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EDITED BY
Jorge Peña,
University of California, Davis, United States

REVIEWED BY
Daniel Rene Mestre,
Aix-Marseille Université, France
Genovefa Kefalidou,
University of Leicester, United Kingdom

*CORRESPONDENCE
Maximilian Landeck,
✉ maximilian.landeck@uni-wuerzburg.de

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# Object Motion Manipulation and time perception in virtual reality

Maximilian Landeck*, Fabian Unruh, Jean-Luc Lugrin and Marc Erich Latoschik

Department of Human-Computer Interaction, Faculty of Mathematics and Computer Science, Julius Maximilian University of Würzburg, Würzburg, Germany

This paper presents a novel approach to altering how time is perceived in Virtual Reality (VR). It involves manipulating the speed and pattern of motion in objects associated with timekeeping, both directly (such as clocks) and indirectly (like pendulums). Objects influencing our perception of time are called 'zeitgebers'; for instance, observing a clock or pendulum tends to affect how we perceive the passage of time. The speed of motion of their internal parts (clock hands or pendulum rings) is explicitly or implicitly related to the perception of time. However, the perceptual effects of accelerating or decelerating the speed of a virtual clock or pendulum in VR is still an open question. We hypothesize that the acceleration of their internal motion will accelerate the passage of time and that the irregularity of the orbit pendulum's motion will amplify this effect. We anticipate that the irregular movements of the pendulum will lower boredom and heighten attention, thereby making time seem to pass more quickly. Therefore, we conducted an experiment with 32 participants, exposing them to two types of virtual zeitgebers exhibiting both regular and irregular motions. These were a virtual clock and an orbit pendulum, each operating at slow, normal, and fast speeds. Our results revealed that time passed by faster when participants observed virtual zeitgebers in the fast speed condition than in the slow speed condition. The orbit pendulum significantly accelerated the perceived passage of time compared to the clock. We believe that the irregular motion requires a higher degree of attention, which is confirmed by the significantly longer gaze fixations of the participants. These findings are crucial for time perception manipulation in VR, offering potential for innovative treatments for conditions like depression and improving wellbeing. Yet, further clinical research is needed to confirm these applications.

KEYWORDS

**mixed reality, extended reality, time perception, object motion, eye tracking, virtual time, virtual zeitgeber**

## 1 Introduction

Time perception, a fundamental aspect of human cognition, is shaped by our interaction with environmental cues, historically known as zeitgebers. These cues serve to synchronize our biological clocks with the natural world. These cues range from the grand motions of celestial bodies to the rhythmic ticking of a clock, each contributing to our understanding and anticipation of events in our environment. These events can be seen as units of perception, influenced by their variability, density, synchronicity, and predictability.

Our understanding of time is deeply intertwined with psychological and emotional contexts. The association with certain zeitgebers, such as clocks, extends beyond their functional role as timekeepers; they often carry implications that can affect our emotional state, for example, inducing stress in time-sensitive situations. An orbit pendulum, which is in particular different from a 'normal' pendulum, characterized by a high degree of irregular motion caused by its interacting rings, likely evokes a different set of associations, perhaps even a sense of relaxation for the observer.

The advent of virtual reality (VR) technology adds a new dimension to this dynamic, allowing us to explore how virtual zeitgebers affect our perception of time. An example is found in Schatzschneider et al. (2016)'s work, where the Sun acts as a virtual zeitgeber within virtual environments (VEs). The concept of virtual zeitgebers was expanded upon within the VR framework developed by Landeck et al. (2020a), which offers a structured virtual laboratory for controlled experiments, complete with customizable logic and a selection of virtual zeitgebers. The framework allows the manipulation of three key axes: velocity, density, and synchronicity of virtual zeitgebers such as clocks, fans, and pendulums. The speed of a simulated movement through a virtual tunnel showed not only an influence on the experience of time, but also a link between perceived passage of time and vection (Landeck et al., 2022). The virtual tunnel served as a unique virtual zeitgeber by occupying a significant portion of the viewer's field of view and creating a sense of self-motion, or vection, by simulating movement towards the user. This example highlights the complex interplay between the interpretation of motion as either internal or external and the user's perspective. In previous work, the influence of seven virtual zeitgebers on the experience of time in VR environments was investigated (Landeck et al., 2023b). These zeitgebers, ranging from clocks to fans to pendulums, served as tools to explore the interplay between their object and motion properties and our perception of time in VEs. It was found that virtual zeitgebers with more complex and irregular motion not only elicit higher ratings of perceived passage of time, but also appear to alleviate boredom. In particular, the correlation between boredom and the passage of time was found to be strongly negative, highlighting the relationship between these two subjective experiences. The clock, as one of the virtual zeitgebers investigated, was associated with significantly higher time duration estimations in seconds and higher time thinking ratings compared to the others. The pronounced influence of the clock on these ratings could be attributed to its established role in time measurement and perception, as discussed in the previous study.

Exploring how boredom, time perception, and virtual zeitgebers interact in VEs could significantly advance our understanding of time modulation by virtual stimuli. This insight is particularly relevant for the design of virtual experiences where time perception can be intentionally manipulated to enhance user engagement and immersion. For example, incorporating objects with faster and irregular motion into 3D environments, interfaces, or animations could make time seem to pass more quickly, potentially reducing user boredom. This concept is related to the psychological theory of flow, where shifts in time awareness and self-consciousness are influenced by engagement, task focus, and difficulty (Csikszentmihalyi, 1990). By designing VEs that strategically employ these elements, designers could promote flow states that enhance the overall user experience. In addition, these design principles could have therapeutic implications. Virtual reality therapies, known for their emerging potential (Emmelkamp and Meyerbröker, 2021), could benefit from using such dynamic virtual zeitgebers to tailor therapeutic environments. These environments could specifically target and modulate time perception to improve outcomes for conditions characterized by disrupted time perception, such as depression (Vogeley and Kupke, 2007; Vogel et al., 2018). The practical application of the integration of faster and irregularly moving objects paves the way for new methods in virtual reality that are not only promising for the creation of novel VR experiences, but also have potential for therapeutic applications in clinical settings. Further research is needed, particularly in clinical settings, to determine the efficacy of VR-based interventions and identify the most appropriate virtual zeitgebers to optimize therapeutic outcomes.

## 2 Related work

### 2.1 Time perception

The concept of *Psychological Time* is influenced by several factors, with particular emphasis on the *passage of time*—how quickly time seems to pass during event perception—and *duration estimation*, which involves retrospectively estimating time frames. A key influencing factor in this context is attention. The division of attention between a task and the perception of time can subjectively alter the speed of time's passage. This phenomenon is encapsulated in the 'attentional gate model' (AGM), proposed by Zakay and Block (1997). According to the AGM, an individual's attentional resources are split between attending to external events and attending to time. Wittmann (2015) expanded on this concept, describing an 'optimal experience' as a state where there's a loss of time and self-awareness. This altered state, often referred to as 'flow', was first identified by Csikszentmihalyi (1990) and has significant implications for time perception. For instance, Rutrecht et al. (2021) observed that participants in a VR video game study experienced higher levels of flow, leading to enhanced performance and time passing more rapidly. The estimation of time also plays a crucial role in our interpretation of 'cause and effect', fundamentally impacting our sense of agency as outlined by Haggard (2017). Variations in time perception are notably present in several pathological mental conditions, including depression, autism, and schizophrenia (Allman, 2015; Kühn et al., 2018; Martin et al., 2019).

Research on time perception has also delved into how subjective experiences can be modulated. Psychological studies have identified various factors and effects that influence our perception of space and time. Two significant phenomena demonstrating the relativity of space-time perception are the 'tau effect' and the 'kappa effect'. The tau effect, as described by Benussi (1913) and Helson and King (1931), suggests that longer time intervals seem to occur over larger spatial distances. Conversely, the kappa effect, introduced by Abe (1935) and Cohen et al. (1953), indicates that longer temporal intervals can appear shorter by decreasing spatial distances between successive events, and *vice versa*. An exploration by Brown (1995) examined the impact of motion stimuli on time perception. Through a series of experiments involving judgments or reproduction tasks, they found that faster speeds made time estimates longer than slower speeds, and intervals with more changes appeared longer than those with fewer changes. Jording et al. (2022) demonstrated that low-level visual stimuli, such as a star field on a computer monitor, can significantly affect the perception of time passing over short intervals. Participants perceived time to pass more quickly when viewing faster-moving and denser star fields. Interestingly, this effect was less influenced by the actual duration of the observed interval or the difficulty of the task.

These results highlight that perceptual changes, rather than actual time elapsed or task complexity, play a central role in the subjective experience of time passing. This supports the concept that the passage of time is primarily shaped by salient changes in the environment or the sequence of external events. These findings underscore the complexity of our temporal experiences and highlight the diverse factors influencing our perception of time.

## 2.2 Time perception in VR

VR serves as a potent tool for investigating human responses in controlled environments, providing a safer alternative for exploring a myriad of questions. According to LaViola (2017), VR is defined as an approach that utilizes displays, tracking mechanisms, and various technologies to immerse users in a virtual environment. This virtual environment is experienced from a first-person perspective through a head-mounted display device. The feeling of really being inside the virtual environment, often termed the ‘sense of presence’, is a key aspect of VR experiences (Steuer, 1992; Bryson, 2013; Lelyveld and Entertainment, 2015). When users genuinely feel as though they are within the virtual space, it enhances the sense of presence. Furthermore, this concept is frequently extended to include the notion of a ‘place illusion’. The ‘place illusion’ revolves around the perceived reality of the virtual environment, and the credibility of events occurring within it is commonly referred to as a ‘plausibility illusion’ (Sanchez-Vives and Slater, 2005; Slater, 2009).

Schneider and Hood (2007); Schneider et al. (2011) showcased the passive influence of VR headsets on time perception by immersing patients in a virtual environment. Their work highlighted the VR headset as an effective distraction mechanism. Building upon this, Malpica et al. (2022) contributed evidence suggesting that larger visual changes, such as the transition from a monitor to a VR setting, have the effect of shortening perceived time. In VR, avatar embodiment and visual fidelity significantly influence time perception, as highlighted by recent studies (Unruh et al., 2021, 2023; Lugrin et al., 2019; Landeck et al., 2022). Embodied avatars in VR are crucial for avoiding additional distortions in the perception of time, which underlines the importance of virtual self-presentation (Unruh et al., 2021, 2023). Moreover, large visual changes inducing the illusion of self-motion (vection) in VR have been found to impact subjective time experiences (Landeck et al., 2022).

## 2.3 Virtual time and zeitgebers

Challenges in studying time perception in VR stem from its dynamic and interactive nature, where factors such as attention, emotion, event density, and predictability can influence the perception of time (Schatzschneider et al., 2016). The concept of zeitgebers, external cues that synchronize our internal biological clock, plays a crucial role (Schatzschneider et al., 2016; Landeck et al., 2020a).

Traditionally, zeitgebers are external signals that provide timing information to an organism’s internal biological clock. They serve a critical role in regulating circadian rhythms to synchronize the physiology and behavior of an organism with its environment. Schatzschneider et al. (2016) extended the term and summarized different categorizations of zeitgebers: internal, according to the traditional use of the term, and external, to denote stimuli in the external world that affect the organism’s experience of time. They developed further subcategories: Absolute zeitgebers, such as the position of the Sun in the sky (time of day), and relative zeitgebers, which indicate the speed at which time passes (thus the speed of the Sun’s motion could be considered a relative zeitgeber). It has been proposed that virtual zeitgebers and their properties, such as speed, density, and synchronicity of (virtual) events, can be manipulated to study their effects on (virtual) time perception (Landeck et al., 2020a). This builds on earlier studies and findings (Brown, 1995; Kaneko and Murakami, 2009).

A summary of time perception related VR studies and a discussion about the effects was recently published (Landeck et al., 2023a). Time experience in a virtual tunnel, which induced the illusion of self-motion through consistent visual changes of tunnel segments, and could also be classified as a virtual zeitgeber, was found to be significantly related to trial length, speed, and the number of tunnel segments visible (Landeck et al., 2022). Increased number of tunnel segments and speed of these were shown to lead to higher passage of time ratings.

However, challenges remain, particularly in understanding the interplay between motion properties, virtual body representations, and time perception in VR. The development of effective techniques for controlled time manipulation in therapeutic settings is promising. The work of Landeck et al. (2023b) compared seven different virtual zeitgebers to test how the different appearance and motion characteristics of virtual zeitgebers manipulate observers’ attention and temporal experience in VR and on a computer monitor. They were able to show higher passage of time ratings for the pendulums, highest for the orbit pendulum zeitgeber which represented a zeitgeber with irregular motion, in contrast to the clock zeitgeber which showed highest duration estimates and time thinking ratings by participants. Using the same framework and virtual environment, we extended these results to a subset of the virtual zeitgebers studied: the clock and the orbit pendulum. We added speed conditions to the subset of the two zeitgebers: slow, normal, and fast. With this new contribution, we are not only able to evaluate the previously found effects, but also to investigate how the internal motion speed of virtual zeitgebers is related to the found effects.

# 3 Contribution

By introducing conditions of different speeds - *slow, normal, and fast* - we provide evidence that the speed of internal motion of

FIGURE 1
The virtual avatar with the ‘unlit’ material.

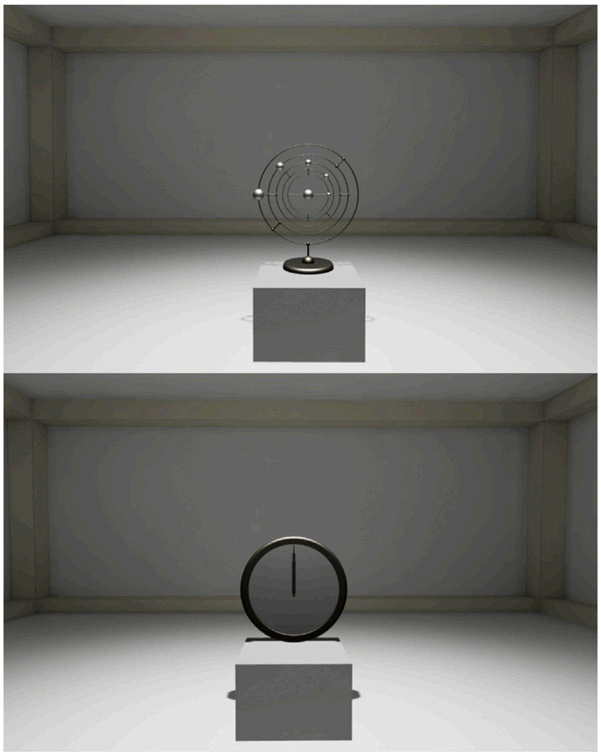


FIGURE 2
The virtual clock and orbit pendulum zeitgebers used for the presented study.

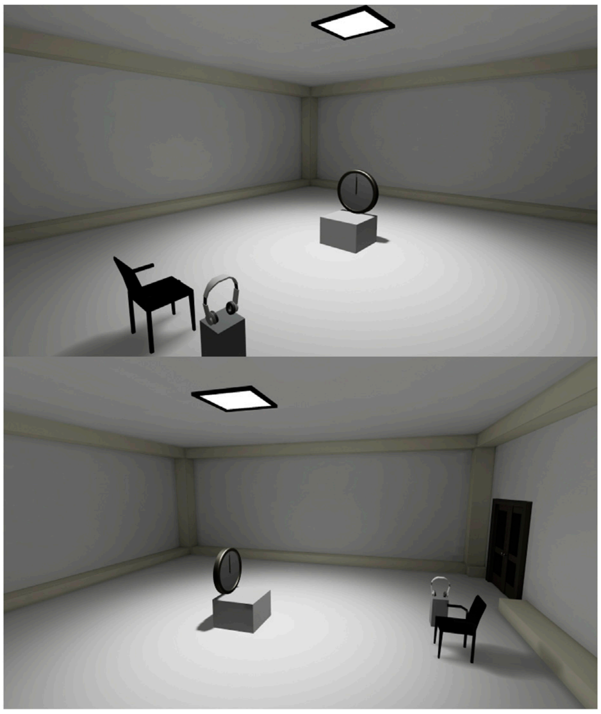


FIGURE 3
The virtual environment used for the presented study from two different perspectives.

a virtual zeitgeber significantly influenced how time in VR is experienced: time passed more slower for slow, and faster for fast internal motion speeds. We observed higher retrospective duration estimations and time thinking ratings for the virtual clock zeitgeber. Additionally, higher passage of time ratings were found for virtual zeitgebers with irregular internal motion (orbit pendulum).

We integrated eye tracking as an objective physiological indicator to increase the reliability and validity of our findings, noting significantly longer gaze durations for virtual zeitgebers with irregular internal motion (orbit pendulum). A significant correlation between gaze duration and passage of time ratings was also identified, establishing a link between visual attention, internal motion of a virtual zeitgeber, and passage of time ratings. This work also contributes to the further development of a framework for VR that provides a structured approach to exploring and understanding the nuances of temporal experience in VEs.

# 4 Materials and methods

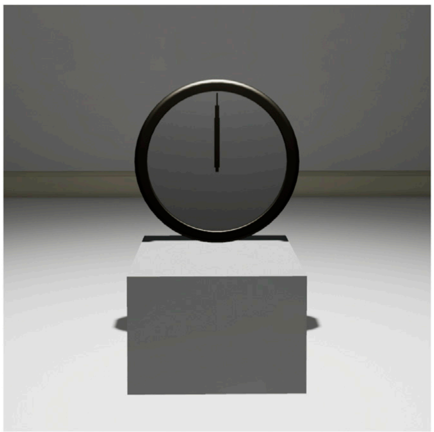
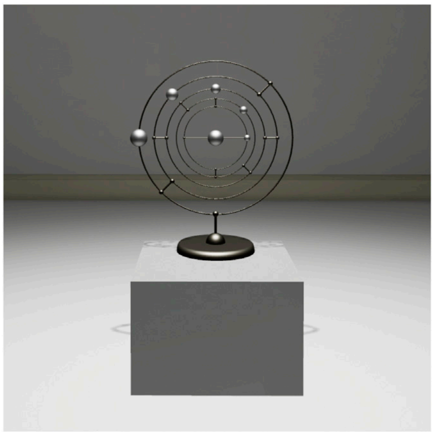
## 4.1 Hypotheses

The following experimental hypotheses were developed:

Experimental Hypotheses for Motion Manipulation and Time Perception:

- **(H1)** Time duration estimations will be lower with fast-speed conditions.

TABLE 1 The virtual zeitgebers used in the presented study with a detailed description about their internal motion and the reference to time perception.

| Virtual Zeitgeber | Description |
|---|---|
|  | • Functionality: Measures time explicitly, displaying absolute time, with internal motion serving as an implicit indicator of time's passage<br>• Moving Parts: Three internal moving parts: the bold arm for hours, the medium arm for minutes, and the smallest arm for seconds<br>• Motion Type: Rotary motion in two dimensions, around the clock's center.<br>• Motion Pattern: Simple - Regular and predictable pattern.<br>• Psychological/Emotional Effects: Looking at a clock is often associated with negative emotion, such as stress or anxiety, and can influence perception of time passing more slowly |
|  | • Functionality: Demonstrates fundamental principles of motion, gravity, and energy conservation, with an implicit demonstration of time's passage through oscillatory internal motion<br>• Moving Parts: Five interconnected rings, ranging from small to large, have balls attached to adjust each ring's center of mass, significantly influencing the orbit pendulum's motion<br>• Motion Type: Three-dimensional oscillatory motion centered around the orbit of the rings, where the attached balls' mass critically affects the kinetic energy and internal motion dynamics<br>• Motion Pattern: Complex - Irregular and less predictable patterns due to the interconnected and oscillating rings<br>• Psychological/Emotional Effects: Observing the pendulum's motion tends to induce a state of relaxation or increased focus |

- **(H2)** Time duration estimations will be lower with irregular motion.
- **(H3)** Time will be perceived as passing more quickly under fast-speed conditions.
- **(H4)** Time will be perceived as passing more quickly with irregular motion.

Experimental Hypotheses for Gaze Behaviour and Time Perception:

- **(H5)** Irregular motion leads to longer gaze fixation durations.
- **(H6)** Zeitgebers in fast-speed conditions will be accompanied by longer gaze fixation durations.
- **(H7)** Gaze fixation durations will correlate positively with the passage of time ratings.

These experimental hypotheses are linked to the presented related work, especially to (Brown, 1995) who investigated moving stimuli speed on retrospective time duration judgements and (Zakay, 1993; Block and Zakay, 1996; Zakay and Block, 1997) with the AGM model and the allocation of attentional ressources and strong connection to boredom and perceivable events and their dynamics. Also it is linked to more recent work published by (Landeck et al., 2020a; 2022; 2023b).

## 4.2 Design

### 4.2.1 Avatar design

We excluded an additional avatar embodiment condition based on previous findings by Landeck et al. (2023b), which showed no significant differences between different levels of embodiment. As a result, and based on the findings of Lugrin et al. (2019); Unruh et al. (2021), we presented all participants with a neutral and generic virtual avatar represented by an 'unlit' material, as shown in Figure 1. This design choice is consistent with studies showing that the presence of a virtual avatar does not significantly affect time perception in scenarios involving waiting or observing and evaluating virtual objects. In particular, Lugrin et al. (2019) and Unruh et al. (2021) demonstrated that perceptual differences in time only occurred in VR conditions without a virtual avatar, supporting the plausibility and congruence theory by Latoschik et al. (2022). These findings guided our decision to use a visually minimalist avatar to ensure that its presence did not interfere with the primary study objectives. The use of full-body MetaHuman avatars (Epic Games, 2022) and custom inverse kinematics to replicate body motion significantly improved the realism and plausibility of the VR environment. The novel 'unlit' avatar, devoid of visible materials and textures, was introduced not only to promote a sense of ownership of the virtual body, but also to minimize distractions from the focus of the study.

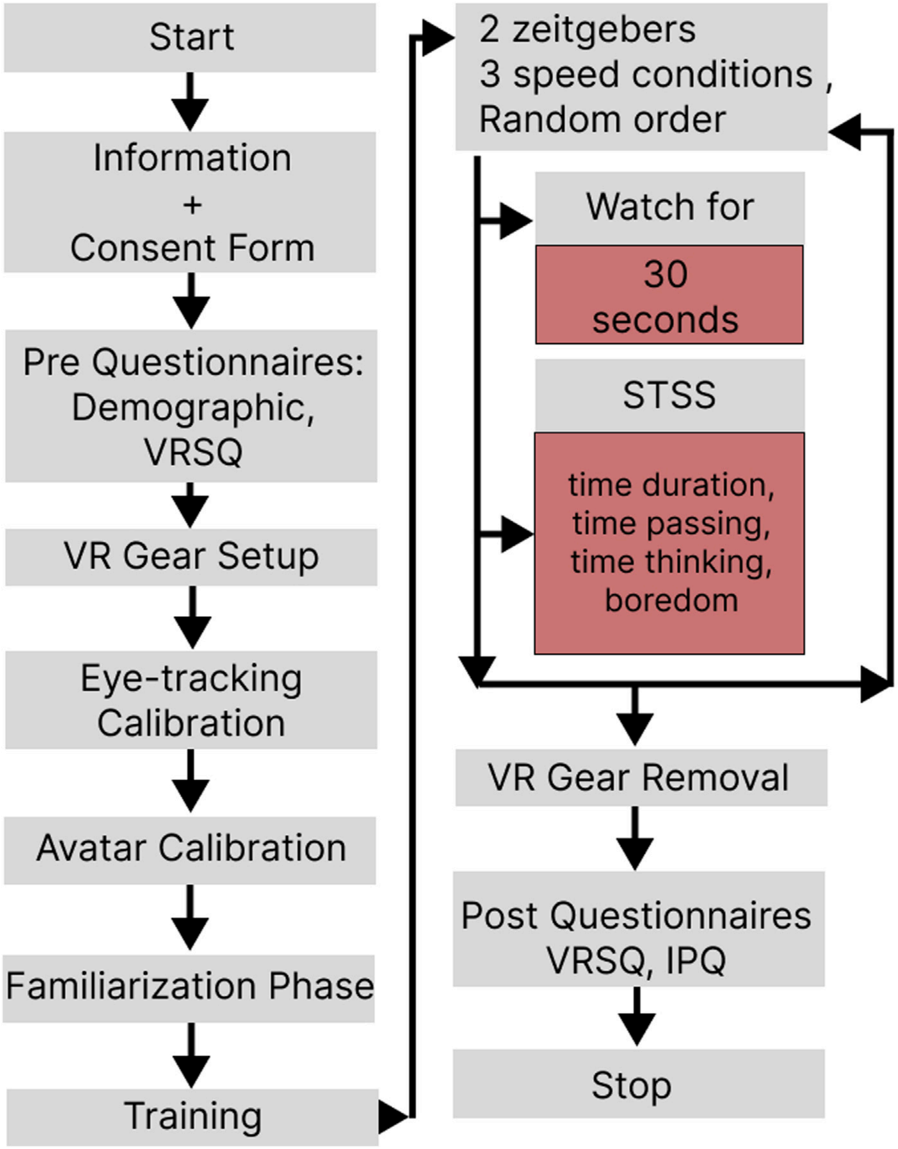


FIGURE 4
The procedure for the presented study.

TABLE 2 Mean overview table for both zeitgebers and all three speed conditions. Abbreviations: time estimates (TE) in seconds, time passing (TP), time thinking (TT) and boredom (B).

| Speed | Clock | | | | Orbit pendulum | | | |
|---|---|---|---|---|---|---|---|---|
| | TE | TP | TT | B | TE | TP | TT | B |
| slow | 18.59 | 31.25 | 65.91 | 57.38 | 15.09 | 48.09 | 38.06 | 31.91 |
| normal | 23.22 | 47.16 | 64.09 | 44.75 | 13.59 | 60.03 | 45.16 | 30.94 |
| fast | 18.47 | 51.78 | 58.88 | 40.5 | 16.69 | 61.53 | 40.88 | 31.75 |

### 4.2.2 Zeitgeber design

The virtual clock and orbit pendulum were chosen as the virtual zeitgebers (see Figure 2 for representations of the zeitgebers in the virtual environment). This was a continuation of their use in previous research (Landeck et al., 2023b). The clock is a familiar zeitgeber that is closely associated with time, with three moving hands that represent rotational motion in two dimensions. The movement of the second hand is most noticeable and fastest. The

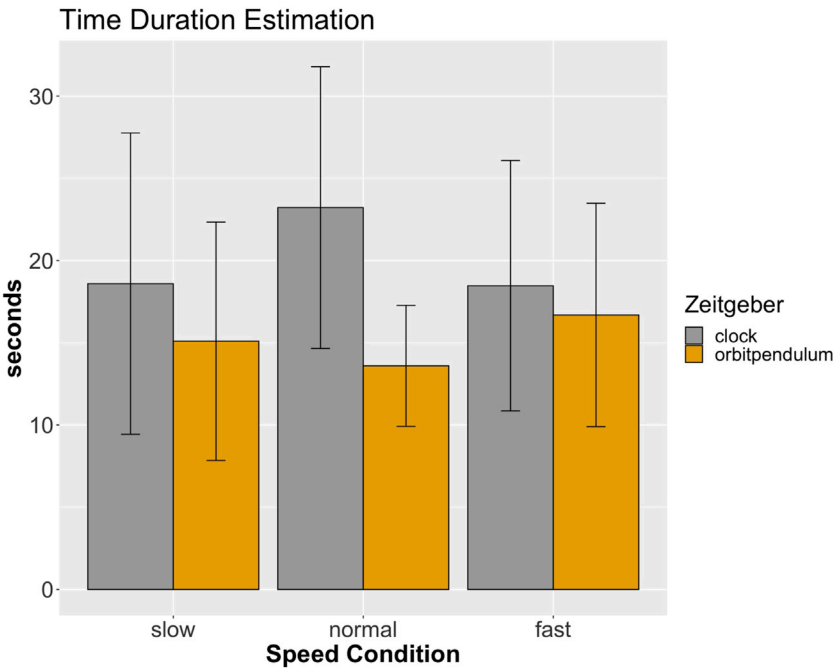


FIGURE 5
Bar plot showing the average time duration estimates for all zeitgebers and speed conditions. With standard deviation bars.

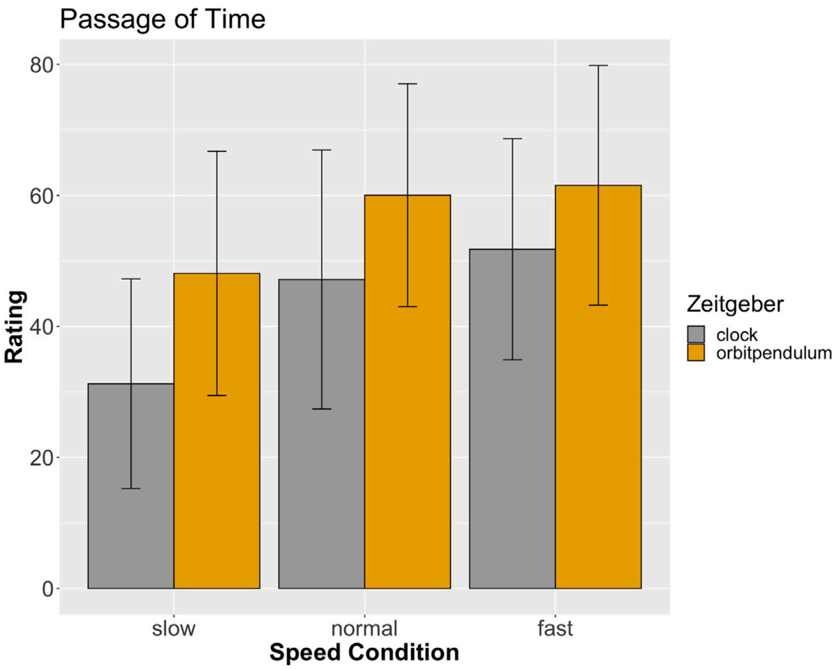


FIGURE 6
Bar plot showing the average passage of time ratings for all zeitgebers and speed conditions. With standard deviation bars.

orbital pendulum, on the other hand, derives its internal motion from simulated virtual gravity on five interdependent rings, showing oscillating motion in three dimensions. Watching an analog clock is often associated with stress, especially in time sensitive situations, while a pendulum suggests relaxation (see Table 1 for a detailed summary).

We defined the ‘normal speed’ condition to reflect the typical movement of clock hands in the real world. To ensure that the

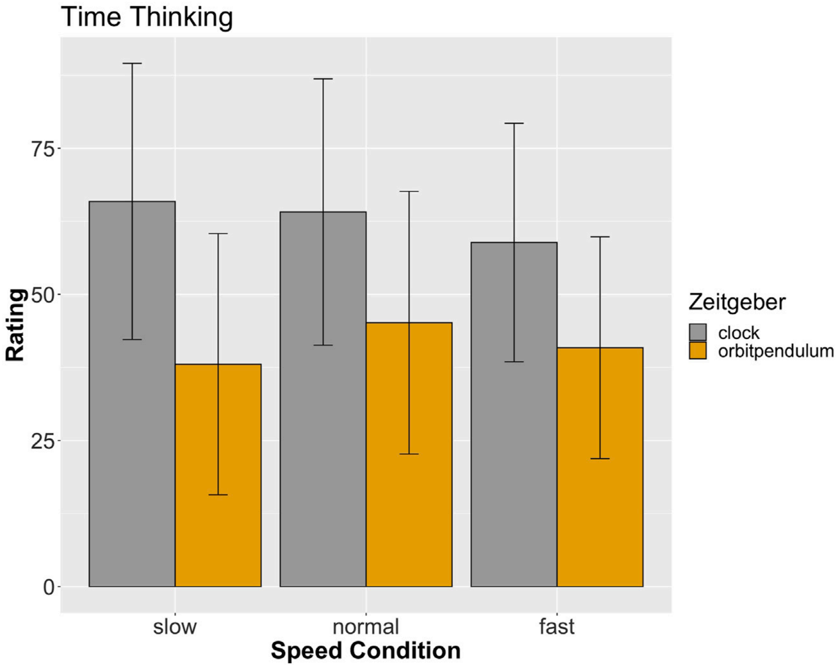


FIGURE 7
Bar plot showing the average time thinking ratings for all zeitgebers and speed conditions. With standard deviation bars.

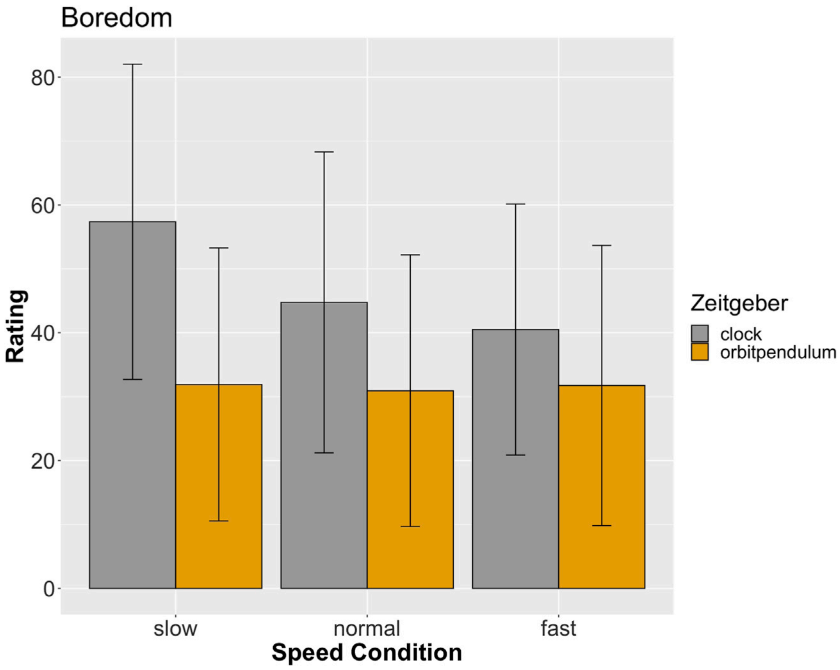


FIGURE 8
Bar plot showing the average boredom ratings for all zeitgebers and speed conditions. With standard deviation bars.

speed variations-‘slow’ and ‘fast’-were both comfortable and recognizable in VR for each zeitgeber studied, we conducted pilot testing. These tests determined that the ‘slow’ condition should be set to one-fifth of normal speed and the ‘fast’ condition should be set to five times normal speed (Beats per minute (BPM) for the virtual clock conditions slow: 12; normal: 60; fast: 300). To measure the resulting speed of different zeitgebers in the virtual environment, we used virtual speed measurement probes

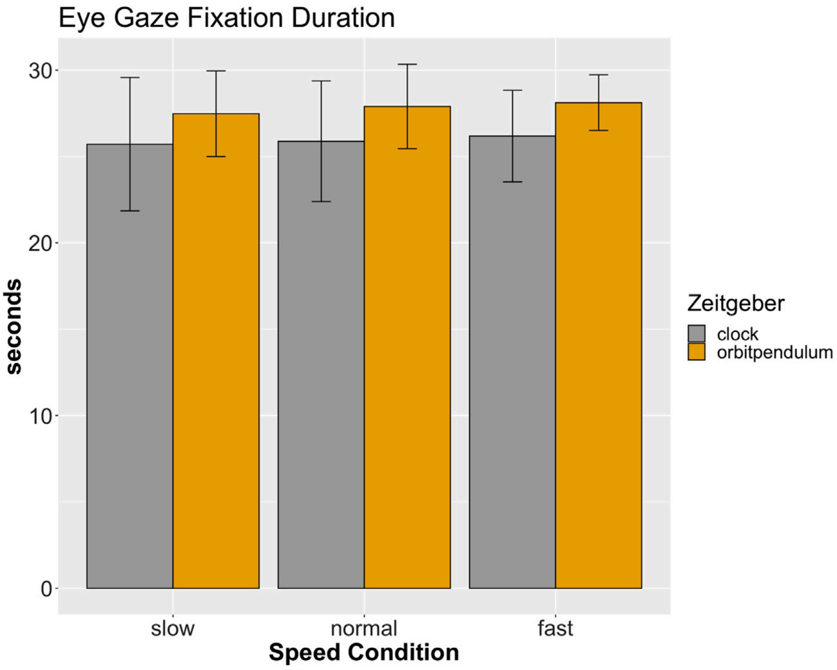


FIGURE 9
Bar plot showing the average eye gaze fixation durations for all zeitgebers and speed conditions. With standard deviation bars.

attached to their internal moving parts. This setup allowed us to track position changes over time, from which we calculated average velocities in *cm*/*s*, to achieve comparable speed settings for different zeitgebers with different motion patterns. Average speed in *cm*/*s* for the investigated zeitgebers: orbit pendulum (slow: 3.85, normal: 11.44, fast: 39.27), clock (slow: 4.01, normal: 10.65, fast: 42.06).

### 4.2.3 Environment design

To enhance the study's control, we minimized color usage to neutral tones to minimize confounding variables. To ensure participants remained focused on the virtual zeitgebers, we designed the zeitgebers, the overall environment, and additional elements like the headphones in neutral tones, specifically avoiding the use of bright or striking colors that could serve as distractions. See Figure 3 for an impression of how the virtual environment looked like.

### 4.2.4 User design/experience

We incorporated an optimized automatic calibration system for seated participants to ensure consistent positioning between the virtual and physical environments, specifically focusing on the alignment with the virtual and physical chair. The application calibrated the user's position, gaze, and gaze detection accuracy, set the experimental parameters, and managed the presentation of the zeitgebers on a central pedestal in random order. A physical chair in the experimental room enhanced the haptic experience by matching the virtual chair to increase presence (Gibbs et al., 2022). The static frame of reference of the virtual chair and room, in contrast to the dynamic zeitgebers, was intended to reduce visually induced motion sickness (Cao et al., 2018), which also served to ensure attention to the zeitgebers (see Figure 3 for the virtual setup). The design of the virtual zeitgebers and environment, based on previous work (Landeck et al., 2023b), used simple materials and colors to minimize confounding variables from reflections, specularity, or interesting colors and materials.

Pilot tests were crucial in refining the automation of calibration, experiment logic, questionnaires, and the presentation of various zeitgeber speeds and conditions.

Additionally, to maintain consistent auditory conditions across trials through white noise, we introduced virtual headphones that matched the haptic feedback provided by the physical headphones attached to the Vive Pro Eye VR headset. This setup not only enhanced the realism of the virtual counterpart but also intensified the sensation of wearing headphones. Putting on the virtual headphones served another purpose: as interaction task during the initial familiarization phase in the virtual environment.

## 4.3 Apparatus

The Metachron framework, developed on Unreal Engine 4.27 (Epic Games, 2022), served as the cornerstone for our VR environment. It was initially introduced by Landeck et al. (2020a) and modified for our study. It is available upon request at Landeck et al. (2020b). The virtual environment mostly aligns with the one used by Landeck et al. (2023b). Metachron supports a variety of virtual environments, from simple to complex environments populated with dynamic agents and configurations of virtual zeitgebers. The zeitgeber library includes a wide range of entities characterized by different types of internal motion and visual properties. It ensures that virtual zeitgebers are properly integrated into the virtual environment and dynamically adjust their properties in response to the experiment's needs. Metachron supports inverse kinematics for virtual avatars, including MetaHuman avatars from Unreal Engine (Epic Games, 2022), enhancing VR visualization. In our experiment, this function enables high-precision three-point tracking while seated (2 controllers, one headset) and ensures precise movement replication of the virtual avatar in the virtual environment. We used the integrated questionnaire system and zeitgeber library, complemented by customized experiment features for our specific conditions. Through a custom C++ plugin, we specifically improved the accuracy and efficiency of eye tracking data collection and analysis, streamlining the export process for statistical evaluation. The system was already used several times for different studies (Lugrin et al., 2019; Unruh et al., 2021; Landeck et al., 2022; Landeck et al., 2023b; Unruh et al., 2023). Latency measurements were repeatedly done to optimize the frame rate to align with the target device refresh rates. To further rule out any inaccuracies or discomfort for participants, it was also focused on minimizing the end-to-end latency, all to ensure the VR experience was of high performance and quality. Latency measurements were done with the sine fitting approach by Stauffert et al. (2020) and end-to-end latency was measured using a high speed camera and manual frame counting.

## 4.4 Procedure

Before the study began, participants were informed of the details of the study and asked to give their consent by signing an informed consent form. They were then provided with a demographic questionnaire and another survey designed to measure their current level of wellbeing and fatigue. Participants were then asked to complete the Virtual Reality Sickness Questionnaire (VRSQ) (Kim et al., 2018). An instructional text was then presented, accompanied by an explanation of the basics of the experiment and an overview of the VR equipment by the experimenter. Participants were seated and put on the VR headset with the help of the experimenter. Together, the eye tracking was calibrated to ensure the accuracy of the collected data. Subjects were then instructed to assume a T-position for the avatar calibration phase, and then to perform specific tasks: 1) visually explore the virtual environment by moving their heads, 2) move their hands, and 3) touch the virtual/physical chair with their hands. Next, they were instructed to look for virtual headphones placed in the virtual room next to where they were sitting. They moved the controller to this position and were able to press the trigger button on the controller to attach the headset to their virtual hand. With the headset in their grasp, they moved it next to their head and released the trigger. The headset was then attached to their virtual head. During this initial calibration phase, participants were able to familiarize themselves with their virtual body representation and the virtual environment around them, accompanied by the described tasks that included head movements for visual exploration, hand movements and tactile interactions with virtual and physical objects. Participants were then asked to continue the exploration of the virtual surroundings until they feel comfortable. Then, the experimenter demonstrated how to respond to questions that appeared at the end of each trial. Trials were randomized, with each of the two virtual zeitgebers displayed for 30 s, repeated three times at different speed conditions (slow, normal, fast). This was followed by fading to black and then returning to the *in vivo* questions related to retrospective time estimation, perception of time passing, time thinking, and feelings of boredom. At the end of the experimental session, participants were asked to complete the VRSQ (Kim et al., 2018) again and, for the first time, to complete the IGroup Presence Questionnaire (IPQ) (Schubert et al., 2001; Regenbrecht and Schubert, 2002; Schubert, 2003). This marked the end of the study and participants were properly dismissed. To see a summary overview of the procedure, please see Figure 4. The entire experiment took approximately 30 min from the time the participant entered to the time they left.

## 4.5 Software and hardware

The demographic questionnaire, the VRSQ and the IPQ were designed and displayed with LimeSurvey version 4.5.0 (Limesurvey GmbH - Carsten Schmitz, 2024). The results were exported from LimeSurvey hosted at the university and analyzed using JASP v.0.14 (JASP Team, 2023) and the programming language R. Participants experienced the VR environment with the HTC Vive Pro Eye head-mounted display (HMD) (HTC Corporation, 2024) with a resolution of 1,440 × 1,600 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, 64 GB RAM, GeForce RTX 3080Ti.

## 4.6 Participants

Thirty-Two participants with an average age of 22.7 (sd = 4.78) years were recruited (26 females and six males). The vast majority were students from the University, recruited via an online platform. This study was approved by the local Ethics Committee of the Institute. 84.38% reported prior VR experience with a head-mounted display. 67.74% played video games within the last 6 months. Of this 67.74% , 38.1% reported they played on average less than 1 hour per week in the last 6 months. 38.1% reported they played on average one to 3 hours per week in the last 6 months. 9.5% reported they played on average three to 5 hours per week in the last 6 months. 4.8% reported they played on average five to 8 hours per week in the last 6 months and 9.5% reported they played on average more than 8 hours per week in the last 6 months.

## 4.7 Measures

### 4.7.1 Duration estimation, passage of time, time thinking and boredom

We implemented the Subjective Time, Self, and Space (STSS) questionnaire by Jokic et al. (2018) to assess the effects of the virtual objects and their internal motion speed on time perception. Two items from the STSS were adapted previously (Landeck et al., 2022) to assess the experience of the passage of time: 1) *Duration Estimation*: “Intuitively, without thinking about it, how long did the trial last?”, 2) *Passage of Time*: “How fast did time pass for you?” (based on Tobin et al., 2010). In addition the item was asked: 3) *Time Thinking*: “How often did you think about time?”, and 4) *Boredom*: “How bored have you been?” (Landeck et al., 2022). 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. Our choice is supported by its successful application in previous both real and virtual waiting time experiments and zeitgeber experiments on time perception and its recognition as a standard technique in experimental studies (Igarzábal et al., 2021; Unruh et al., 2021; Landeck et al., 2022; 2023b).

### 4.7.2 Eye tracking

We used the eye-tracking functionality of the VIve Pro Eye headset and integrated it into the virtual environment, where a gaze beam is calculated based on the participant’s head position and the offsets of both eyes within the virtual 3D space. This system detects when the gaze beam intersects with a virtual zeitgeber and records both the duration and frequency of these interactions. For our analysis, we compared the average fixation durations for each zeitgeber across different speed conditions. Following the methodology proposed by (Clay et al., 2019), we defined virtual zeitgebers as objects of interest and collected precise data on the times and durations of gaze interactions. This approach allows us to rigorously assess participants’ visual attention and engagement with these objects, supported by evidence such as Borys and Plechawska-Wójcik (2017); Toreini et al. (2020). In addition, we ensured participant engagement by verifying that both eyes remained open throughout the sessions.

### 4.7.3 VRSQ

The Virtual Reality Sickness Questionnaire (VRSQ) by Kim et al. (2018) was used to assess simulator sickness before and after the experiment. This is a shortened version of the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). It has been adapted for use in VR. It includes the two subscales ‘Oculomotor’ and ‘Disorientation’ from which the ‘Total’ score is calculated.

### 4.7.4 IPQ

We were interested in the general feeling of presence the virtual environment produced, with the Igroup Presence Questionnaire (IPQ) (Schubert et al., 2001; Regenbrecht and Schubert, 2002; Schubert, 2003). 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.

## 4.8 Statistical analysis

We conducted two-way repeated-measures ANOVAs to test the effects of perceived objects on duration estimates, time passage, time thinking, and boredom ratings. Duration estimates, passage of time, time thinking and boredom ratings were analyzed with the interval measurement scale (Pfeifer et al., 2016; Jokic et al., 2018). Normality was tested using the Shapiro-Wilk test. The assumption of sphericity was checked with the Mauchly test, and sphericity corrections were made with the Greenhouse-Geisser correction if necessary. To compare the VRSQ scores and its subscales, the items were analyzed using a dependent *t*-test, assuming normality and homogeneity of variance. The test for normality was the Shapiro-Wilk test and the test for homogeneity of variance was the Levene test. A Wilcoxon signed rank test was performed when a normal distribution could not be assumed. A Welch (or Satterthwaite) approximation was used if the assumption of homogeneity of variance was violated. Pearson correlations between the four dependent variables duration estimation, passage of time, time thinking and boredom were performed. The eye-tracking data, which consisted of gaze fixation durations and the amount of this occurrences, was analyzed with a repeated-measures ANOVA to test the effects of perceived objects and internal motion speed. R and RStudio Team (2020) and JASP Team (2023) were used for the analyses.

## 4.9 Results

An overview table for all mean values can be found in Table 2.

### 4.9.1 Duration estimation

Variance homogeneity, but not normality, was assumed for this dependent variable. We performed the ANOVA with log-transformed duration estimates, even though the ANOVA is quite robust to violations of normality. For the duration estimates a statistically significant two-way interaction between zeitgeber and speed could be found, $F(2,62) = 6.047, \quad p = 0.004, \eta_p^2 = 0.163$. For the *post hoc* test of the simple main effect we ran an one-way model of the first variable (zeitgeber) at each level of the second variable (speed). Considering the Bonferroni adjusted *p*-value (p.adj), it can be seen that the simple main effect of zeitgeber was only significant at the speed condition normal $(F(1,31) = 35.7, p < .0001, \eta_p^2 = 0.536)$. Pairwise comparisons show that the mean time duration estimation was significantly different between the orbit pendulum and the clock zeitgeber at normal $(t(31) = 5.98, p < .0001)$ and slow $(t(31) = 2.45, \quad p = 0.02)$ but not at fast speed conditions $(orbit, slow: M = 2.61, sd = 0.648; clock, slow: M = 2.82, sd = 0.478; \quad orbit, normal: M = 2.57, sd = 0.271; clock, normal: M \quad = 3.06, sd = 0.431; orbit, fast: M = 2.75, sd = 0.36; clock, fast: \quad M = 2.83, sd = 0.441)$. Please see Figure 5 for a bar plot of the mean time duration estimates.

### 4.9.2 Passage of time

For the dependent variable passage of time, no significant two-way interaction was found, but statistically significant main effects from the ANOVA output: zeitgeber $(F(1,31) = 24.944, p < .0001, \eta_p^2 = 0.446)$ and speed $(F(2,62) = 16.688, p < .0001, \eta_p^2 = 0.350)$. Post-hoc pairwise comparisons revealed a significant difference between the zeitgeber groups $(clock: M = 43.4, sd = \quad 19.5, orbit\,pendulum: M = 56.6, sd = 18.8; p < .0001; p.adj)$. For the speed condition comparisons, passage of time ratings for normal speed were significantly different from slow speed $(slow: M = 39.7, sd = 19.2, normal: M = 53.6, sd = 19.4; p < .0001; p.adj)$ and fast speed was significantly different from slow speed $(slow: M = 39.7, sd = 19.2, fast: M = 56.7, sd = 18.1; p < .0001; p.adj)$. Please see Figure 6 for a bar plot of the mean passage of time ratings.

### 4.9.3 Time thinking

No significant two-way interaction for the dependent variable time thinking was found, but a significant main effect: zeitgeber ($F(1,31) = 39.183, p < .0001, \eta_p^2 = 0.558$). Post-hoc pair-wise comparisons showed a significant difference between the zeitgeber groups: clock and orbit pendulum ($orbit$: $M = 41.4, sd = 21.3, clock$: $M = 63.0, sd = 22.3$; $p < .0001$; $p.adj$). There was no significant difference between the speed conditions. Please see Figure 7 for a bar plot of the mean time thinking ratings.

### 4.9.4 Boredom

There was a statistically significant interaction between zeitgeber and speed on the boredom score, $F(2,62) = 3.328$, $p = 0.042$, $\eta_p^2 = 0.097$. Therefore, the effect of the zeitgeber variable was analyzed at each speed condition. $p$-values were adjusted using the Bonferroni multiple testing correction method. The effect of zeitgeber was significant at slow speed ($p = 0.0002$) but not at normal and fast speed ($normal$, $p = 0.078$; $fast$, $p = 0.171$; $p.adj$). Pairwise comparisons, using paired $t$-test, show that the mean boredom score was significantly different between the clock and orbit pendulum zeitgeber at slow speed ($clock$: $M = 57.4, sd = 24.7, orbit$: $M = 31.9$, $sd = 21.4$; $p < .0001$; $p.adj$) and normal ($clock$: $M = 44.8, sd = 23.5, orbit$: $M = 30.9$, $sd = 21.3$; $p = 0.026$; $p.adj$) but not at fast speed conditions ($clock$: $M = 40.5, sd = 19.6, orbit$: $M = 31.8, sd = 21.9$; $p = 0.058$; $p.adj$). Please see Figure 8 for a bar plot of the mean boredom ratings.

### 4.9.5 Eye tracking

For the analysis of the eye tracking data we needed to remove eight participants due to technical difficulties and calibration issues with the eye tracking headset. Normality could not be assumed for this dependent variable, therefore we performed the ANOVA with log-transformed gaze fixation durations. No significant interaction was found between zeitgeber and speed in the gaze fixation duration data, but a significant main effect of zeitgeber ($F(1,21) = 24.226, p < .0001, \eta_p^2 = 0.536$). Bonferroni adjusted *post hoc* pairwise comparison t-tests were performed. The average gaze fixation durations of the clock were significantly different from the fixation durations of the orbit pendulum ($clock, M = 3.25, sd = 0.14, orbit, M = 3.32, sd = 0.08$; $p < .0001$). Please see Figure 9 for a bar plot of the mean gaze fixation durations.

### 4.9.6 VRSQ

The VRSQ 'total', 'oculomotor', and 'disorientation' scores did not show a normal distribution. Therefore a Wilcoxon signed rank test was performed. The 'total' ($pre$: $M = 7.5, sd = 7.58$; $post$: $M = 6.82$, $sd = 6.11$), 'oculomotor' ($pre$: $M = 13.54, sd = 12.48$; $post$: $M = 11.98, sd = 10.36$) and 'disorientation' ($pre$: $M = 1.46, sd = 3.27$; $post$: $M = 1.67, sd = 3.39$) scores were not significantly different between the pre- and post-VR exposure scores. For this questionnaire, the Cronbach's alpha value was $\alpha = 0.77$.

### 4.9.7 IPQ

The IPQ general score ($M = 5.28, sd = 1.49$) and it is subscales: 'Spatial Presence' ($M = 4.71, sd = 0.81$), 'Involvement' ($M = 4.52$, $sd = 0.78$) and 'Realism' ($M = 3.88, sd = 0.99$) average values seemed to be high enough and are comparable to recent experiments in VR that used realistic looking virtual environments and humanoid virtual avatar representations (Schwind et al., 2019; Landeck et al., 2023b; 2022). The Cronbach's alpha value for the questionnaire was $\alpha = 0.85$.

### 4.9.8 Correlations

A significant inverse correlation could be found for the variables passage of time and boredom ($r(190) = -0.23$, $p = 0.001$). Another significant inverse correlation was found between the variables passage of time and time thinking ($r(190) = -0.29, p < .0001$).

A significant medium correlation could be found for time thinking and boredom ($r(190) = 0.43, p < .0001$). A significant and medium correlation was also found for time duration estimates and time thinking ratings ($r(190) = 0.42, p < .0001$). Finally, a significant inverse correlation was found among time duration estimates and passage of time ratings ($r(190) = -0.26$, $p = 0.0003$). Regarding the recorded data of eye gaze fixation durations on the presented zeitgebers, a significant correlation was found among eye gaze fixation duration and passage of time ratings ($r(130) = 0.324$, $p = 0.0002$) and between eye gaze fixation duration and time thinking ratings ($r(139) = 0.292$, $p = 0.0007$).

## 5 Discussion

Our study provides insights into how manipulating the internal motion speed of virtual zeitgebers modulates temporal perception in VR environments. We investigated the effect of virtual zeitgebers' internal motion speed on temporal perception by presenting a virtual clock and orbit pendulum in three speed conditions (*slow, normal, fast*) without the distraction of parallel tasks, unlike (Schatzschneider et al., 2016). In contrast to (Landeck et al., 2023b), which used seven zeitgebers, our study focused on two zeitgebers and their internal motion speed as additional condition, with consistent trial lengths of 30 s.

Exposure to slow and normal speed conditions revealed significant differences in retrospective time duration estimates between the virtual clock and the orbit pendulum, suggesting a nuanced interplay between zeitgeber speed and time perception. Despite observing a significant two-way interaction indicating a complex relationship, the absence of a main effect for speed led us to reject H1. Likewise, no significant differences were found in the fast speed conditions, which leads us to reject H2, hinting at a potential threshold influence of zeitgeber motion on temporal assessments.

The differences between slow vs normal and slow vs fast conditions were significant, confirming that faster conditions are perceived as accelerating the passage of time, supporting H3. The lack of a significant difference between normal and fast conditions may indicate a nonlinear relationship in how the speed of the zeitgeber affects time perception. Furthermore, this suggests the existence of individual thresholds for detecting variations in speed, beyond which variations no longer have a similar effect on time perception.

The perception of time passing faster when observing the virtual orbit pendulum compared to the virtual clock supports H4 and is consistent with the findings from Landeck et al. (2023b), indicating that irregular internal motion, such as that of the orbit pendulum, accelerates time perception. This phenomenon may arise from the increased cognitive demands of processing irregular motion, suggesting a model for how virtual zeitgebers' internal motion properties can influence temporal perception.

The significant inverse correlation between boredom ratings and ratings of the passage of time supports the idea that subjective experiences of time are closely related to emotional states such as boredom. Consistent with Landeck et al. (2023b), these findings support theoretical models such as the Attentional Gate Model (AGM), which argues that attention and interest critically shape time perception (Zakay and Block, 1995). Furthermore, the observed inverse correlation between the passage of time and time thinking, along with a significant correlation between boredom and time thinking, supports this relationship. These correlations not only validate the theoretical framework, but also highlight the profound impact of emotional and cognitive factors on time perception. By highlighting these interdependencies, our research paves the way for more targeted and effective interventions in virtual reality settings and suggests broader implications for psychological applications.

We found significant higher time thinking ratings for the virtual clock zeitgeber. This relation was previously found and the strong association of a virtual clock with time by itself was discussed (Landeck et al., 2023b).

We incorporated physiological measures, specifically gaze fixations through eye tracking, to further validate our findings. Significant longer fixation durations on the orbit pendulum indicate increased engagement, suggesting that irregular motion captures visual attention more effectively, supporting H5. Despite the lack of significant effects across speed conditions (rejecting H6), the variation in fixation durations underscores the impact of the type of zeitgeber on both attention and time perception. Furthermore, the significant correlation between fixation durations and time passing ratings confirms H7, which is in line with the literature on how visual attention influences temporal perception. The significant correlation between gaze fixation durations and time thinking ratings opens avenues for further investigation into the cognitive dynamics of attention and time perception. This relationship, along with the differential effects observed between the virtual clock and the orbit pendulum, underscores the potential of using virtual zeitgebers to explore cognitive processes related to time perception. In particular, the orbit pendulum's ability to attract greater visual attention and alter time perception provides a unique opportunity to study the interaction of attention, virtual zeitgeber, and time perception.

This study suggests a complex interplay between virtual zeitgebers, visual attention, cognitive engagement, and emotional responses (e.g., boredom) in shaping time perception in VR. The different effects of the virtual clock and orbit pendulum on participants' time perception and attention levels suggest different efficacy of virtual zeitgebers in manipulating perceived time. The orbit pendulum seemed to produce higher amount of visual attention, shorter retrospective duration estimations, higher passage of time ratings and is rated less boring. How plausible virtual objects are perceived in a virtual environment may also affect processing and cognitive resource load, in line with the plausibility and congruence theory of Latoschik et. (2022). We want to highlight the importance of real-world expectations and how even small deviations from reality could affect cognitive load, interest, and the perception of time. The challenge of accurately replicating real-world objects in VR, such as the pendulum, may affect cognitive processing and perceived time, highlighting the importance of design and realism in VEs in influencing user experience. Small differences between virtual reality and reality can increase cognitive load, but also raise interest and reduce boredom.

## 6 Implications and future work

Our study lays a foundation for future investigations into the manipulation of time perception within VEs. Expanding on this research, it would be valuable to explore the underlying neural mechanisms that contribute to the observed differences in time perception induced by various zeitgeber types and their internal motion speed. Neuroimaging studies could provide insights into the brain regions involved in processing temporal information during exposure to different variations of virtual zeitgebers. Additionally, considering the potential applications of our findings, future research could explore the integration of zeitgeber and internal motion speed manipulation in VR scenarios aimed at therapeutic interventions. Understanding how time perception can be consciously influenced may have implications for fields such as stress management, mindfulness, and cognitive-behavioral therapies within virtual settings. Furthermore, investigating the long-term effects of zeitgeber manipulation on the perception of time could provide a more comprehensive understanding of its sustainability and potential adaptation effects. Longitudinal studies exploring how individuals acclimate to an altered time perception in VR environments could inform the development of more tailored and effective interventions. Qualitative data could also be analyzed in the next steps, and this could provide additional interesting insights.

The manipulation of internal motion speed of a virtual zeitgeber emerges as a promising tool for shaping (virtual) temporal experiences, opening up avenues for both theoretical exploration and practical applications in diverse fields. As we continue to investigate this relationship, the potential for innovative interventions and enhanced virtual experiences becomes increasingly promising.

## 7 Limitations

We did not compare the virtual environment to a real example with a real pendulum or a real clock. The sample size consisted of a high proportion of female participants, and this is important to address as a limitation of this study. Also, the sample consisted of a high proportion of participants who had previous experience with head-mounted displays; any effects found should also be validated with a control sample of inexperienced participants. Qualitative data that could have enriched our findings were not collected.

## 8 Conclusion

In this paper, we show that virtual zeitgebers characterized with irregular internal motion increased perceived passage of time, as well as virtual zeitgebers with faster internal motion. Our experiment revealed that time passed faster when participants observed a virtual clock and orbit pendulum in the fast speed condition than in the slow speed condition. The orbit pendulum significantly accelerated the perceived passage of time compared to the clock. We believe that irregular movement can create the perception that time is moving more quickly by reducing boredom and raising interest and visual attention, which is confirmed by the significantly longer gaze fixations of the participants. The prolonged eye gaze fixation durations support the idea that the use of virtual zeitgebers extends to a deeper level of cognitive engagement. Our study introduces a novel approach to alter how time is perceived in VR. This is achieved by adjusting the internal speed for specific objects, virtual zeitgebers, that are directly (like the clock) or indirectly (like the pendulum) linked to timekeeping. Our study has shown that manipulating the internal speed of motion of virtual objects, such as the predictable motion of a virtual clock and the unpredictable motion of other virtual zeitgebers, is a promising way to achieve this effect. This modulation not only enriches novel VR experiences, but also fills a gap in the existing literature. In the future, these findings will be used to develop novel VR applications for therapeutic purposes, especially for disorders such as depression, autism, and schizophrenia, which are often associated with disturbances in time perception. Therapeutic scenarios could include environments in which the perception of time is deliberately altered - either accelerated or slowed down - by controlled manipulation of virtual zeitgebers to recalibrate the patient's sense of time. Applications in the form of novel VR experiences could target the manipulation of time perception to increase the user's passage of time, reduce boredom, and increase overall user acceptance and exposure duration.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving humans were approved by Ethics Committee of the Institute for Human-Computer-Media, Julius-Maximilians-Universität Würzburg, Würzburg, Germany. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

ML: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. FU: Conceptualization, Methodology, Writing–review and editing. J-LL: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing–review and editing. ML: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

## Publisher's note

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2024.1390703/full#supplementary-material

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