

Anticipating Physical Processes in VR: Environment Type and Scale Alter Temporal Expectations

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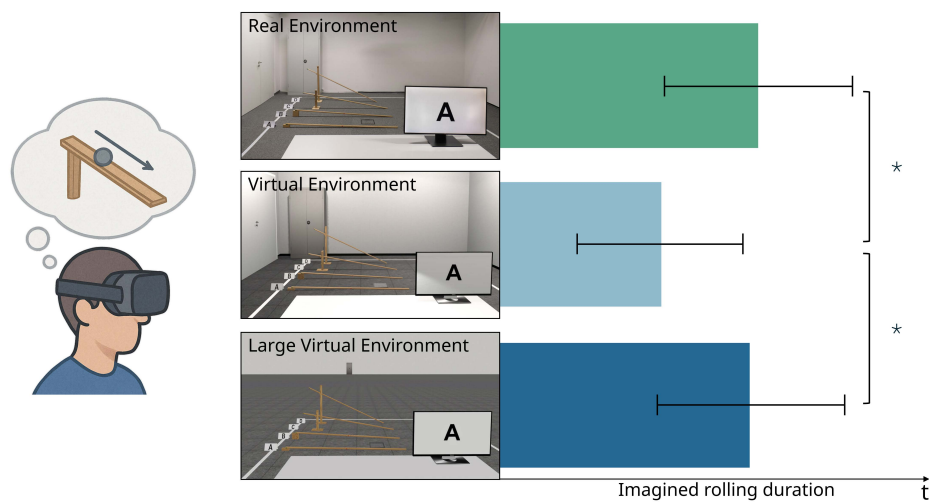


Figure 1: Schematic illustration of the experimental task and the key result: Participants imagined a ball rolling down ramps in different environments, with shorter expected durations in a 1:1 VR lab compared to the physical lab, and longer durations in a large-scale VR room compared to the 1:1 VR lab.

Abstract

Accurate temporal expectations support interaction in virtual reality (VR), yet it remains unclear whether the internal models that guide such expectations in the real world transfer unchanged to immersive VR. We report two experiments examining expected durations of gravity-driven motion across real and virtual environments. In Experiment 1, participants imagined a ball rolling down ramps in a physical lab, a 1:1 VR replica, and an up-scaled VR room and produced the time the imagined process would take. Results revealed systematic distortions: durations were underestimated in VR relative to the physical lab, and larger virtual spaces elicited longer durations. Experiment 2 assessed whether participants incorporated gravity laws into their simulations. Although gravitational

acceleration was consistently underestimated, it was incorporated in both real and virtual environments. Our findings show that VR and its spatial scale bias temporal expectations, with implications for the design of temporally coherent and physically plausible VR experiences.

CCS Concepts

• **Human-centered computing** → **Virtual reality**; **Empirical studies in HCI**.

Keywords

virtual reality, time perception, space-time interaction, spatial scale, mental imagery, gravity, physical processes

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1 Introduction

Immersive virtual reality (VR) presents users with a world that resembles our physical world, with familiar objects, spaces, and physical relationships. A key question for VR research, however, is whether people rely on the same mental models in such environments as they do in the real world. As in the physical world, interaction in VR requires continuous predictions (e.g., how long movements take, when moving objects arrive, and how gravity affects them). Such temporal and physical expectations guide perception, action, and decision-making processes. Understanding whether real-world expectations transfer to virtual environments therefore addresses a fundamental question about perception and action in VR. Exploring the similarities and differences in users' temporal expectations between real and virtual environments, and identifying the factors that shape these expectations, provides foundational insight into how people internally model physical dynamics in VR. This is crucial for designing VR systems whose dynamics are plausible and predictable for users, whether in time-critical interactions, simulation, or physics-based applications.

Although prior work has shown that temporal experience in VR can differ from the physical world in certain contexts, little is known about whether users expect physical processes in VR to unfold in the same way as in the real world, or whether VR produces systematic shifts in the mental models that guide such expectations. A growing body of research suggests that time is not perceived identically in virtual and physical environments. Several studies report a phenomenon known as time compression, a tendency to experience shorter durations in VR compared to the real world [38, 41, 54]. Yet these findings primarily concern abstract time perception, such as the estimation of seconds or minutes, rather than the users' expectations about the duration of dynamic events. Recent work has begun to move in this direction by applying mental imagery tasks in real and virtual environments to examine how users' temporal expectations of physical processes differ between the two settings. Mental imagery paradigms offer a powerful tool to probe such expectations because they reveal users' internal models of how physical events unfold without being confounded by properties of rendered motion in VR, such as visual fidelity, animation quality, physics-engine implementation, or system latency. By asking participants to imagine an event rather than observe it, researchers can directly assess the cognitive expectations that guide predictions about physical dynamics across environments. Bogon et al. [6], for example, successfully used this approach and showed that users' expectations about the duration of an imagined event (water pouring from a bottle) differed between real and virtual environments—even though basic time perception remained unchanged. This suggests that while subjective time perception may remain stable, internal models of physical dynamics can shift across environments and alter temporal expectations. However, the processes studied so far involve relatively simple dynamics and do not fully capture the role of fundamental physical laws such as gravity. To address this gap, in this study we focus on a more straightforward and physically grounded case: gravity-driven motion. Using the scenario of a ball rolling down a ramp, we investigate whether imagining such an event in VR leads to systematic distortions in expected duration compared to imagining the same

event in real environments. Beyond overall duration, we further examined whether participants anticipated gravitational acceleration in their mental simulations, and whether such expectations differed across real and virtual environments.

In addition to the type of environment and the type of physical process, the spatial context of an environment can shape the temporal dynamics of perceived or imagined events. People tend to overestimate durations in larger rooms [20, 31, 40, 50], reflecting a perceptual coupling of space and time [16, 58]. As VR entails a high potential to expand the design space—allowing room size, object scale, and layout to be manipulated without physical constraints—interactions between the spatial scale of virtual environments and VR-induced changes in temporal expectations can provide important information for the design of VR scenarios where users need to interpret object motion, anticipate outcomes, and interact with dynamic scenes. Yet most prior work on how temporal judgments are affected by spatial characteristics of virtual environments has focused on abstract intervals or static contexts [8, 9, 11, 31, 42, 53, 57], leaving it an open question whether spatial transformations in VR also affect how users anticipate the duration of dynamic physical events. In this study, we therefore compare temporal expectations between real and virtual environments, and we include a third condition with an upscaled virtual room to additionally examine whether spatial scaling in VR alters imagined durations of gravity-driven motion and influences participants' anticipation of gravitational acceleration.

Based on these gaps, our work addresses the following research questions:

- **RQ1:** Does the medium of VR per se alter users' expectations about the duration of physical processes—such as gravity-driven motion—compared to a real laboratory environment?
- **RQ2:** Does spatial scaling in VR (i.e., an upscaled virtual room) further bias temporal expectations about the duration of dynamic physical events?
- **RQ3:** Do participants anticipate gravitational acceleration when simulating such motion, and do these expectations differ across real and virtual environments?

We report two experiments that investigated how immersive VR and its spatial scale affect temporal expectations of physical processes. In Experiment 1, participants imagined a ball rolling down ramps of different gradients and reproduced its expected duration across three settings: a real laboratory, a 1:1 virtual replica, and a spatially up-scaled version of the virtual room. Results show that both the shift from real to virtual environments and changes in perceived room size systematically biased imagined durations. In Experiment 2, we assessed whether participants accounted for gravitational acceleration by setting duration estimates for the first and second halves of the same ramp in relation to each other. Although acceleration was quantitatively underestimated, participants consistently incorporated accelerative dynamics in their simulations in both real and virtual environments. Together, our findings demonstrate that imagining gravity-driven motion in VR leads to systematic distortions of expected duration, shaped by both environment type and spatial scale. These insights inform the design of VR systems that rely on accurate temporal predictions of physical dynamics, such as in training, simulation, and interactive applications.

2 Related Work

To examine whether temporal expectations that guide perception and action in the real world transfer to immersive virtual environments, and to identify which factors of VR shape these expectations, we draw on prior work in three areas of research: (1) subjective time perception in VR, (2) expectations about physical processes in VR, and (3) the influence of spatial scale on temporal experience.

2.1 Subjective Time in VR

Research on time perception in VR has shown that immersive environments can systematically alter how users experience the passage of time. One reported phenomenon is *time compression*—the tendency for durations to feel shorter in VR than in the physical world [38, 41]. This effect is often attributed to heightened arousal or attentional engagement [15, 57]. Recent experimental work further supports this view, showing that user engagement and environmental dynamics can significantly modulate perceived duration in VR, with active users tending to underestimate elapsed time [44]. However, these effects may not be uniform. For example, Mullen et al. [42] reported both compression and expansion of perceived time depending on the spatial configuration of the virtual environment. Such results indicate that contextual features—such as environment size—can modulate temporal judgments in VR.

Beyond these contextual factors, several studies have investigated whether VR as a medium inherently alters basic temporal processing. One line of work has examined whether distortions in temporal experience arise from changes in embodiment or multi-sensory integration. For example, manipulating the speed of participants' own movements, or their visual feedback, can shift perceived duration [3]. Other studies suggest that immersive VR may induce dissociative states or disrupt interoceptive processing, both of which are known to affect the experience of time [17, 21]. These findings not only suggest that temporal experience in VR may differ from real-world perception but also raise the possibility that it can be deliberately shaped. Researchers have exploited this in interactive applications, for example by slowing down or speeding up the world in response to user movement [3, 36], or by simulating altered diurnal rhythms [35, 53].

In most of these studies, time perception was investigated in VR using rich and interactive settings, often involving emotional or cognitive load. As a result, it has remained unclear whether VR *per se*—in the absence of such contextual influences—alters the basic sense of elapsed time. Addressing this, Bogon et al. [6] compared subjective time perception in matched real and virtual laboratory environments under low-interaction conditions. Participants reproduced numerical durations (e.g., “eight seconds”) without external stimuli, and the results showed no differences between real and virtual settings, suggesting that the basic sense of elapsed time remains largely intact in immersive VR. However, their work also hinted that this temporal stability might not generalize to all forms of timing in VR, which we explore in the next section.

2.2 Expectations about Physical Processes in VR

Bogon et al. [6] also examined a different type of timing: temporal expectations for familiar physical processes. In a second task, participants were asked to mentally simulate water pouring from

an inverted bottle and to indicate the start and the end of this process. Unlike the abstract interval task, this physical-process task revealed a significant effect of the environment: Participants produced longer durations for this imagined process in VR than in the real world. These findings introduced a critical distinction between *time perception per se* and *temporal expectations about physical processes*. Their findings suggest that while immersive VR does not distort the internal sense of elapsed time, it can affect users' temporal expectations about the duration of physical processes. This dissociation raises important questions for research and design: How do users internally model physical processes in VR compared to real world scenarios? Are expectations about motion, gravity, or causality preserved, or are these concepts reshaped by the context of the virtual environment? Such questions are central for understanding how users internally represent physical dynamics in VR, a foundational question that also informs the design of coherent and predictable virtual environments.

While Bogon et al. [6] provide the only direct comparison between VR and the physical world, several other studies have used VR primarily as a methodological tool to investigate intuitive physics. VR enables controlled manipulations of self-perception, motion cues, and physical laws that are not feasible in real-world settings, making it well suited for studying how people adapt and apply their internal models of physical dynamics. For example, Pouke et al. [47] demonstrated that when users experience a mismatch in the spatial relation between the virtual self and the surrounding environment—such as perceiving themselves as extremely large or small—they often judge physically incorrect object behavior (e.g., unrealistic falling speeds) as more plausible than physically accurate motion. Moreover, immersive VR has been used to study how people represent gravity-driven motion by presenting rolling balls in VR and asking participants to adjust either the slope of the virtual surface or the acceleration of the ball until the motion appeared natural, with judgments broadly consistent with Newtonian mechanics when rich visual context was available [14]. Extending this line of work, rolling and falling balls have been combined with motor-interception tasks and time-to-contact judgments, showing that internal models of gravity robustly shape perceived naturalness, interception accuracy, and temporal predictions—even when motion cues are manipulated or partially occluded [19, 34]. While these studies provide valuable insights into perceptual responses to physically animated stimuli in VR, they share two important limitations: They all rely on visible object motion, and they lack real-world baselines. As a result, it remains open how users form temporal expectations of gravity-driven motion in VR without the confounding influence of direct visual input or physical interaction, and whether these expectations rely on the same internal models that guide perception in the real world.

The study of such internal models is enabled by mental imagery tasks, which have been increasingly applied over the past decades [45, 46, 52]. Although independent from direct sensory input, mental imagery activates similar neuronal networks as direct perception [2, 22, 60], promoting the understanding of mental imagery as a *weak form of perception* [45, 46]. Accordingly, mental imagery tasks have been effectively employed to investigate spatial representations [4, 12], memory processes [26, 52], perceived self-location [30, 37] and intuitive physics [10, 24, 28]. A specific advantage over

the conventional approach of timing directly experienced intervals is that the timing of imagined events offers the intriguing possibility of studying the expected (rather than perceived) duration of an event [6, 25]. This enables to study the users' internal models of how physical processes unfold over time [24]. Especially with respect to VR, this makes mental imagery an ideal method for testing whether the medium alone changes temporal expectations for physical processes, entirely independent of any physically simulated or displayed motion [6].

2.3 Influence of Environmental Scale on Temporal Experience

While VR allows users to engage with dynamic events and simulate physical processes, it also offers unparalleled flexibility in manipulating the spatial context in which these processes unfold. Unlike physical laboratories, virtual environments are not constrained by architectural or material limitations—spaces can be scaled, distorted, or expanded without practical cost. This flexibility raises an important question: Do changes in the spatial scale of an environment affect how users internally model the timing of events?

There is growing evidence for a close relationship between spatial and temporal representations, suggesting that manipulating spatial context can systematically influence temporal judgments. Numerous studies have demonstrated that time intervals tend to be judged as longer in larger environments, indicating a coupling between spatial extent and perceived duration [20, 31, 40, 42, 50]. Although some evidence suggests the opposite under specific conditions [42], the dominant trend supports the idea that larger spatial contexts lead to dilated temporal experience. In a seminal study, DeLong [20] asked participants to imagine performing everyday activities in miniature model environments and to indicate when 30 minutes had passed. The results revealed a compression of perceived time in smaller spaces. This finding was replicated by Mitchell and Davis [40] and aligns with the idea of a shared cortical magnitude system for processing space, time, and quantity [16, 51, 58]. Taken together, these findings suggest that spatial scale can systematically shape temporal judgments, raising the question of whether enlarging or shrinking environments in immersive VR also alters how users anticipate the duration of physical processes in VR.

2.4 Summary

Prior research shows that immersive VR can alter temporal experience, but the mechanisms and boundary conditions remain unclear. Interval timing often appears robust across real and virtual environments [6], yet several studies report distortions such as time compression [41, 54]. These inconsistencies suggest that contextual factors—such as arousal, task demands, or environment size—systematically modulate perceived time [3, 42].

Beyond abstract intervals, VR also appears to influence expectations about physical processes. For example, water pouring was expected to last longer in VR than in the real world [6], and manipulations of body–environment relations can make implausible object motion appear more plausible than accurate physics [47]. At the same time, studies with visible motion suggest that internal models of gravity still support perception and action in VR [14, 19, 34]. Taken together, prior studies have advanced our understanding

of perception and action under altered physics in VR, but they do not resolve whether temporal expectations for simple, well-defined physical processes are altered by the switch from real to virtual environments or remain anchored in real-world principles such as gravitational acceleration.

Finally, spatial scale is known to bias perceived duration, with larger environments eliciting longer judgments [20, 31, 40, 50]. However, prior demonstrations have largely relied on passive viewing of environments or on abstract interval judgments, leaving it open whether such space–time interactions also shape temporal expectations when people imagine dynamic physical processes unfolding within those environments.

The open question, therefore, is to determine whether immersive VR and its spatial scale fundamentally reshape temporal expectations for simple physical events, or whether these expectations remain consistent with real-world principles such as gravitational acceleration.

3 Experiment 1

The first experiment examined how immersive virtual reality affects users' temporal expectations about the duration of dynamic physical processes, and whether these expectations are modulated by the spatial scale of the virtual environment. Specifically, we asked whether a physically plausible event—a ball rolling down a ramp—is expected to take the same amount of time when imagined in a real-world lab, a virtual replica of that lab, or an up-scaled virtual room. Participants mentally imagined the ball's movement down ramps of varying slope and produced the duration of the imagined event. This paradigm enabled us to probe two core questions: First, does the medium of virtual reality per se alter users' expectations about the duration of physical processes—such as gravity-driven motion—compared to a real laboratory environment (RQ1)? And second, does spatial scaling in VR (i.e., an upscaled virtual room) further bias temporal expectations about the duration of dynamic physical events (RQ2)?

3.1 Method

3.1.1 Participants. A total of 42 participants were recruited from our institution and the local community. Participants took part voluntarily or in exchange for course credits. The initial sample size of 42 participants was based on the intention of achieving an effective final sample size of at least 34 participants after potential exclusions. This sample size ensured that, with an alpha level of .05, the study has sufficient statistical power ($> .85$) to detect an effect size of $\eta_p^2 = .15$ (MorePower, version 6.0.4; [13]). Due to difficulties in keeping up concentration (tiredness), the data of one participant were excluded from analysis. The final sample consisted of 41 participants (20 females, 21 males) with a mean age of 29.7 years ($SD = 5.7$, ranging from 21 to 43). In terms of prior experience with virtual reality, 30 participants (73.2%) reported having used VR at least once before. Only one participant (2.4%) indicated frequent use of VR headsets, 28 (68.3%) reported rare use, and the remaining 13 participants (31.7%) had never used VR before. Prior to the experiment, all participants provided informed, written consent.

3.1.2 Apparatus. Participants were presented with four wooden ramps (203 cm length, 4.1 cm width, 1.9 cm height), each allowing a

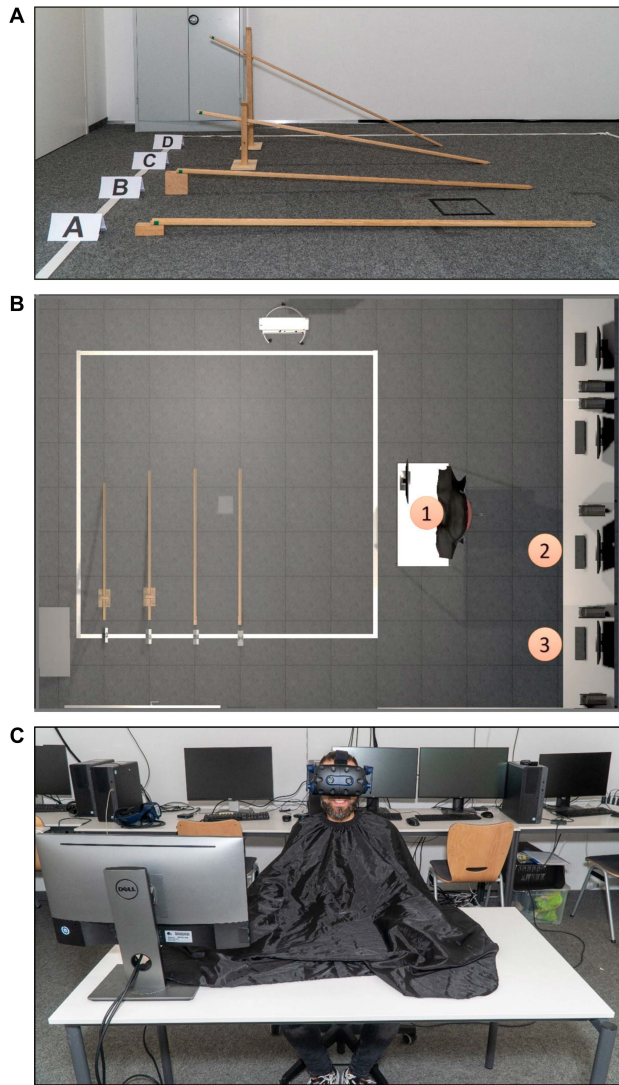


Figure 2: Experimental Setup. A: Photograph of the custom-designed wooden ball tracks used in the experiment. B: Schematic representation of the experimental setup viewed from above with (1) the position of the participant during the time production tasks, (2) the workspace with the questionnaires, and (3) the study conductor's workspace. C: Participant in the experimental setup, wearing a barber cape and VR headset

ball to roll down (see Figure 2A). Ramps were visibly labeled as "A", "B", "C" and "D" and varied in slope (1.4, 3.6, 10.3, and 25.1°), which was adjusted to produce rolling durations of 8, 4, 2 and 1 seconds. As response times The use of supra-second durations precluded effects of response times use of these The effective rolling distance for the experiment was 2 meters. The additional 3 cm in length allowed for the placement of a green marker exactly at the 2 m point, which served as the imagined starting position for the ball (Figure 2A).

Participants sat on a chair, facing the four ramps. For the VR conditions, participants wore a head-mounted display (HMD; HTC Vive Pro 2) with a refresh rate of 120 Hz, a resolution of 4896 x 2448 pixels per eye, and a horizontal field-of-view of 120°. The virtual environments and task presentation were implemented using Unity 3D (version 2019.2.1f1, <https://unity.com/>). Participants wore a black barber cape that concealed their hands and arms. This ensured comparable bodily awareness across conditions. Although arm tracking would have been technically possible, it would have introduced additional visual and proprioceptive cues that differed between real and virtual environments. Covering the arms and hands with the cape therefore provided the cleanest way to keep bodily information consistent across all conditions by preventing participants from seeing their own arm movements and mouse clicks.

3.1.3 Task and Stimuli. Participants were asked to imagine a ball rolling down one of the four ramps, starting at the green marker to the end of the ramp, and to produce the duration of this imagined event. Each trial began with the display of one ramp identifier (A-D). Participants were instructed to press the mouse button once when they imagined the ball starting at the green marker, and a second time when they imagined the ball arriving at the ramp's end. Thus, the produced interval between the two button presses indicates the imagined duration of the event. After the first button press, screen color changed to green until the second press. The intertrial interval was set to 2 s after the second button press.

3.1.4 Environment Conditions. Three environments were tested. In the real environment (RE) condition, participants performed the time production task in the real laboratory environment (see Figure 3A) without wearing the HMD. In the virtual reality conditions, participants completed the task in a normal-sized virtual version of the laboratory (VR_{normal}; see Figure 3B) and in an up-scaled virtual version of the same environment (VR_{large}; see Figure 3C). Virtual environments were presented via the HMD. For the VR_{large} condition, both width and length of the room was expanded by a factor of 9, and height was tripled. The distances between the ramps and the table desk remained constant across the three environments (Figure 3). Importantly, the ball was never shown moving in either environment. Participants only imagined the motion, as our aim was to measure their internal expectations about gravity-driven dynamics in VR without providing any visual or simulated physical cues. As a result, no virtual physics (e.g., gravity, friction, or motion animation) was implemented, and participants were not informed about any physical or spatial parameters of the environments. This ensured that any differences between conditions would reflect participants' spontaneous expectations based on being in the respective environments rather than assumptions about potential changes in the implemented physics.

3.1.5 Questionnaires. After each experimental block, participants answered two questions regarding fatigue and dizziness, each rated on a 7-point Likert scale (ranging from "not at all" to "very strong"). These items were selected from the Simulator Sickness Questionnaire ([33]).

To assess participants' sense of presence in the VR environments, the Igroup Presence Questionnaire (IPQ; [55]) was administered

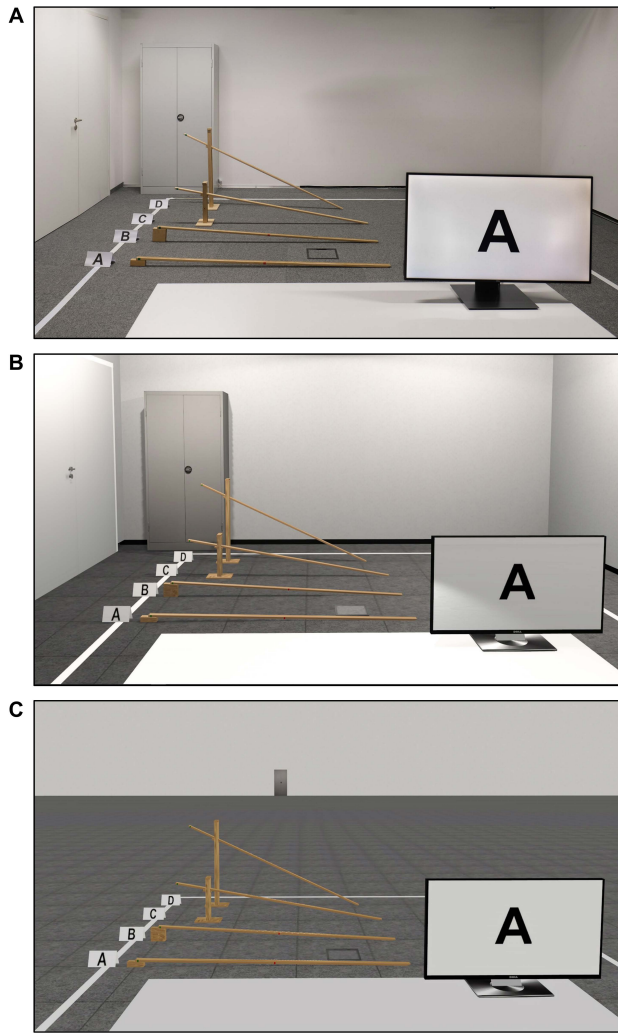


Figure 3: Environment conditions. The task was performed in (A) the real laboratory environment (RE), in (B) a normal-sized virtual version of the laboratory (VR_{normal}), and in (C) an up-scaled virtual version of the laboratory (VR_{large}).

after the last VR_{normal} and VR_{large} block of Experiment 2 (which was conducted directly after Experiment 1, including the same participants, the same technical set-up and the same environment conditions). The IPQ consists of 14 items rated on a 7-point Likert scale and measures three subscales (Spatial Presence, Involvement, and Experienced Realism), as well as an additional single item for general presence. The questionnaire was administered in its German version. We included the IPQ to document participants' general sense of being located in the VR environments, which they could actively explore by head movements. This measure served as a basic check to ensure that presence levels did not differ substantially between VR conditions based on the room size.

3.1.6 Procedure. The experimental procedure is illustrated in Figure 4. Each participant completed the time production task in all

three environment conditions (RE , VR_{normal} , VR_{large}). The order of the three environment conditions was counterbalanced across participants using a balanced Latin square to control for potential order effects.

Each environment condition was tested twice, resulting in six experimental blocks. Each block consisted of 20 trials, with five trials for each of the four standard intervals (1, 2, 4, and 8 s). The presentation order of the ramp identifiers (A, B, C, D) was randomized within each block. In total, participants performed 120 trials across the six blocks.

Before the main experiment, participants completed an interaction phase and a practice block in the RE condition. During the interaction phase, participants were instructed to observe each of the four ball tracks and to roll a glass ball down each ramp once, starting at the green marker. At this stage, participants were not informed about the upcoming time production task to minimize the risk of inducing internal counting strategies. Following the interaction phase, participants were seated at the central position in front of the ramps (see Figure 2). The black barber cape was adjusted to conceal their hands and arms. Participants then performed the practice block, consisting of one duration production trial for each ramp in randomized order, to ensure task comprehension and verify system functionality.

After the practice block, participants completed a demographic questionnaire. For the VR conditions, the HMD was positioned and calibrated before each block.

Each experimental block began with the display of a randomly selected ramp identifier (A–D) on the monitor. Participants performed the time production task as described above. After completing a block, participants were shown a cross to indicate the end of the block and were then asked to complete the questionnaire. In the VR conditions, the HMD was removed after each block to allow participants to complete the questionnaire.

The entire experimental session (consisting of Experiment 1 and Experiment 2) lasted approximately 60 minutes.

This study was conducted in accordance with the ethics and privacy regulations of our institution and, thus, following the policies of our country and funding body. Throughout the user study, participants did not face any immediate risks or dangers. The study did not involve vulnerable groups, and no intense emotions or physical stress were induced. All participants were informed about the study's purpose and explicitly informed that they can withdraw from the voluntary participation at any time. The data of all participants were anonymized in all data sets. All authors were dedicated to the highest ethical standard and adhered to the institution's code of conduct.

3.1.7 Statistical Analyses and Design. All analysis scripts and associated raw data are available via the Open Science Framework (OSF, project link: <https://osf.io/qd5py/>).

Produced intervals were standardized by calculating ratio scores between produced intervals and standard intervals. Ratios greater than 1 indicate an overestimation of the actual interval, whereas ratios below 1 indicate an underestimation. A ratio of 1 would indicate accurate reproduction of the standard interval. Before applying statistical tests, we inspected the distribution of the ratio scores to

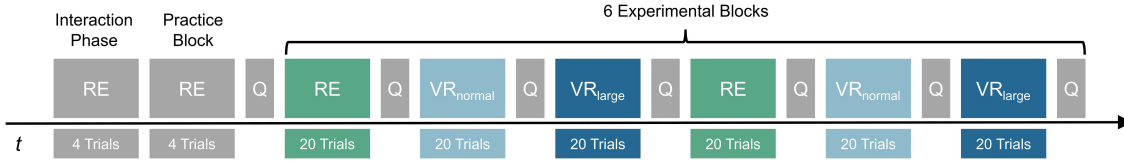


Figure 4: Schematic overview of the experimental procedure of Experiment 1. Each participant completed the time production task in all three environment conditions (RE, VR_{normal}, VR_{large}). Participants completed a questionnaire (Q) after each condition. Before the experimental blocks, participants completed an interaction phase and a practice block in the RE condition. During the interaction phase, participants observed a glass ball physically rolling down each ramp, without being informed about the following time production task.

assess normality. Since the distribution of the ratio scores was positively skewed, we log-transformed the ratio scores to normalize the distribution before statistical testing. We refer to the transformed variable as $\text{ratio}_{\log}$. To obtain corresponding interpretable non-standardized effect sizes, we additionally report mean ratio values that are derived by back-transforming the mean $\text{ratio}_{\log}$ values ($\text{ratio} = e^{\text{ratio}_{\log}}$). No extreme outliers were identified, defined as $\text{ratio}_{\log}$ scores exceeding three times the standard deviation of the respective individual cell means. Full preprocessing and diagnostic checks are available in the OSF repository.

Data were analyzed in R (version 4.5.0; [48]) using repeated-measures ANOVAs and t -tests. For preprocessing, we used the *tidyverse* package bundle (version 2.0.0; [59]), and for statistical analyses the package *rstatix* (version 0.7.2; [32]). Effects with violations of sphericity were Greenhouse–Geisser corrected and are reported with corresponding ϵ estimates.

To analyze the effect of environment conditions on time perception, we conducted a 3×4 repeated measures ANOVA including the within-subjects factors *environment* (RE, VR_{normal}, VR_{large}) and *standard interval* (1, 2, 4, and 8 s).

3.2 Results

All analysis scripts and associated raw data are available via the Open Science Framework (OSF, project link: <https://osf.io/qd5py/>).

3.2.1 Timing Performance. Back-transformed mean $\text{ratio}_{\log}$ scores as a function of environment and standard interval are illustrated in Figure 5A. The results of the 3×4 within-subjects ANOVA on the $\text{ratio}_{\log}$ scores revealed significant main effects of *environment*, $F(2, 80) = 4.42$, $p = .015$, $\eta_p^2 = .10$, and *interval*, $F(1.29, 51.43) = 310.07$, $p < .001$, $\eta_p^2 = .89$, $\epsilon = .429$. The interaction between environment and interval was not significant, $F(4.40, 176.13) = 0.81$, $p = .533$, $\eta_p^2 = .02$, $\epsilon = .734$.

To further explore the main effect of environment, we conducted pairwise t -tests on the $\text{ratio}_{\log}$ scores averaged across intervals (see Figure 5B). Reported p values were corrected for multiple comparisons using false discovery rate (FDR) estimation [5]. Ratio scores were significantly higher in the RE condition compared to VR_{normal}, $t(40) = 2.32$, $p = .039$, $d = .36$, 95% CI [0.10, 0.62]. Similarly, scores were significantly higher in VR_{large} compared to VR_{normal}, $t(40) =$

2.77 , $p = .026$, $d = .43$, 95% CI [0.17, 0.68]. No significant difference was found between RE and VR_{large}, $t(40) = 0.19$, $p = .848$, $d = .03$, 95% CI [-0.28, 0.34].

3.2.2 Questionnaire Data. As a control, we assessed simulator sickness by analyzing fatigue (Q1) and dizziness (Q2) ratings in one-way repeated-measures ANOVAs. Although mean values were generally low across all conditions, both analyses revealed significant main effects of *environment* (Q1: $F(2, 80) = 26.53$, $p < .001$, $\eta_p^2 = .40$; Q2: $F(2, 80) = 22.17$, $p < .001$, $\eta_p^2 = .36$). For Q1, fatigue ratings were lowest in RE ($M = 1.14$), higher in VR_{normal} ($M = 1.97$), and highest in VR_{large} ($M = 2.07$). Post-hoc paired t -tests with FDR adjustment confirmed higher fatigue in both VR conditions compared to RE ($p_{FDR} < .001$), while VR_{normal} and VR_{large} did not differ ($p_{FDR} = .33$). For Q2, dizziness ratings followed the same pattern (RE: $M = 0.33$; VR_{normal}: $M = 0.99$; VR_{large}: $M = 1.04$). Both VR conditions differed significantly from RE ($p_{FDR} < .001$), whereas VR_{normal} and VR_{large} did not differ ($p_{FDR} = .52$).

The IPQ results revealed significant differences for two subscales. Spatial presence was higher in VR_{large} ($M = 3.74$) compared to VR_{normal} ($M = 3.41$), $t(40) = 2.48$, $p = .017$, $d = .39$. For experienced realism, scores were higher in VR_{normal} ($M = 2.41$) than in VR_{large} ($M = 2.07$), $t(40) = 2.05$, $p = .047$, $d = .32$. Other subscales did not differ significantly between conditions (all $p > .079$).

3.3 Discussion

The data of Experiment 1 reveal that the imagined duration of a ball rolling down a ramp was generally overproduced across all environments (Figure 5B). Importantly, the duration of the same gravity-driven process was imagined to last shorter within a virtual model of the environment (VR_{normal} condition in Figure 5B), compared to the real laboratory (RE condition in Figure 5B). Addressing RQ1, these results demonstrate that the medium of VR alters users' expectations about the duration of gravity-driven motion: Such events are imagined to last shorter in VR than in the real environment.

Addressing RQ2, a direct comparison between the two virtual environments (differing only in room size) reveals that spatial scale influenced the expected duration of the same gravity-driven process. In the large virtual room, the imagined duration of the ball rolling

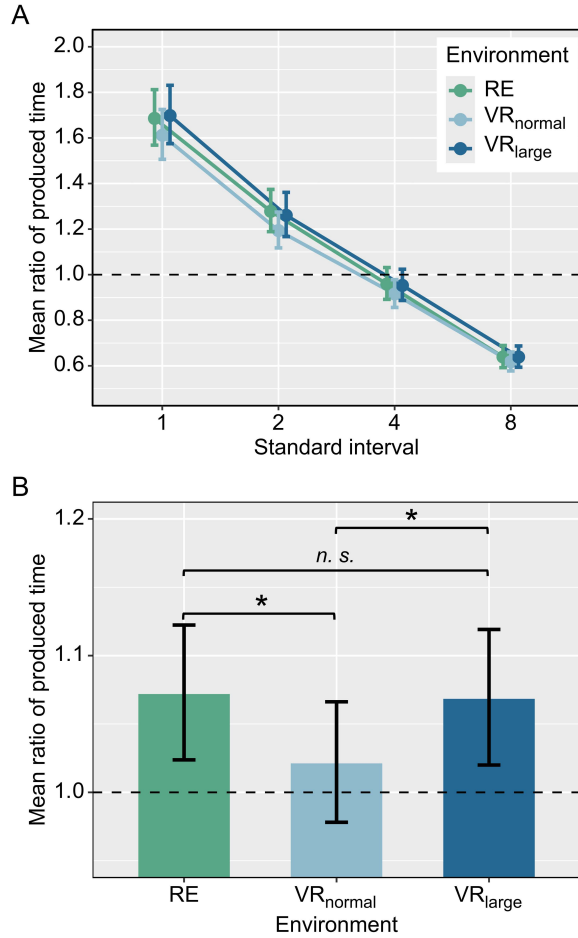


Figure 5: Results of Experiment 1. Mean ratios between produced time and standard durations. Values above 1 indicate overestimation (longer imagined duration of the ball rolling down the ramp), and values below 1 indicate underestimation. Error bars represent standard errors of the mean. (A) Ratios by environment and standard interval. (B) Ratios averaged across intervals by environment. (Significance: * indicates $p < .05$; n.s. indicates $p \geq .05$)

down the ramp was longer than in the normal-sized virtual room (VR_{large} vs. VR_{normal} condition in Figure 5B).

4 Experiment 2

Experiment 1 demonstrated that temporal expectations regarding physical processes varied depending on the type of environment (real vs. VR) and on the spatial size of the virtual rooms. However, it did not provide information as to whether and to what extent participants incorporated gravitational acceleration into their mental simulation of the physical process, or whether they instead imagined a constant (physically incorrect) speed of motion. To address RQ3, we designed Experiment 2 to test this by dividing the ramps into two equidistant sections (i.e., each 1 m in length) and asking

participants to indicate the imagined time for the first and second halves separately.

The duration of a ball rolling down a ramp can be calculated with the formula $t = \sqrt{\frac{2L}{a_{eff}}}$ where L is the ramp's length and a_{eff} is the effective acceleration. Hence, the exact durations the ball needs for the first and for the second half depend on a_{eff} , a parameter unknown to the participants, as it in turn depends on the ramp's slope and the friction caused by the material. Calculating the ratio between the produced duration for the first and the second half circumvents this issue, because a_{eff} falls out of the equation:

$$\frac{t(first)}{t(second)} = \frac{t(first)}{t(all) - t(first)} = \frac{\sqrt{\frac{L}{a_{eff}}}}{\sqrt{\frac{2L}{a_{eff}}} - \sqrt{\frac{L}{a_{eff}}}} = 2.4$$

Therefore, irrespective of the actual value of a_{eff} (i.e., irrespective of ramp slope and friction), the ratio between the produced durations for first and second halves should always equal 2.4, if the acceleration is taken into account in a physically correct manner.

4.1 Method

The same participants who completed Experiment 1 also took part in Experiment 2. Both experiments were conducted within the same testing session and used the same environment conditions (RE, VR_{normal}, VR_{large}). While participants completed the final questionnaire of Experiment 1, the experimenter prepared Experiment 2, so the transition introduced no meaningful break in the session.

4.1.1 Apparatus and Procedure. The apparatus and technical setup were identical to Experiment 1, except that only the two longest ramps (4 s and 8 s) were used, each marked at its midpoint with a red indicator.

In each trial, participants imagined a ball rolling down one of the two ramps and produced the durations of the first and the second half of the motion separately. This was done by three mouse presses: The first to indicate the start of the motion, the second when the ball was imagined to reach the midpoint, and the third when it was imagined to reach the end of the ramp. Each trial thus yielded two consecutive duration productions. Participants completed one block per environment condition (RE, VR_{normal}, VR_{large}), resulting in three experimental blocks of 20 trials (10 per ramp; randomized), totaling 60 trials per participant. The order of environment conditions was counterbalanced via a Latin square and kept constant for each participant across Experiments 1 and 2.

4.1.2 Statistical Analyses and Design. All analysis scripts and associated raw data are available via the Open Science Framework (OSF, project link: <https://osf.io/qd5py/>).

Data were analyzed in R (version 4.5.0; [48]) using repeated-measures ANOVAs and t -tests. For preprocessing, we used the *tidyverse* package bundle (version 2.0.0; [59]), and for statistical analyses the package *rstatix* (version 0.7.2; [32]).

To quantify the extent to which participants correctly accounted for physical laws about gravity in their mental simulation of physical processes, we calculated an "acceleration index (AI)" for each trial by dividing the produced duration for the first half of the ramp by the produced duration for the second half. According to physical

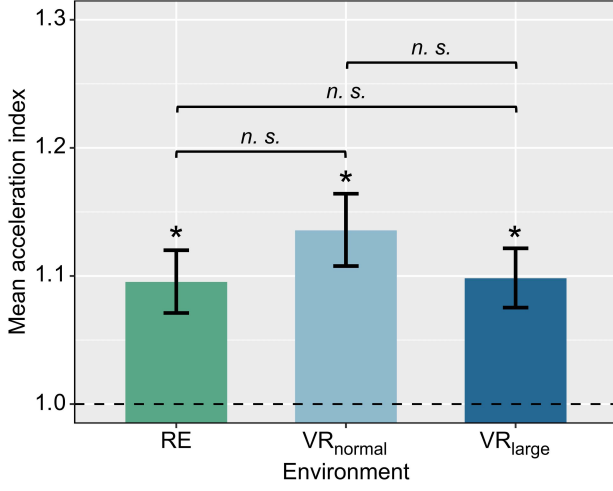


Figure 6: Results of Experiment 2. Mean acceleration indices (AI), defined as the ratio between produced durations for the first and second halves of the ramp. AI values greater than 1 indicate that the first half was judged to take longer—consistent with directionally correct mental simulation of gravitational acceleration. Across all conditions, AI values were significantly greater than 1 (FDR-corrected one-sample t -tests against 1), indicating consistent directional alignment with gravitational acceleration. These significant results are indicated in the plot using asterisks placed above the corresponding bars. However, AI values remained substantially below the value corresponding to physically correct acceleration (2.4). No significant differences between environment conditions were observed (all FDR-corrected pairwise comparisons were non-significant). Error bars represent standard errors of the means. (Significance: * indicates $p < .05$; n.s. indicates $p \geq .05$)

laws of motion on inclined planes, a rolling object accelerates as it moves downward. Therefore, the first half of the ramp should take longer than the second half, resulting in acceleration indices above 1. The physically accurate acceleration index would be 2.4. Since the distribution of acceleration indices was positively skewed, it was log-transformed before statistical testing. To obtain corresponding interpretable non-standardized effect sizes, we additionally report mean acceleration indices that are derived by back-transforming the mean AI_{log} values ($AI = e^{AI_{log}}$). No extreme outliers were identified, defined as AI_{log} scores exceeding three times the standard deviation of the respective individual cell means. To analyze the effect of environment conditions on AI_{log} , we conducted a 3×2 repeated measures ANOVA with the within-subject factors environment (RE, VR_{normal}, VR_{large}) and standard interval (4 s, 8 s).

4.2 Results

All analysis scripts and associated raw data are available via the Open Science Framework (OSF, project link: <https://osf.io/qd5py/>).

Acceleration indices as a function of environment are illustrated in Figure 6. The results of the 3×2 within-subjects ANOVA on the

AI_{log} scores revealed no significant main effect of environment, $F(2, 80) = 2.70$, $p = .073$, $\eta_p^2 = .06$, or interval, $F(1, 40) = 0.09$, $p = .765$, $\eta_p^2 < .01$. The interaction between environment and interval was also not significant, $F(2, 80) = 2.60$, $p = .080$, $\eta_p^2 = .06$.

For all three environment conditions, the acceleration index was significantly lower than the physically correct value of 2.4 ($AI_{log} = \log(2.4) \approx 0.875$), indicating that participants did not fully simulate gravitational acceleration (RE: $t(40) = -25.79$, $p < .001$; VR_{normal}: $t(40) = -22.07$, $p < .001$; VR_{large}: $t(40) = -27.51$, $p < .001$). At the same time, the acceleration index was significantly above a value of one ($AI_{log} = 0$). One-sample t -tests against 1 revealed significant deviations in all three environments (RE: $t(40) = 2.99$, $p_{FDR} = .005$; VR_{normal}: $t(40) = 3.75$, $p_{FDR} = .002$; VR_{large}: $t(40) = 3.30$, $p_{FDR} = .003$), indicating that the duration of the second half was imagined as being shorter than the duration of the first half, which is consistent with directionally correct mental simulation. Reported p -values were adjusted using the FDR procedure [5] to account for multiple comparisons.

4.3 Discussion

The results of Experiment 2 demonstrate that participants incorporated accelerative dynamics into their mental simulations, but in a substantially underestimated form. Although the degree of imagined acceleration was far below the physically correct value, participants nevertheless imagined the ball covering the second half of the ramp in a shorter interval than the first (indicating that they assumed an accelerative pattern) in all environments. The underestimation of physical acceleration was not modulated by the type of environment and therefore seems to reflect a general underestimation of gravitational acceleration in imagined physical processes, rather than an effect of immersive VR (see also [10]).

5 General Discussion

In the present study, we examined how immersive VR and its spatial scale affect the internal models that guide temporal expectations for simple physical processes. To address this question, we compared the durations of an imagined gravity-driven process in real and virtual environments. Participants imagined a ball rolling down ramps of varying slopes and produced the duration of these mental simulations. Our findings address three research questions: (RQ1) whether immersive VR alters temporal expectations compared to a real environment, (RQ2) whether the spatial scale of virtual environments biases these expectations, and (RQ3) whether mental simulations of physical processes in VR adhere to gravitational acceleration. We discuss each of these aspects in the following sections, followed by implications, limitations and directions for future research.

5.1 Effects of Immersive VR

Addressing RQ1, our results show that immersive VR alters temporal expectations of gravity-driven motion compared to a real environment. Participants imagined the same physical process – a ball rolling down a ramp – to take less time in VR than in the physical lab. Because participants never observed the ball rolling in VR, the observed differences reflect internal expectations rather than responses to simulated physics in VR.

This finding aligns with prior evidence that immersive VR can distort perceived durations, but it also refines the interpretation of such effects. Earlier work often attributed time compression in VR to general changes in time perception [15, 41, 54]. More recent studies, however, suggest that distortions may instead arise from contextual factors, such as emotional content [57] or altered expectations about physical processes [6, 49]. Our results support this latter view: Rather than reflecting a fundamental change in time perception, the differences we observed seem to be driven by how participants internally simulate physical dynamics in VR.

A particularly relevant point of comparison is the study by Bogon et al. [6], which likewise contrasted temporal expectations for a physical process between real and virtual environments. Beyond providing a direct methodological parallel, this comparison also offers clues as to why VR alters temporal expectations in the first place. Despite the use of different physical processes (“ball rolling down a ramp” in the present study vs. “water running out of a bottle” in Bogon et al. [6]), produced durations in the RE condition exhibit considerable overlap between studies (as revealed by a comparison between Figure 4 here and Figure 3 in Bogon et al. [6]). The duration of processes corresponding to an actual duration of 1 and 2 seconds were over-produced, 4-second processes were approximately accurately produced, and 8-second processes were under-produced. However, despite comparable duration judgments in the RE condition, the effect of immersive VR was reversed across studies. In [6], water flowing out of a bottle was expected to take longer in VR than in RE, whereas in the present study, a ball rolling down a ramp was expected to require less time in VR than in RE. One possible explanation for this divergence could lie in the nature of the underlying physical processes and how they are mentally simulated under different sensory conditions. Estimating the duration of imagined water flowing out of a bottle [6] may depend on internal assumptions about viscosity and flow rate. In contrast, estimating the duration of an imagined ball rolling down a ramp, as in the present study, may rely on assumptions about surface friction and resistance. Although these ideas remain speculative, they suggest the possibility of material-specific biases in how users extrapolate physical behavior from virtual cues. For instance, fluids in VR often lack convincing dynamic detail and could therefore be mentally represented as more viscous, leading participants to implicitly imagine “virtual” water as thicker and flowing more slowly. Conversely, rigid bodies such as ramps and balls are typically rendered with higher visual clarity and may appear more idealized, potentially encouraging mentally simplified representations in which friction is underestimated. Clarifying whether such process- or material-specific biases indeed contribute to the direction of VR-induced differences in temporal expectations of physical processes will require targeted empirical studies.

Overall, our findings suggest that the medium of immersive VR can shift the mental models that guide users’ predictions about physical processes. The mental models used to simulate and anticipate physical processes in the real world do not fully transfer to immersive VR. This highlights that VR can subtly reshape such models even when no visual motion or physical process is shown, which is highly relevant for understanding perception and action in VR.

5.2 Effects of Spatial Room Size

Addressing RQ2, our results show that temporal expectations are systematically influenced by the spatial scale of the surrounding environment. In our study, the same process (a ball rolling down a ramp) was imagined as taking longer in a large-scale virtual room than in a smaller one. This finding extends previous work that has shown that when entire rooms of different sizes are presented for a fixed duration, larger rooms tend to be judged as lasting longer than smaller ones [20, 31, 40, 50], by demonstrating that temporal expectations for physical processes in VR are likewise modulated by spatial scale. Thus, the changes in temporal judgments, induced by the spatial size of the room, are not restricted to the perceived duration of being in a scene, but also affect the expected duration of physical processes occurring *within* it.

5.3 Internal Models of Acceleration in Real and Virtual Environments

Addressing RQ3, the analysis of the acceleration index (ratio between the produced durations for the first and second halves of each ramp) revealed that although this index was below the physically correct value of 2.4, it was consistently greater than 1 across all environments. This pattern indicates that participants incorporated acceleration into their mental simulations in both real and virtual environments, demonstrating that gravity-like expectations persist even when the event is imagined in immersive VR.

The general underestimation of gravitational acceleration is in line with previous findings [10, 24], which likewise reported that acceleration is often underestimated or not fully incorporated in mental imagery (but see [28]). Crucially, however, all conditions in our study showed the characteristic signature of accelerative dynamics: The duration of the mentally simulated ball rolling down the first half of the ramp was consistently produced as longer than the duration for the second half. This provides clear evidence that participants’ mental simulations did not treat the motion as constant-velocity but instead reflected an internal model that includes accelerative forces, and that this accelerative pattern was preserved when the event was imagined in VR.

5.4 Implications

Our findings have foundational implications for understanding how users form expectations about physical dynamics in immersive VR. They show that the mental models guiding the anticipation of physical processes in the real world do not simply carry over into virtual environments. Instead, basic temporal expectations, such as how long a gravity-driven event should take, can shift as a function of the medium and the spatial properties of the virtual environment. This indicates that designers of VR environments and applications cannot assume that users apply real-world physical expectations in VR in a straightforward way when aiming to create coherent and predictable virtual environments.

Building on these foundational insights, one area in which such expectations become particularly relevant is the use of VR for training and skill transfer. VR is already employed in domains such as sports, manufacturing, medical coordination, and surgical training, and its use in these contexts is likely to increase in the future [29, 43].

Many of these scenarios require users to accurately anticipate physically determined temporal dynamics such as trajectories, gravity, or acceleration. Our results indicate, however, that the temporal expectations users bring from the real world do not always transfer identically to immersive VR and that spatial scale can further modulate these expectations. While the observed differences are subtle, they highlight that VR may shape how users internally represent the timing of simple physical events, which may impair the accuracy of perception and action coordination in VR contexts involving physically moving objects. Our study therefore suggests that it may be valuable to examine under which conditions VR-trained timing aligns with real-world expectations and when design strategies – such as instructional cues or calibration of motion dynamics – could support effective transfer.

A related implication concerns potential mismatches between users' expected durations of physical processes in VR and the durations of implemented physical processes in VR, which may negatively affect user experience. Our study shows that a gravity-driven physical process is anticipated as faster in VR, whereas other work has demonstrated that other physical processes are expected to be slower in VR than in the real world (e.g., water flow [6]). These differences indicate that temporal expectations in VR do not always align with those shaped by real-world dynamics. In situations where users must rely on accurate timing to coordinate perception and action, such mismatches may influence how coherent or comfortable an interaction feels. For example, if a process unfolds more slowly than anticipated, delays and waiting times can arise that are known to negatively affect user experience and behavior [7, 39]. Conversely, if a process is completed more quickly than expected, users may experience discomfort because their temporal preparation is misaligned, as predictive mechanisms linking perception and action [23] fail to match the actual course of events. These considerations imply that designers may benefit from considering how the timing of physics-based events relates to user's expectations when physically grounded interactions are intended. Our findings, however, point to the possibility that strict physical "authenticity" may not always be the right choice for achieving that goal, as users' mental models of physics in VR can deviate from real-world physical laws.

A further implication concerns the role of spatial scale in VR. Our results show that enlarging the virtual room systematically increased the expected duration of a physical process, demonstrating that spatial scale directly biases temporal judgments. This finding highlights that room size in VR is not a neutral design parameter but shapes how users anticipate dynamic events unfolding within it. Designers should therefore consider that manipulations of spatial scale—whether deliberate or incidental—may alter the timing expectations of users and, in turn, influence the plausibility and usability of VR applications.

5.5 Limitations and Future Work

Because our paradigm relies on mental imagery, it naturally exhibits substantial inter-subject variability [18, 46]. Unlike conventional timing tasks in which the to-be-judged event is directly perceived, imagery-based duration productions can reflect individual

differences in prior experience and knowledge. Since this variability primarily affects between-subject comparisons, we focused on within-subject comparisons throughout the study, computed each mean ratio from several productions per condition and carefully determined a sample size capable of detecting the effects targeted in our within-subject design of Experiment 1 despite this variability. Nevertheless, in Experiment 2, the comparatively small acceleration differences and the reduced number of ratio values contributing to each mean, together with the general inter-subject variability of the paradigm, may have contributed to the absence of significant differences between the environment conditions. While this constitutes a limitation of the present study, it also motivates future work to examine acceleration-related expectations with increased statistical power by extending sample size and trial numbers. Importantly, the same characteristic that introduces variability – that mental imagery is shaped by individually different prior assumptions rather than by perceptual input [46] – renders this method an attractive tool for revealing information with respect to naive expectations about the duration of physical processes in VR. This issue cannot be addressed with conventional duration judgment tasks in which duration judgments are anchored to a physical reference.

We also note that the experimental design of the present study does not constitute a full 2×2 factorial design. The inclusion of a large-scale real environment would have resulted in such a design and could have further strengthened the interpretability of medium- and scale-related effects. However, implementing such a condition would also introduce additional factors known to influence temporal judgments, such as differences in room appearance [1] and changes in bodily arousal of participants due to the physical effort and time required to move between experimental rooms [56]. More importantly, our research questions focus on how temporal expectations transfer from the real world to VR, and how VR-specific spatial scaling shapes these expectations. A large-scale physical room would therefore address a related, but conceptually distinct question. While our design focused on VR-related effects and minimized potential confounding factors, a replication of our basic results in a study including a large-scale real-environment condition could nevertheless help consolidate our findings.

A further consideration arises from the divergence between our findings and those of Bogon et al. [6], who reported that water flow was expected to last longer in VR than in the real world, whereas we observed shorter expected durations for a rolling ball. Although this divergence cannot be resolved on the basis of the present results, one could speculate that it may relate to how users mentally represent the properties of VR-simulated materials (as elaborated in Section 5.1). Future research could test this speculative interpretation more directly by parametrically manipulating visual cues related to viscosity and friction in VR and measuring their effects on time perception. In addition, individual differences in physical intuition or prior VR experience may moderate these effects. In the present study we did not differentiate between participants with different levels of familiarity with VR. However, it seems plausible that users' mental models of physics in VR are influenced by the extent and quality of their prior VR experience, which in turn may shape expectations about the fluency and timing of physical processes in virtual environments. Future studies should therefore examine

how different levels of VR experience shape temporal expectations of physical processes in VR.

Another critical point concerns the perceived length of the ramps, which may have been influenced by the size of the surrounding virtual environments. Larger spaces can bias judgments of object dimensions. For example, wider rooms have been shown to affect perceived distances of embedded objects [27]. If a similar effect occurred here, ramps might have appeared shorter in the large virtual room. However, our data speak against this interpretation: Produced durations were even longer in the large virtual room compared to the small one. If the ramps had indeed appeared shorter, the imagined ball should have reached the end earlier rather than later.

The present study focused on the mental imagery of physical processes and the associated temporal expectations. A central open question for future research is how these expectations differ between the physical and the virtual worlds when physical processes are directly implemented in VR rather than only imagined. Deviations from such expectations may simply be accepted, with user models adjusting accordingly, but they may also reduce the experienced plausibility of VR. Prior work suggests that, with rich visual cues, users can perceive both physically accurate and implausible object dynamics as natural in VR [14, 34, 47]. However, systematic comparisons between real and virtual settings are still lacking. Building on our findings, future work should therefore investigate how environment type shapes the perception of physical processes. This could include manipulating gravity in VR and using augmented reality as an intermediate setting for systematic alterations within a real-world context. Such studies would help to identify situations in which internal temporal expectations mismatch actual physical processes and assess their impact on presence, usability, and task performance. These insights will inform design strategies for creating virtual environments that feel coherent and support effective interaction, even when strict physical accuracy is not maintained.

6 Conclusion

In this work, we examined how immersive VR shapes users' temporal expectations of gravity-driven motion. Across two experiments, participants imagined a ball rolling down ramps under different environmental conditions, including a physical lab, a 1:1 VR replica, and an up-scaled VR room. We found systematic distortions: Participants imagined shorter durations in VR than in the physical lab and larger virtual spaces led to longer expected durations compared to smaller virtual spaces. Moreover, although gravitational acceleration was underestimated, participants nevertheless relied on a simplified, gravity-like internal model of acceleration in both real and virtual environments. These findings demonstrate that temporal expectations for simple physical processes are not stable across real and virtual settings but are biased by both the medium and the spatial scale of VR. Taken together, our results show that the expectations that guide perception and action in the real world do not fully transfer to immersive VR. Instead, users rely on internal models whose qualitative structure – such as assuming acceleration – is preserved, while their quantitative expression shifts with properties of the virtual environment. These findings provide

foundational insight into how people internally model physical dynamics in VR, even when no motion is seen, and thus help explain why temporal predictions in VR can diverge from their real-world counterparts. These insights have broader implications for understanding perception and interaction in immersive VR. Designers and researchers working with physics-based VR experiences may benefit from considering how such context-sensitive expectations shape users' interpretations of dynamic events, without assuming that real-world timing intuitions apply unchanged in VR. Future work should therefore examine how these expectations unfold during active interaction with implemented VR physics, how prior VR experience shapes the underlying internal models, and how VR systems might be designed to support coherent and predictable experiences.

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References

- [1] Vanessa Aeschbach, Sonja Ehret, Joanna Post, Miriam Ruess, and Roland Thomaschke. 2022. The effect of waiting environment and perceived atmosphere on temporal experience. *Advances in Cognitive Psychology* 18, 2 (June 2022), 132–143. doi:10.5709/acp-0351-3
- [2] Anke M. Albers, Peter Kok, Ivan Toni, H. Chris Dijkerman, and Floris P. de Lange. 2013. Shared representations for working memory and mental imagery in early visual cortex. *Current Biology* 23, 15 (Aug. 2013), 1427–1431. doi:10.1016/j.cub.2013.05.065
- [3] Ambika Bansal, Séamas Weech, and Michael Barnett-Cowan. 2019. Movement-Contingent Time Flow in Virtual Reality Causes Temporal Recalibration. *Sci Rep* 9, 1 (March 2019), 4378. doi:10.1038/s41598-019-40870-6
- [4] Jacob L.S. Bellmund, Lorena Deuker, Tobias Navarro Schroeder, and Christian F. Doeller. 2016. Grid-cell representations in mental simulation. *eLife* 5 (Aug. 2016), e17089. doi:10.7554/eLife.17089
- [5] Yoav Benjamini and Yosef Hochberg. 1995. Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society Series B: Statistical Methodology* 57, 1 (Jan. 1995), 289–300. doi:10.1111/j.2517-6161.1995.tb02031.x
- [6] Johanna Bogon, Julian Högerl, Martin Kocur, Christian Wolff, Niels Henze, and Martin Riemer. 2024. Validating Virtual Reality for Time Perception Research: Virtual Reality Changes Expectations about the Duration of Physical Processes, but Not the Sense of Time. *Behavior Research Methods* 56, 5 (2024), 4553–4562. doi:10.3758/s13428-023-02201-6
- [7] Johanna Bogon, Sabrina Hößl, Christian Wolff, Niels Henze, and David Halbhuber. 2025. Cognitive Integration of Delays: Anticipated System Delays Slow Down User Actions. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, 2025-04-26). ACM, 1–14. doi:10.1145/3706598.3713475
- [8] Johanna Bogon, Cindy Jagorska, Ella Maria Heinz, and Martin Riemer. 2025. Presentation Time Shapes Perceived Room Size in Visual and Auditory Modalities. *Cognitive Research: Principles and Implications* 10, 1 (June 2025). doi:10.1186/s41235-025-00644-3
- [9] Johanna Bogon, Cindy Jagorska, Isa Steinecker, and Martin Riemer. 2024. Age-related changes in time perception: Effects of immersive virtual reality and spatial location of stimuli. *Acta Psychologica* 249 (Sept. 2024), 104460. doi:10.1016/j.actpsy.2024.104460
- [10] Daniel Bratzke and Rolf Ulrich. 2021. Mental Imagery of Free Fall: Does a Falling Apple Accelerate in Our Minds? *Timing & Time Perception* 9, 2 (Jan. 2021), 150–160. doi:10.1163/22134468-bja10022
- [11] Gerd Bruder and Frank Steinicke. 2014. Time perception during walking in virtual environments. In *2014 IEEE Virtual Reality (VR)*. IEEE, Minneapolis, MN, USA, 67–68. doi:10.1109/VR.2014.6802054
- [12] Patrick Byrne, Suzanna Becker, and Neil Burgess. 2007. Remembering the past and imagining the future: A neural model of spatial memory and imagery. *Psychological Review* 114, 2 (April 2007), 340–375. doi:10.1037/0033-295X.114.2.340
- [13] Jamie I. D. Campbell and Valerie A. Thompson. 2012. MorePower 6.0 for ANOVA with relational confidence intervals and Bayesian analysis. *Behav Res Methods*

- 44, 4 (2012), 1255–65. doi:10.3758/s13428-012-0186-0
- [14] Francesca Ceccarelli, Barbara La Scaleia, Marta Russo, Benedetta Cesqui, Silvio Gravano, Maura Mezzetti, Alessandro Moscatelli, Andrea d'Avella, Francesco Lacquaniti, and Myrka Zago. 2018. Rolling Motion Along an Incline: Visual Sensitivity to the Relation Between Acceleration and Slope. 12 (2018), 406. doi:10.3389/fnins.2018.00406
- [15] Andrea Chirico, Massimiliano D'Aiuto, Monica Pinto, Carla Milanese, Alessandro Napoli, Franca Avino, Giovanni Iodice, Giuseppe Russo, Michelino De Laurentiis, Gennaro Ciliberto, Antonio Giordano, and Fabio Lucidi. 2016. The Elapsed Time During a Virtual Reality Treatment for Stressful Procedures. A Pool Analysis on Breast Cancer Patients During Chemotherapy. In *Intelligent Interactive Multimedia Systems and Services 2016*, Giuseppe De Pietro, Luigi Gallo, Robert J. Howlett, and Lakhmi C. Jain (Eds.). Springer International Publishing, Cham, 731–738. doi:10.1007/978-3-319-39345-2_65
- [16] Giorgia Cona, Martin Wiener, and Cristina Scarpazza. 2021. From ATOM to GradiATOM: Cortical Gradients Support Time and Space Processing as Revealed by a Meta-Analysis of Neuroimaging Studies. *NeuroImage* 224 (Jan. 2021), 117407. doi:10.1016/j.neuroimage.2020.117407
- [17] Arthur D. Craig. 2009. Emotional Moments across Time: A Possible Neural Basis for Time Perception in the Anterior Insula. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 1525 (July 2009), 1933–1942. doi:10.1098/rstb.2009.0008
- [18] Xu Cui, Cameron B. Jeter, Dongni Yang, P. Read Montague, and David M. Eagleman. 2007. Vividness of mental imagery: Individual variability can be measured objectively. *Vision Research* 47, 4 (Feb. 2007), 474–478. doi:10.1016/j.visres.2006.11.013
- [19] Sergio Delle Monache, Gianluca Paolucci, Francesco Scalici, Allegra Conti, Francesco Lacquaniti, Iole Indovina, and Gianfranco Bosco. 2023. Interception of Vertically Approaching Objects: Temporal Recruitment of the Internal Model of Gravity and Contribution of Optical Information. *Frontiers in Physiology* 14 (Nov. 2023), 1266332. doi:10.3389/fphys.2023.1266332
- [20] Alton J. DeLong. 1981. Phenomenological Space-Time: Toward an Experiential Relativity. *Science* 213, 4508 (Aug. 1981), 681–683. doi:10.1126/science.7256273
- [21] Daniele Di Lerna, Silvia Serino, Giovanni Pezzulo, Elisa Pedrolì, Pietro Cipresso, and Giuseppe Riva. 2018. Feel the Time. Time Perception as a Function of Interceptive Processing. *Frontiers in Human Neuroscience* 12 (March 2018). doi:10.3389/fnhum.2018.00074
- [22] Nadine Dijkstra, Sander E. Bosch, and Marcel A.J. Van Gerven. 2019. Shared neural mechanisms of visual perception and imagery. *Trends in Cognitive Sciences* 23, 5 (May 2019), 423–434. doi:10.1016/j.tics.2019.02.004
- [23] Jacqueline Gottlieb. 2007. From Thought to Action: The Parietal Cortex as a Bridge between Perception, Action, and Cognition. 53, 1 (2007), 9–16. doi:10.1016/j.neuron.2006.12.009
- [24] Silvio Gravano, Myrka Zago, and Francesco Lacquaniti. 2017. Mental Imagery of Gravitational Motion. *Cortex* 95 (Oct. 2017), 172–191. doi:10.1016/j.cortex.2017.08.005
- [25] Madeleine A. Grealy and Gillian F. Shearer. 2008. Timing processes in motor imagery. *European Journal of Cognitive Psychology* 20, 5 (Sept. 2008), 867–892. doi:10.1080/09541440701618782
- [26] Demis Hassabis and Eleanor A. Maguire. 2009. The construction system of the brain. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364, 1521 (May 2009), 1263–1271. doi:10.1098/rstb.2008.0296
- [27] Lindsay A. Houck, Dwight J. Kravitz, and John W. Philbeck. 2022. Environment width robustly influences egocentric distance judgments. *PLOS ONE* 17, 2 (Feb. 2022), e0263497. doi:10.1371/journal.pone.0263497 Publisher: Public Library of Science.
- [28] Susanne Huber and Horst Krist. 2004. When Is the Ball Going to Hit the Ground? Duration Estimates, Eye Movements, and Mental Imagery of Object Motion. *Journal of Experimental Psychology: Human Perception and Performance* 30, 3 (2004), 431–444. doi:10.1037/0096-1523.30.3.431
- [29] Johannes Hummel, Robin Wolff, Tobias Stein, Andreas Gerndt, and Torsten Kühlen. 2012. An Evaluation of Open Source Physics Engines for Use in Virtual Reality Assembly Simulations. In *Advances in Visual Computing*, David Hutchison, Takeo Kanade, Josef Kittler, Jon M. Kleinberg, Friedemann Mattern, John C. Mitchell, Moni Naor, Oscar Nierstrasz, C. Pandu Rangan, Bernhard Steffen, Madhu Sudan, Dimitris Terzopoulos, Doug Tygar, Moshe Y. Vardi, Gerhard Weikum, George Bebis, Richard Boyle, Bahram Parvin, Darko Koracin, Charles Fowlkes, Sen Wang, Min-Hyung Choi, Stephan Mantler, Jürgen Schulze, Daniel Acevedo, Klaus Mueller, and Michael Papka (Eds.). Vol. 7432. Springer Berlin Heidelberg, Berlin, Heidelberg, 346–357. doi:10.1007/978-3-642-33191-6_34
- [30] Silvio Ionta, Lukas Heydrich, Bigna Lenggenhager, Michael Mouthon, Eleonora Fornari, Dominique Chapuis, Roger Gassert, and Olaf Blanke. 2011. Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. *Neuron* 70, 2 (April 2011), 363–374. doi:10.1016/j.neuron.2011.03.009
- [31] Cindy Jagorska, Isa Steinecker, and Martin Riemer. 2025. Interferences between time and space in advanced age. *Memory & Cognition* (Aug. 2025). doi:10.3758/s13421-025-01775-0
- [32] Alboukadel Kassambara. 2023. *rstatix: Pipe-friendly Framework for Basic Statistical Tests*. <https://CRAN.R-project.org/package=rstatix> R package version 0.7.2.
- [33] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lienthal. 1993. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology* 3, 3 (1993), 203–220. doi:10.1207/s15327108ijap0303_3
- [34] Barbara La Scaleia, Francesca Ceccarelli, Francesco Lacquaniti, and Myrka Zago. 2020. Visuomotor Interactions and Perceptual Judgments in Virtual Reality Simulating Different Levels of Gravity. *Frontiers in Bioengineering and Biotechnology* 8 (Feb. 2020), 76. doi:10.3389/fbioe.2020.00076
- [35] Maximilian Landeck, Fabian Unruh, Jean-Luc Lugin, and Marc E. Latoschik. 2020. Metachron: A framework for time perception research in VR. In *26th ACM Symposium on Virtual Reality Software and Technology*. ACM, Virtual Event Canada, 1–3. doi:10.1145/3385956.3422111
- [36] Maximilian Landeck, Fabian Unruh, Jean-Luc Lugin, and Marc E. Latoschik. 2024. Object motion manipulation and time perception in virtual reality. *Frontiers in Virtual Reality* 5 (July 2024), 1390703. doi:10.3389/frvir.2024.1390703
- [37] Bigna Lenggenhager, Michael Mouthon, and Olaf Blanke. 2009. Spatial aspects of bodily self-consciousness. *Consciousness and Cognition* 18, 1 (March 2009), 110–117. doi:10.1016/j.concog.2008.11.003
- [38] Jean-Luc Lugin, Fabian Unruh, Maximilian Landeck, Yoan Lamour, Marc E. Latoschik, Kai Vogeley, and Marc Wittmann. 2019. Experiencing waiting time in virtual reality. In *25th ACM Symposium on Virtual Reality Software and Technology*. ACM, Parramatta NSW Australia, 1–2. doi:10.1145/3359996.3364807
- [39] Michael Meehan, Sharif Razzaque, Mary C. Whittom, and Frederick P. Brooks. 2003. Effect of Latency on Presence in Stressful Virtual Environments. In *IEEE Virtual Reality, 2003. Proceedings*. (Los Angeles, CA, USA, 2003). IEEE Comput. Soc, 141–148. doi:10.1109/VR.2003.1191132
- [40] C. Thomas Mitchell and Roy Davis. 1987. The perception of time in scale model environments. *Perception* 16, 1 (Feb. 1987), 5–16. doi:10.1068/p160005
- [41] Grayson Mullen and Nicolas Davidenko. 2021. Time compression in virtual reality. *Timing & Time Perception* 9, 4 (May 2021), 377–392. doi:10.1163/22134468-bja10034
- [42] Grayson Mullen, Nicolas Davidenko, and Alan Kingstone. 2025. Virtual reality's effect on time estimation is inconsistent and depends on environment size. *Timing & Time Perception* (2025), 1–34. doi:10.1163/22134468-bja10118
- [43] Daiki Nasu, Takamichi Baba, Takumi Imamura, Masumi Yamaguchi, Yoshitake Kitanishi, and Makio Kashino. 2024. Virtual reality perceptual training can improve the temporal discrimination ability of swinging during softball batting. *Frontiers in Sports and Active Living* 6 (Feb. 2024), 1332149. doi:10.3389/fspor.2024.1332149
- [44] Sahar Niknam, Stéven Picard, Valentina Rondinelli, and Jean Botev. 2024. Some times fly: The effects of engagement and environmental dynamics on time perception in virtual reality. In *30th ACM Symposium on Virtual Reality Software and Technology* (Trier Germany, 2024-10-09). ACM, 1–9. doi:10.1145/3641825.3687726
- [45] Joel Pearson. 2019. The human imagination: The cognitive neuroscience of visual mental imagery. *Nature Reviews Neuroscience* 20, 10 (Oct. 2019), 624–634. doi:10.1038/s41583-019-0202-9
- [46] Joel Pearson, Thomas Naselaris, Emily A. Holmes, and Stephen M. Kosslyn. 2015. Mental imagery: Functional mechanisms and clinical applications. *Trends in Cognitive Sciences* 19, 10 (Oct. 2015), 590–602. doi:10.1016/j.tics.2015.08.003
- [47] Matti Pouke, Katherine J. Mimnaugh, Alexis P. Chambers, Timo Ojala, and Steven M. LaValle. 2021. The plausibility paradox for resized users in virtual environments. *Frontiers in Virtual Reality* 2 (April 2021). doi:10.3389/frvir.2021.655744
- [48] R Core Team. 2025. *R: A Language and Environment for Statistical Computing (version 4.5.0)*. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>
- [49] Martin Riemer. 2023. Interval timing in virtual reality: Merits, goals, and premises. In *Workshopband Der Mensch Und Computer 2023*. Gesellschaft für Informatik e.V., Rapperswil, Schweiz. doi:10.18420/muc2023-mci-ws05-433
- [50] Martin Riemer, Jonathan P. Shine, and Thomas Wolbers. 2018. On the (a)symmetry between the perception of time and space in large-scale environments. *Hippocampus* 28, 8 (Aug. 2018), 539–548. doi:10.1002/hipo.22954
- [51] Martin Riemer, Thomas Wolbers, and Hedderik van Rijn. 2024. Memory traces of duration and location in the right intraparietal sulcus. *NeuroImage* 297 (Aug. 2024), 120706. doi:10.1016/j.neuroimage.2024.120706
- [52] Daniel L. Schacter, Donna Rose Addis, Demis Hassabis, Victoria C. Martin, R. Nathan Spreng, and Karl K. Szpunar. 2012. The future of memory: Remembering, imagining, and the brain. *Neuron* 76, 4 (Nov. 2012), 677–694. doi:10.1016/j.neuron.2012.11.001
- [53] Christian Schatzschneider, Gerd Bruder, and Frank Steinicke. 2016. Who turned the clock? Effects of manipulated Zeitgebers, cognitive load and immersion on time estimation. *IEEE Transactions on Visualization and Computer Graphics* 22, 4 (April 2016), 1387–1395. doi:10.1109/TVCG.2016.2518137
- [54] Susan M. Schneider, Cassandra K. Kisby, and Elizabeth P. Flint. 2011. Effect of virtual reality on time perception in patients receiving chemotherapy. *Supportive Care in Cancer* 19, 4 (April 2011), 555–564. doi:10.1007/s00520-010-0852-7

- [55] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The experience of presence: Factor analytic insights. *Presence: Teleoperators and Virtual Environments* 10, 3 (2001), 266–281. doi:10.1162/105474601300343603
- [56] Alice Teghil and Marc Wittmann. 2025. How the body and brain process time. *Neuroscience & Biobehavioral Reviews* 179 (Dec. 2025), 106416. doi:10.1016/j.neubiorev.2025.106416
- [57] Ineke J. M. van der Ham, Fayette Klaassen, Kevin van Schie, and Anne Cuperus. 2019. Elapsed Time Estimates in Virtual Reality and the Physical World: The Role of Arousal and Emotional Valence. *Computers in Human Behavior* 94 (May 2019), 77–81. doi:10.1016/j.chb.2019.01.005
- [58] Vincent Walsh. 2003. A Theory of Magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences* 7, 11 (Nov. 2003), 483–488. doi:10.1016/j.tics.2003.09.002
- [59] Hadley Wickham, Mara Averick, Jennifer Bryan, Winston Chang, Lucy D'Agostino McGowan, Romain François, Garrett Golemund, Alex Hayes, Lionel Henry, Jim Hester, Max Kuhn, Thomas Lin Pedersen, Evan Miller, Stephan Milton Bache, Kirill Müller, Jeroen Ooms, David Robinson, Dana Paige Seidel, Vitalie Spinu, Kohske Takahashi, Davis Vaughan, Claus Wilke, Kara Woo, and Hiroaki Yutani. 2019. Welcome to the tidyverse. *Journal of Open Source Software* 4, 43 (2019), 1686. doi:10.21105/joss.01686
- [60] Jonathan Winawer, Alexander C. Huk, and Lera Boroditsky. 2010. A motion aftereffect from visual imagery of motion. *Cognition* 114, 2 (Feb. 2010), 276–284. doi:10.1016/j.cognition.2009.09.010