 and 180 seconds. In VR, the participants had to complete the time production task (600s) and perform the workload task. Following immersion, they were asked to produce two separate time intervals of 10 and 180 seconds in the same way as in the baseline measurements session. The post-VR time productions were initiated immediately after a participant removed the VR head-mounted display.

3.4 Setup

Since our study is based on the original study of Schatzschneider et al. [34], we developed the VR application with Unity 5.6.1 to closely resemble the original study's setup (for more details, see Schatzschneider et al. [34]). In contrast to the original study, the cognitive workload task was presented on a blackboard and not suspended mid-air in front of the participants. Figure 1 illustrates the environment, the sun chair, and the blackboard.

The virtual sun was placed horizontally at $-37.5°$ relative to the sun chair. While this position allowed the virtual sun to be always within the participants' field of view, it also ensured they did not have to look straight into the bright virtual sun. The virtual sun was elevated at 15.75° above the horizon. The sun rotated around the origin of the coordinate system of the virtual world. The rotation angle is calculated by multiplying a factor m (0, 1, 2), indicating the speed-up relative to natural sun movement, with the sun's natural movement speed (one full rotation per day), as well as the elapsed time Δt in the experiment. The Unity project, including an executable, is available in Appendix A.

The study was conducted in a sound-proof laboratory without windows to avoid the influence of other zeitgebers. We used a HTC Vive (90Hz, 1080 × 1200 per eye, 110° field of view), powered by an Intel Xeon E5-2670 v3 CPU and a Nvidia Quadro M6000 GPU.

3.5 Tasks

The study employed the dual-task paradigm, which required the participants to divide attention between a primary and a secondary task.

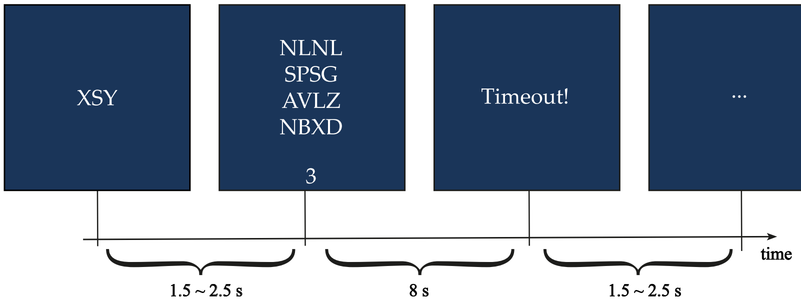


Figure 2: A schematic representation of the secondary task with timings. Participants first saw three letters. In the next step, they checked if these letters were in the grid as often as the number below the grid indicated. If they did not respond within about 8s, the trial timed out. Otherwise, the answer was recorded as either correct or incorrect.

3.5.1 Primary Task: Time Production. Temporal tasks can be divided into two groups: temporal tasks performed during VR and temporal tasks completed after VR. As mentioned above, we employed a different method of time estimation using time interval productions instead of temporal estimates used in the original study since the original technique is susceptible to a whole number response bias [46]. In the experiment, participants produced time intervals of 600 seconds while in VR and shorter intervals of 10 and 180 seconds after the VR experience. The primary reason for the varying lengths of the in-VR and post-VR intervals was to prevent the experiment from becoming too lengthy and to avoid potential progressive effects, such as increasing fatigue, boredom, and a decline in performance [14]. Additionally, Luthman et al. [24] used a similar research design, measuring subsequent time perception by asking participants to produce intervals of 10 and 60 seconds after playing video games.

Time Productions in VR. When participants were immersed in VR, they were required to produce temporal intervals of 600 seconds (10 minutes) via verbal "start" and "stop" commands. If a participant did not stop the temporal task, we terminated the task after 20 minutes from the "start" command.

Time Productions after VR. After each VR session, participants were instructed to produce 10- (short) and 180-second (long) intervals. The first interval was measured by saying "start" and "stop" commands, with the first "stop" indicating the start of the next interval. The second "stop" marked the end of the second interval. There were no breaks between the 10- and 180-second intervals to ensure measurements were taken immediately after VR immersion. Note that short and long durations were also measured at the beginning of the experiment as a baseline.

3.5.2 Secondary Task: Cognitive Load. As a secondary task, we employed a visual search and short-term memory task [20] (as opposed to a verbal and spatial working memory task used in the original study [34]). This task was selected to examine the impact of different factors under varying levels of cognitive workload. Depending on the workload condition, one to four target letters were shown to the participants for a time interval randomized within the range of 1.5 to 2.5 seconds, allowing them to memorize the target letters (see Figure 2). One to two letters were shown in the low workload condition, whereas three to four target letters were displayed in the high workload condition. Then, a 4 × 4 grid of random letters with a random number underneath was displayed for a fixed amount of time (8 seconds). Participants were required to scan the grid, look for the target letters, and count their occurrences. Within this interval, the subjects had to answer whether the number of target letters found in the grid was equal to the random number displayed. They did this by pressing buttons on the controllers. If participants responded within 8 seconds, their answers were checked for correctness. An answer was recorded as correct if the participant accurately confirmed that the displayed random number matched the number of target letters they counted in the grid. An answer was considered incorrect if the participant either incorrectly confirmed that the displayed number matched the target letters or if they did not respond within the 8-second time limit. In cases where no response was given within this timeframe, the feedback "Timeout!" was displayed. Response time, defined as the time between the moment when the individuals saw the 4x4 grid of random letters and the moment they pulled a trigger on one of the controllers, was recorded as a measure of performance for further analysis. The no workload condition consisted of no cognitive workload task, meaning the individuals only performed the primary temporal task in the immersive virtual environment. Figure 2 illustrates the high workload condition.

3.6 Measures

The demographic questionnaire gathered data on the gender, age, and educational background of the participants. Additionally, we asked if they had any health conditions or were taking any medications (e.g., sedatives) that might affect their perception of time (yes/no). [2]. If they answered yes, they were excluded from the experiment. The questionnaire also included items on previous experience with any VR headsets.

4 RESULTS

We analyzed the results using a two-way mixed analysis of variance (ANOVA). We tested normality by analyzing QQ-plots and using Shapiro-Wilk tests. If not reported otherwise, data followed approximately a normal distribution. Greenhouse-Geisser correction was applied to degrees of freedom where the sphericity assumption was violated.

The between-subjects variable was represented by the movements of the virtual sun, whereas the within-subjects variable was cognitive workload.

For the primary task analysis (i.e., time production), two dependent variables were examined: time estimations made *in VR* and *after* the VR experience. The dependent variables were represented as raw time productions in seconds. Subsequently, means (M) and standard deviations (SD) are reported in seconds (s).

To analyze the secondary task, we investigated three dependent variables: the ratio of incorrect answers provided by the participants, the ratio of timeouts (when a participant did not provide an answer), and the average response time of participants in seconds. The study compared participants' performance under low and high cognitive workload. We do this to ensure that both workload conditions are sufficiently different.

4.1 Task Performance

We found a statistically significant main effect of cognitive workload on the proportion of incorrect answers $[F(1, 67) = 182.4, p < .001, \eta_p^2 = .73]$, the ratio of timeouts $[F(1, 67) = 62.9, p < .001, \eta_p^2 = .49]$, and the response time of participants $[F(1, 67) = 592.9, p < .001, \eta_p^2 = .9]$.

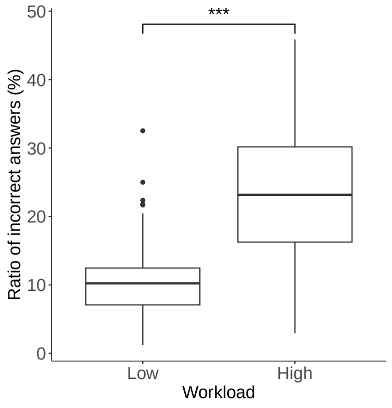
Pairwise comparisons showed that, in the low workload condition, the participants provided on average 12.7% less incorrect answers $[t(69) = 13.5, p < .001]$ and had 4.9% less timeouts $[t(69) = 8.1, p < .001]$ than in the high workload condition (cf. Figure 3a and Figure 3b). The participants spent an average of 1.62 seconds ($SD = 0.55$s) more on solving the high-difficulty questions than on solving the low-difficulty questions $[t(69) = 24.7, p < .001]$ (cf. Figure 3c). This indicates that high workload conditions resulted in more timeouts and incorrect answers, and participants took longer to complete each task trial on average.

4.2 Time Productions in VR

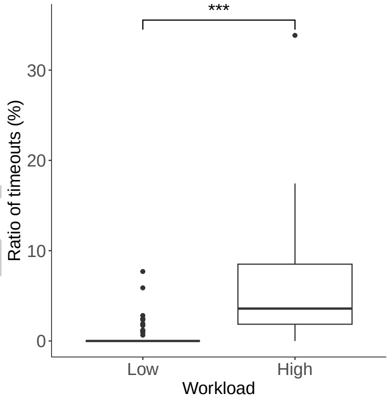
We found a significant main effect of cognitive workload $[F(2, 134) = 4.43, p = .01, \eta_p^2 = .06]$ on time productions of 600s in VR (cf. Figure 4a). Pairwise comparisons revealed that the participants produced significantly longer durations in the high workload condition ($M = 684$s, $SD = 221$s, $p = .02$) compared to the no workload condition, where time judgments tended to be relatively accurate ($M = 603$s, $SD = 192$s; the target was 600s). However, the remaining conditions had no significant differences in time production.

The test showed no significant main effect of the virtual sun on the dependent variable $[F(2, 67) = 0.94, p = .39, \eta_p^2 = .03]$. This suggests no significant difference in the time interval productions made in VR between the three groups.

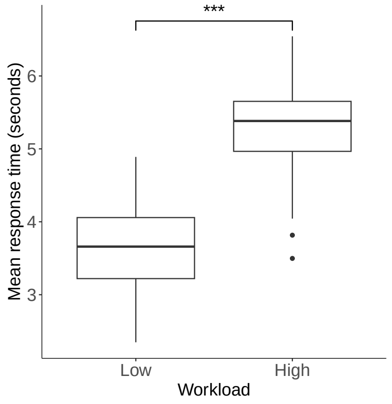
The interaction between the sun and workload did not show statistical significance $[F(4, 134) = 0.73, p = .57, \eta_p^2 = .02]$. This indicates no change in time intervals produced in VR over the workload conditions for the three groups.



(a) Incorrect answers



(b) Timeouts

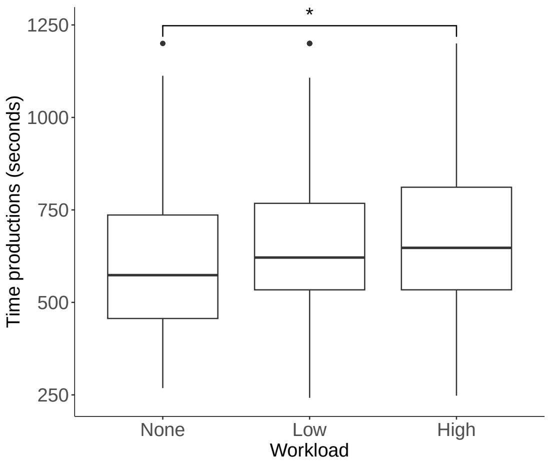


(c) Response time

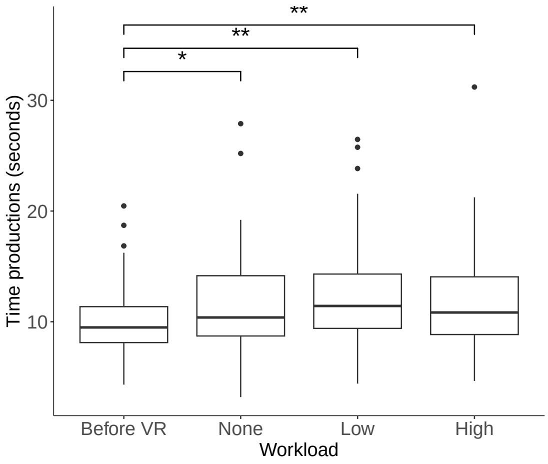
Figure 3: Results of participants' performance on the cognitive workload task in low and high workload conditions, including (a) ratio of incorrect answers, (b) ratio of timeouts, and (c) participants' response time. The results are grouped by workload condition.

4.3 Time Productions after VR

4.3.1 Short Intervals. We found no statistically significant differences between the 10-second productions performed after each VR immersion, regardless of sun speed or workload task in VR (p>.05). However, we found a significant difference between the baseline interval (before VR) and the interval after each individual VR condition $[F(2.55, 171.03) = 11.1, p < .001, \eta_p^2 = .14]$ (every participant had to do three sessions with no, low, and high workload



(a) Time productions of 600s in VR



(b) Time productions of 10s after VR

Figure 4: Results of participants' time productions during VR immersion (a) and after VR immersion (b), grouped by workload condition. Target intervals were 600 and 10 seconds, respectively.

in randomized order; cf. Figure 4b). Post hoc tests revealed that the subjects tended to perceive the short durations of 10 seconds as significantly longer after experiencing the no workload (M = 11.7s, SD = 4.53s, p = .001), low workload (M = 12.1s, SD = 4.64s, p < .001), and high workload (M = 11.8s, SD = 4.51s, p = .002) conditions compared to their judgments of short intervals before the VR immersion (M = 9.89s, SD = 3.1s), regardless of sun speed.

Besides that, there was no significant effect of the sun's movement speed on time productions [$F(2, 67) = 0.69$, $p = .5$, $\eta_p^2 = .02$] after VR, suggesting that there was no impact of the various sun speeds on the experience of time after VR. Similarly, the interaction between the cognitive workload conditions and the virtual sun's movement did not produce significant results [$F(5.11, 170.03) = 0.82$, $p = .54$, $\eta_p^2 = .02$].

4.3.2 Long Intervals. Neither cognitive workload [$F(3, 201) = 0.98$, $p = .4$, $\eta_p^2 = .01$] nor the sun's movement speed [$F(2, 67) = 0.73$, $p = .5$, $\eta_p^2 = .02$] had a significant effect on the 180-second productions performed after each VR immersion. Likewise, the interaction between those factors was not statistically significant [$F(6, 201) = 1.27$, $p = .27$, $\eta_p^2 = .04$].

5 DISCUSSION

5.1 Validity of Task

Participants made more errors and had difficulty providing responses when the task difficulty was high compared to when it was low. With that, we consider our workload manipulation successful.

5.2 No Influence of Sun, but Clear Effect of Workload

In the original study, Schatzschneider et al. [34] found no workload-independent influence of the sun's speed on time perception. In addition, Schatzschneider et al. [34] reported that participants overestimated time in the static sun/no workload condition compared to the dynamic sun/no workload conditions, with no significant differences in the remaining workload conditions [34]. In contrast, we found no main effect of the virtual sun on perceived time in VR, regardless of cognitive workload. This suggests that the sun's effect on time perception in the original study might be an artefact due to the sample or another confounding variable. Our results are consistent with other replications [31] and related studies [22], suggesting that the sun alone is not a robust factor influencing time perception in VR.

Future research should investigate whether natural engagement with a VE (e.g., ability to walk, touch), more apparent shadows, or a sun that is closer to the horizon (leading to a more noticeable change in colours) can make individuals more aware of their virtual environment and notice changes introduced by the sun as a visual zeitgeber (similar to movement in the study of [6]). It is also possible that there was not enough differentiation between sun speeds. Future studies should also examine whether faster sun movements and subsequent changes in an immersive environment have a more pronounced effect on time perception in VR. Alternatively, it may take longer for the sun's movement to have a noticeable effect on individuals (shorter durations have been researched [31] and are, thus, less likely to have an influence). Since the average duration of VR immersion in this study was about 11 minutes, this may not have been enough time for the participants to observe the changes in their surroundings. For example, the within-subjects design in the original study by Schatzschneider et al. [34] may have allowed for more observation time per participant. In contrast, in our study, each participant experienced only one sun movement scenario across all three VR sessions to reduce potential drawbacks of the within-subject research design (i.e., attrition, carryover effect, fatigue, boredom, and cybersickness). Mullen and Davidenko [26] argue that a novelty effect impacts time perception (or time compression); thus, we opted for a between-subject design (similar to the other replication of Schatzschneider et al. [34] done by Sabat et al. [31]).

Consistent with previous work Sabat et al. [31], Schatzschneider et al. [34], we found that cognitive workload led to an underestimation of time spent *in VR* in the presence of a high-difficulty task compared to the no-task condition. The results also align with previous research on general human perception of time [48] and previous research on duration estimation in non-immersive environments [41]. The findings can be explained by a link between attentional processes and time judgment mechanisms: the more attention is devoted to processing non-temporal information, the less attentional resources are available for processing temporal information [10, 47]. Interestingly, while we found a significant difference between the no-workload and high-workload conditions, there was no significant difference between no-workload and low-workload or low-workload and high-workload conditions. It appears that a certain workload level is necessary to affect time perception significantly. Consequently, while it is evident that workload affects time perception, the precise nature of this relationship remains unresolved.

5.3 Time Perception: Before vs After Immersion

Beyond providing additional evidence for (i.e., the effect of cognitive workload) and against (i.e., the effect of the virtual sun in some workload conditions) the findings of Schatzschneider et al. [34], our study also contributes to the understanding of altered time perception *after VR*. Based on the original study's findings, we initially hypothesized that since the virtual sun may affect the experience of time in an immersive virtual environment, the altered perception of time may persist after immersion in VR. Similar to the results of the in-VR-condition, we found no effect of the sun's movement on time perception. However, we observed significant differences between productions of short intervals (10s) before and after VR immersions for each workload condition, but not for longer durations (180s). Specifically, the participants produced longer intervals, meaning that they underestimated time after each VR immersion. Given that the differences occurred regardless of workload between the time measured before and after each VR immersion, these differences are likely due to the engagement in VR itself. Similarly, Luthman et al. [24] have found that productions after a non-immersive video game session were significantly longer than productions before video game play. These results align with other studies looking at the impact of VR itself on time perception *in VR*, which showed altered time perception [5, 36]. Based on this, the results suggest that engagement in any entertainment application may lead to underestimation. Note that we only found the effect to be present for short intervals, which means that the effect may diminish over time, or time perception may reset.

The distortion of time perception following VR immersion may have several implications for users. Individuals may have difficulty accurately estimating the duration of short-term events or may react with impaired performance in tasks requiring immediate responses. This can have a negative impact on decision-making in critical tasks such as performing a take-over manoeuvre after enjoying in-car VR entertainment [17]. Similarly, altered time perception might impact other professions that rely on reactive decision-making after VR immersion, such as operations in cross-reality [16], if the effect holds in further investigations. With the advent of devices that can seamlessly transition between augmented reality and VR, such as the Apple Vision Pro[4], understanding all after-effects (especially if they are potentially harmful) is crucial as it then allows designers to integrate user interface patterns that mitigate adverse effects (such as transitions that last longer than the altered time perception persists).

5.4 Limitations and Future Work

The main strengths of our study are the tight coupling to the original and other replication studies and the comparatively large sample size with a between-within design. Nevertheless, it is essential to acknowledge its main limitations. One of the limitations, specific to the replication aspect, is that we changed the workload task. However, we argue that the replication of Sabat et al. [31], using the same workload task as Schatzschneider et al. [34], sufficiently confirmed the effect of workload — thus, we opted to see if the type of workload is a relevant factor. Another notable limitation specific to the replication aspect relates to the virtual sun's minimal movement, which is only about 15 degrees per hour. Since participants spend approximately 10 minutes in VR, this subtle movement is likely insufficient to produce noticeable differences in time perception even in the fast sun movement conditions. Additionally, the experiments' relatively short duration may not fully capture the potential effects of more prolonged VR exposure on time perception. Future studies should consider longer VR sessions with more pronounced virtual sun movements to assess their impact on time perception better.

A significant limitation of this study is the absence of measurement for participants' sense of presence, which includes factors such as spatial presence, involvement, and experienced realism in the virtual environment [38]. Future research should improve this work by comprehensively analysing presence and realism in VR settings and the interaction with time perception. The overall experimental task (beach scene with mental workload task) is subject to limitations in external validity, which must be considered when generalizing the results. To address this, future studies can implement tasks that simulate real-world tasks. For instance, requiring individuals to engage in familiar activities in VR, such as shopping, cooking, or driving, can allow researchers to examine how time perception is affected by the cognitive demands of these routine tasks. In addition, VR simulations of professional activities, including teaching, performing surgery, or practising public speaking, can help understand how time is experienced during high-stress, high-stakes, or precision-dependent tasks. This can provide insights that are relevant to both training and performance evaluation in a multitude of careers. In addition, the post-VR time productions were performed in an isolated lab without other zeitgebers or cues that would be present in real life and potentially "restore" accurate time estimation post-VR and, by that, mitigate the effect we measured. Future research could address this issue by incorporating common zeitgebers, such as simulated natural light cycles or ambient sounds, in a laboratory setting to simulate a more naturalistic environment and observe their effects on time perception post-VR.

As there is still no agreement on which factors in VR lead to changes in time perception, future studies must continue exploring

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[4] https://www.apple.com/apple-vision-pro/

which factors within VR environments, such as visual stimuli, spatial cues, and sensory feedback, contribute to temporal distortions. Additionally, as VR is increasingly used for various purposes, it would be beneficial to conduct comparative studies to assess how different types of VR experiences (e.g., gaming, educational, therapeutic) influence time perception. Finally, future studies could develop techniques to mitigate known after-effects of VR, including altered time perception, to ensure a safe and optimal user experience.

6 CONCLUSION

In conclusion, our constructive replication study provides valuable insights into time perception during VR immersion and after VR immersion. Regarding the influence of sun speed, our findings diverge from those of Schatzschneider et al. [34], indicating no significant effect of virtual sun movement on time perception in VR, regardless of cognitive workload. This suggests that the previously reported effect of the sun's movement on time perception may be an artefact or influenced by other variables not considered in the original study. We strengthen previous findings on workload's effect and confirm that workload influences time perception in VR. Furthermore, our study contributes to understanding the altered time perception after VR. We found significant differences in time perception, specifically an underestimation, before and after VR immersion for 10s intervals.

These findings underscore the importance of considering time perception during VR and immediately after the experience during application design. With the rapid development of VR, it is not unlikely that future users will spend as much time in VR as they do on computers. Our insights are crucial when designing immersive experiences to mitigate potential adverse effects and to leverage potential beneficial effects of altered time perception by designing for, around, or against altered time perception, especially as VR technology becomes more integrated into daily life and professional settings.

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A DIGITAL APPENDIX

Supplemental material is available at https://zenodo.org/doi/10.5281/zenodo.11550848.