Some Times Fly: The Effects of Engagement and Environmental Dynamics on Time Perception in Virtual Reality

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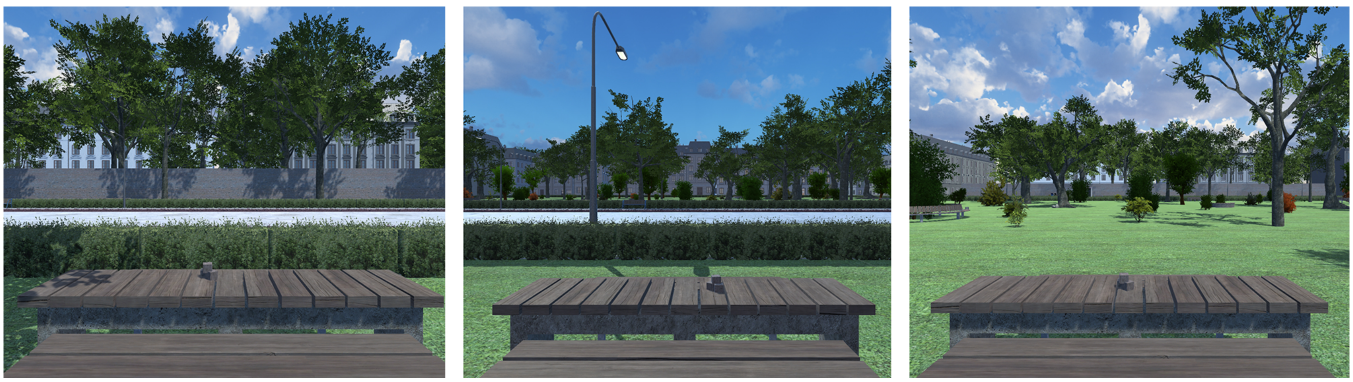

Figure 1: Randomly selected locations in the virtual environment for testing the experiment conditions with varying durations.

ABSTRACT

An hour spent with friends seems shorter than an hour waiting for a medical appointment. Many physiological and psychological factors, such as body temperature and emotions, have been shown to correlate with our subjective perception of time. Experiencing virtual reality (VR) has been observed to make users significantly underestimate the duration. This paper explores the effect of virtual environment characteristics on time perception, focusing on two key parameters: user engagement and environmental dynamics. We found that increased presence and interaction with the environment significantly decreased the users' estimation of the VR experience duration. Furthermore, while a dynamic environment lacks significance in shifting perception toward one specific direction, that is, underestimation or overestimation of the durations, it significantly distorts perceived temporal length. Exploiting these two factors' influence smartly constitutes a powerful tool in designing intelligent and adaptive virtual environments that can reduce stress, alleviate boredom, and improve well-being by adjusting the pace at which we experience the passage of time.

CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Empirical studies in interaction design**.

KEYWORDS

Virtual Reality, Time Perception, User Engagement, Environmental Dynamics

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1 INTRODUCTION

Humans perceive the passage of time subjectively. Two healthy individuals may not share a similar temporal concept of *one minute.*

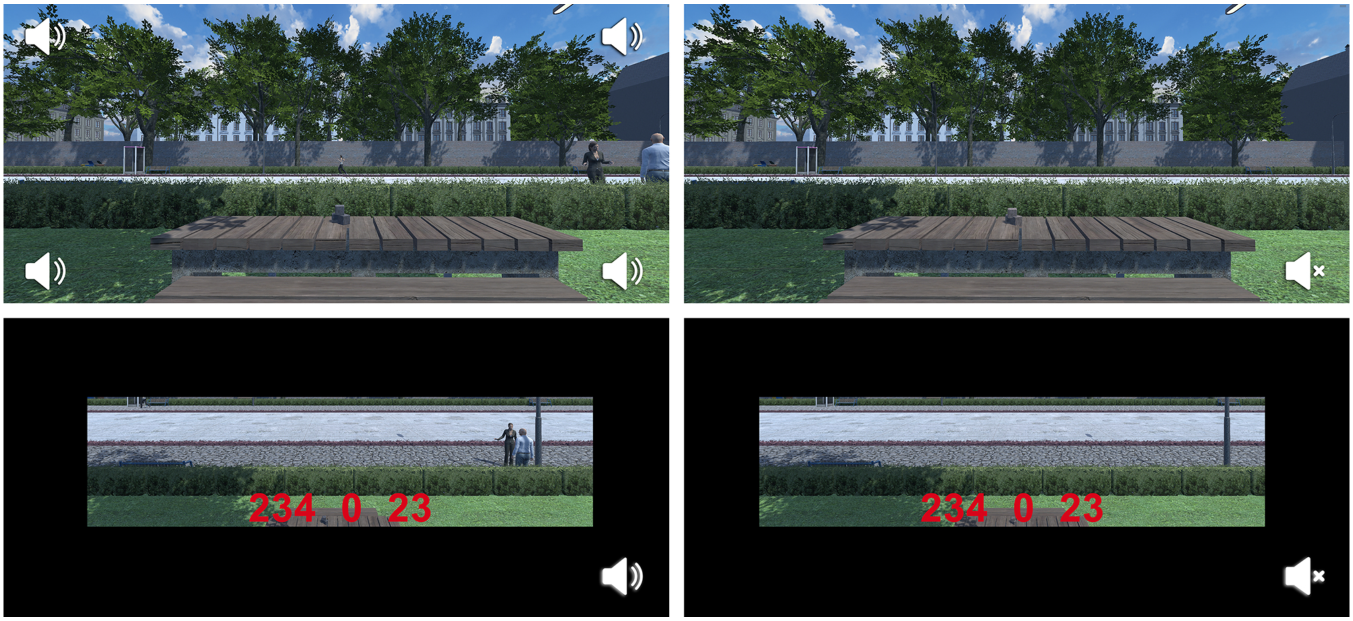

Figure 2: The study's four conditions; top left: dynamic environment w/ active user (DA), top right: static environment w/ active user (SA), bottom left: dynamic environment w/ passive user (DP), bottom right: static environment w/ passive user (SP).

Even more critically, a person under different physical or psychological conditions may perceive the same duration longer or shorter. A slew of parameters have been identified as being correlated with the pace at which we perceive the passage of time, including but not limited to age [18, 46, 47], body temperature [36, 43, 44], emotions [1, 8, 35], cognitive load [3, 4, 24], attention [28, 31, 34], and the amount of processed information [16, 39, 49].

Playing video games has also been shown to significantly alter users' perception of time, to the point where *time loss* during gaming can have detrimental effects on individuals' daily lives and well-being, often associated with mood changes and addictive behaviors. Researchers have attempted to explain this phenomenon by highlighting gamers' strong attentional focus and intense emotional arousal during gameplay, driven by highly engaging content and narratives [27, 38, 48]. However, beyond the game content, design features like immersive environments also significantly contribute to this temporal distortion. For example, Virtual Reality (VR), in general, has been reported to have a compressing effect on time perception [25, 26, 33]; time spent in VR is perceived shorter than the objective duration.

1.1 Related Work

Despite its significance, research on time perception modulation in VR is in its nascent stages and mostly limited to observation reports. These have been primarily justified using purely psychological literature and concepts, lacking a primarily VR perspective.

For example, Schatzschneider et al. [32] investigated the efficacy of real-world temporal clues simulated in VR. Weber et al. [45] used VR as a platform to validate the transferability of *magnitude* modulation of time perception [9, 17, 20] in terms of speed affordance, from observed objects to self. In another work, Malpica et al. [22] studied the magnitude modulator in affordances, including luminance, field of view, and visual complexity in VR, by displaying real images and videos. While these works paved the research path and made valuable contributions to understanding time perception in VR, the absence of VR perspective is noticeable.

However, in the last few years, a handful of studies have begun to explore the modulation of time perception using fundamental VR concepts and features. Lugrin et al. [21] researched the effect of embodiment and environment visualization on perceived waiting time. They recreated a plain waiting room and a seated avatar, once using 360-degree pictures and again with 3D models, and compared it with waiting in an identical but real space. Their results showed no significant difference in participant estimation of their 7.5-minute waiting time among the three conditions. Nevertheless, the same team of researchers continued their work by adding a complementary condition of a 3D model of the same waiting room, but without the embodiment and also focusing separately on the duration estimation versus the perceived pace of the passage of time [40]. This time, they observed a significant effect of the no-avatar condition on slowing down the perceived passage of time, but not on estimating duration. The authors refined their results by adding user interaction and reproduced the same results [41].

Read et al. [30, 31] has taken another significant step in understanding the intricacies of time perception in VR. They investigated time perception by asking participants to estimate the duration of their 3.5-minute experience in three virtual environments. These environments, sourced from two commercial games, elicited different levels of user engagement and varied spatial characteristics. Using these settings, the authors studied three conditions including a passive user in a dynamic environment, an active user in a static environment, and an active user in a dynamic environment.

The work's findings indicate a significant influence of a dynamic environment over a static one, while no difference was observed between the active and passive user conditions.

This paper follows suit by hypothesizing that user engagement and environmental dynamics have the potential to modulate the perception of time in virtual environments. However, despite intriguing results, the work of Read et al. [30, 31] suffers from specific methodological shortcomings, which we aim to address. Firstly, we developed a custom-designed environment, with complete control over parameters, as opposed to the commercial games used by Read et al. [30, 31]. Secondly, we set up all conditions within a single environment, which makes them more comparable. Additionally, Read et al. [30, 31] described and ranked the virtual environments used in their study as dynamic or engaging in a general and non-systematic manner. However, we offer a clearly delineated description for the settings of these two parameters, supported by VR literature. Finally, we also tested the missing condition in the work of Read et al. [30, 31], that is, a passive user in a static environment.

As much as accurate timing plays an essential role in different aspects of everyday and professional life, modulating the perception of time can have a critical impact on improving general well-being. For example, feeling that time is passing quickly while working under a tight timeframe can induce stress and negatively affect decision-making. Boredom, on the other hand, makes us perceive time as dragging and consequently can decrease focus and attention. By modulating time perception, we can improve decision-making, performance, and harmony in collaborative settings [5]. Understanding the precise ways through which VR influences users' perception of time, provides us with a powerful tool for developing adaptive virtual environments and workplaces for enhancing user experience.

2 MATERIALS AND METHODS

The experiment was designed to test the hypothesis that *user engagement* and *environmental dynamics* can modulate the perception of time. To test this hypothesis, we developed a dedicated virtual environment simulating an outdoor scene in a public park as the base platform. This environment was configured with two levels of user engagement and environmental dynamics in a 2×2 study design, with three repeated measurements.

User engagement. This parameter takes two values: *active user* and *passive user*. Active user in our work is defined by three features: partial embodiment (arms and hands), interaction with the environment, and a supported sense of presence by situating participants at a natural height and making ambient sound spatial (Figure 2, first row). In contrast, in the passive user case, hand-tracking is disabled, and therefore the user does not interact with the environment. In addition, the camera simulating the user's perspective was positioned at an elevated height, creating an observer viewpoint. The user's field of view (FOV) in the passive case was also limited and enclosed by a black frame to add to the user's sense of detachment from the environment. Environmental sounds in this case were 2D and muffled by applying a low-pass filter (Figure 2, second row).

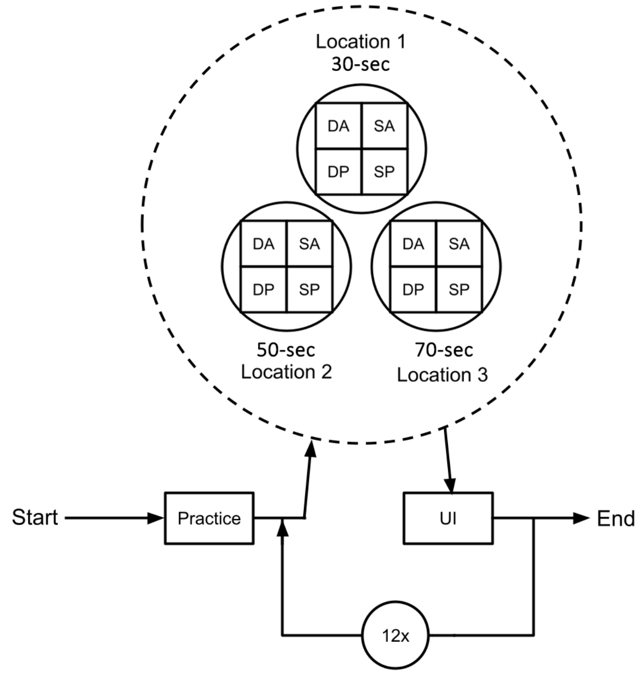

Figure 3: Flowchart of the experimental procedure.

Environmental dynamics. This parameter also takes two values: *dynamic environment* and *static environment*. We defined the dynamic environment as an environment with variation in both visual and auditory modalities. In the dynamic environment, we implemented animated human avatars, such as a jogger passing by and two office workers talking on the sidewalk. Furthermore, ambient sounds like birds chirping and a distant siren were added to the environment (Figure 2, first column). On the contrary, the static environment was a silent scene without any animated object (Figure 2, second column).

Consequently, we had four conditions, representing permutations of these two parameters: a static environment with a passive user (*SP*), a static environment with an active user (*SA*), a dynamic environment with a passive user (*DP*), and a dynamic environment with an active user (*DA*). All four conditions were tested three times, each round with a different duration (30, 50, and 70 seconds) and at a different location in the same environment (Figure 1). We repeated conditions in three different locations to prevent the repetition from diminishing the dynamism effect; however, the locations were randomly selected from the same environment to keep repeated measures comparable. That resulted to a total of 12 trials, which were presented to all participants in random order, ensuring that each participant experienced a different sequence of trials (Figure 3).

During the experiment, participants were seated on a swivel chair and informed that they were free to rotate and look around 360 degrees. For the VR experience, we used the HTC Vive Pro Eye[1] headset with a mounted Leap Motion Controller[2] for high-precision hand-tracking. The virtual environment in this experiment was

[1]https://www.vive.com/sea/product/vive-pro-eye/overview/
[2]https://www.ultraleap.com/product/

built with the Unity Game Engine[3], using ready-made assets, such as the Microsoft Rocketbox Avatars library[4] [13].

2.1 Tasks

During each trial, participants had two tasks to complete: estimating the duration of the trials with *verbal estimation* method [2, 7, 42], and memorizing three random numbers: a single-, a double-, and a triple-digit. We implemented the memory task, firstly, as a parallel task to the timing task to prevent participants from using explicit timing techniques, like counting the seconds. Secondly, participants' performance on the memory task provides us with further insight into possible side effects of time perception modulation, such as impaired cognitive function and unproductive distraction. In the active scenario, participants were placed seated behind a wooden table. In front of them, three cubes were placed on the table, each with a number engraved on one side. The participants were required to grab and turn the cubes to see the numbers. In the passive scenario, numbers were presented to participants printed on a screen attached to the camera.

After each trial, a user interface (UI) appeared, where participants entered their estimations of the trial duration and the three numbers. This gesture-based UI consisted of a 1-second resolution slider from 10 to 120 seconds for the timing task, and a numeric pad for the memory task (Figure 4). Using a slider for a verbal estimation task has the advantage of associating temporal length with physical length, reducing the likelihood of wild guessing that can occur with a numeric pad that limits input to numbers. The slider's range was selected primarily to avoid centrality bias by making the range asymmetrical around the mean trial duration (50 seconds). Additionally, the lower range (0-10 seconds) was removed as an improbable range, to provide a wider slider within the limited field of view, enhancing user control.

Figure 4: The study's gesture-based input user interface.

Before the study, participants had a short practice session with two trials to get familiar with the tasks and the UI (Figure 3). The first trial simulated an active user condition for 90 seconds, and the second one a passive user for 10 seconds; both trials were implemented in an empty environment.

[3]https://unity.com/
[4]https://github.com/microsoft/Microsoft-Rocketbox

2.2 Sample Size

We conducted an *a priori* sample size calculation using G*Power software [10, 11] for a repeated measures analysis of variance (RM-ANOVA) within subjects. The parameters were set as follows: effect size (Cohen's f) of 0.25, significance level (α) of 0.05, and statistical power ($1-\beta$) of 0.8, while the dependent variable, *perceived duration*, is measured three times for each of the four conditions (SP, SA, DP, and DA). Based on these parameters, the required sample size was 28 participants.

2.3 Recruitment

Participants were recruited via flyers posted on campus and nearby social venues, as well as through university email lists. The inclusion criteria were normal or corrected-to-normal vision and proficiency in English, while the exclusion criteria included a history of neurological disorders and susceptibility to motion or cybersickness. A total of 30 participants (8 identifying as women, 22 identifying as men), aged 18 to 46 years (Mean=28.3, SD=6.7), were recruited. Participants were informed both verbally and in writing of their right to ask questions, pause or exit the study at any time, and withdraw their consent without any consequences. Written informed consent was obtained from all participants before the experiment, and a debriefing session explaining the study's objectives was provided afterward. The full procedure took 30 minutes on average to complete, and upon completion, the participants were compensated with a gift card worth 15 euros. The study received ethical approval from the Ethics Review Panel of the University of Luxembourg, under approval number ERP 23-059.

3 RESULTS

Participant interval timings were, first, normalized for variation in trial duration by calculating the *normal estimation error* (NEE) using the following formula:

$$\text{NEE} = \frac{\text{Estimation - Objective duration}}{\text{Objective duration}}$$

such that a positive deviation means overestimation, negative, underestimation, and accurate estimation returns 0 (Figure 5). The results of a one-sample t-test on the NEE values show that, in general, the participants significantly underestimated durations ($t(359) = -2.92$, $p = 0.0037$).

In addition, estimation errors needed to be adjusted for individual differences in emotional state, working memory capacity, or the level of familiarity with VR, as these factors could indirectly affect the performance on the timing task in the experiment. Therefore, to remove the individuals' baseline error, we calculated *zero-mean NEEs* (ZM-NEE) for each participant:

$$\text{ZM-NEE} = \text{NEE} - \text{mean}(\mathbf{NEE}_x) \quad \text{for participant } x,$$

where $\mathbf{NEE}_x$ is the set of 12 NEE values recorded for the participant x (Figure 6 and Figure 7).

Afterward, the *Shapiro-Wilk* test was conducted to assess normality, yielding a p-value of 0.5422, indicating the normal distribution of the residuals ($p > 0.05$). The RM-ANOVA on ZM-NEE values revealed a significant effect of experimental conditions ($F(3, 87) = 11.22$, $p < .0001$, $\eta p^2 = 0.28$). The following *Bonferroni*-corrected post-hoc t-tests indicate significant differences between every possible

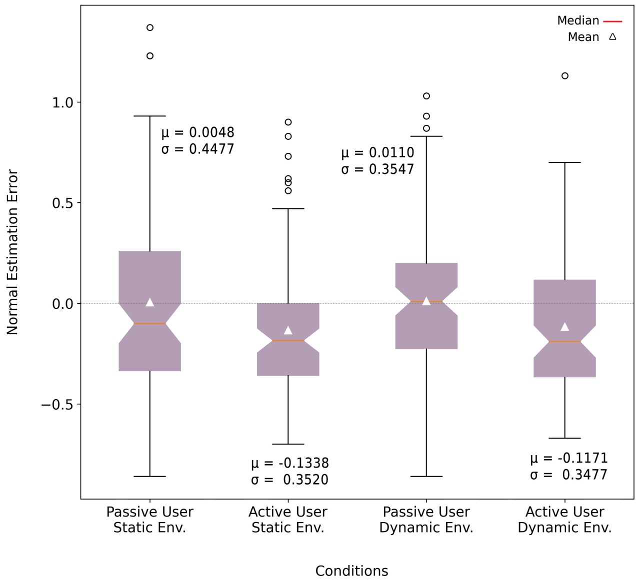

Figure 5: Normal duration estimation errors, grouped by conditions.

pair of active versus passive users. The contrast is most pronounced first in the DP-SA contrast, then in the dynamic environment, and least pronounced in the static environment. However, the environmental dynamics pairs under the same level of user engagement did not show a significant effect on ZM-NEE (Table 1 and Figure 7).

Table 1: Comparison of the conditions with ZM-NEE values

Contrast	$t(29)$	p-corr (bonf)
DA - DP	−4.5409	**0.0005**
DA - SA	0.6150	1.0000
DA - SP	−4.0017	**0.0024**
DP - SA	5.5416	**<.0001**
DP - SP	0.1522	1.0000
SA - SP	−3.4831	**0.0010**

Furthermore, we performed an RM-ANOVA on the absolute values of ZM-NEE to evaluate the intensity of time perception distortion, regardless of the direction of distortion toward underestimation or overestimation of durations. With absolute values, the RM-ANOVA exhibited a significant influence of conditions on the dependant value ($F(3, 87) = 4.65$, $p = 0.0046$, $\eta p^2 = 0.06$). However, the following post-hoc tests indicate the DA-SP contrast as the only significant difference among the conditions ($t(29) = -3.21$, $p = 0.0193$).

We also evaluated performance on the memory task by subtracting 1 point for each forgotten digit, resulting in scores ranging from -6 to 0 for one trial, and -72 to 0 in total. Participants scored -0.56 points on average for the memory task. Similar to the NEE values, each participant scores on the memory task were centered to have a mean of 0, too. In addition, to account for different memorizing time span that participants had in different trials, we calculated the zero-mean scores for each of the three trial durations (30, 50, and 70 seconds). Afterward, an RM-ANOVA was run on the memory task's scores recorded under the four experimental conditions. The results show a significant impact of the conditions on the memory performance ($F(3, 87) = 5.14$, $p = 0.0025$, $\eta p^2 = 0.15$). The following post-hoc tests indicate two significant contrasts in DA-SP ($t(29) = -3.16$, $p = 0.0222$) and SA-SP ($t(29) = -3.28$, $p = 0.0164$) pairs (Figure 8). But the evidence is insufficient to reject or accept a correlation between memory task performance and ZM-NEE (*Pearson*'s $r = -0.0514$, $p = 0.3311$).

However, the *Pearson* analysis shows a significant negative correlation between ZM-NEE and duration of the trials (*Pearson*'s $r = -0.4023$, $p < .0001$). See Figure 9. To further investigate the nature of the relationship between the duration of the trials and ZM-NEE, we ran RM-ANOVA on dataset subsets grouped by duration. The results show user engagement as the only parameter with a significant effect on estimated duration in all three duration groups, consistent with the observations on the whole dataset (Table 2 and Figure 6).

4 DISCUSSION

This study found that user engagement with and within the virtual environment significantly affects duration estimation. Active users with partial embodiment who interacted with the environment and had a supported sense of presence tend to underestimate the duration of their VR experience (Table 1). Conversely, despite the observation that the increased dynamism in the environment made the trial duration perceived longer, the effect is not significant (Figure 6 and Figure 7, second row). Nevertheless, the influence of environmental dynamics on time perception cannot be ruled out; on the contrary, it may be significant but in another dimension. We observed the effect of user engagement level to be significant in both dynamic and static environments. However, it is more pronounced in the dynamic environment. Furthermore, the most significant deviation of time perception happens in the DP-SA contrast, that is, when both parameters have opposite values, but most importantly when the dynamic environment is coupled with the passive user (Table 1). These results can be interpreted by considering that time perception modulation operates along two axes: direction and intensity (Figure 10).

By increasing user engagement, we can move along the *direction* axis and shift time perception from the feeling that time is passing fast to slow or vice versa. On the other hand, by changing the level of dynamism in a virtual environment, we can move along the *intensity* axis and increase or decrease time perception deviation.

In general, performance on the memory task shows a weak negative correlation with user engagement (Figure 11).

Similarly, Figure 8 shows slightly lower performance scores in both active user conditions compared to the passive user's conditions, especially the passive user in a static environment. This confirms the well-known fact that having successful interaction within a virtual environment consumes attentional resources and adds to the cognitive load. Nevertheless, the average score of participants on the memory task (-0.56 on a scale of -6 to 0) indicates that the cognitive load imposed by the task was not significant enough

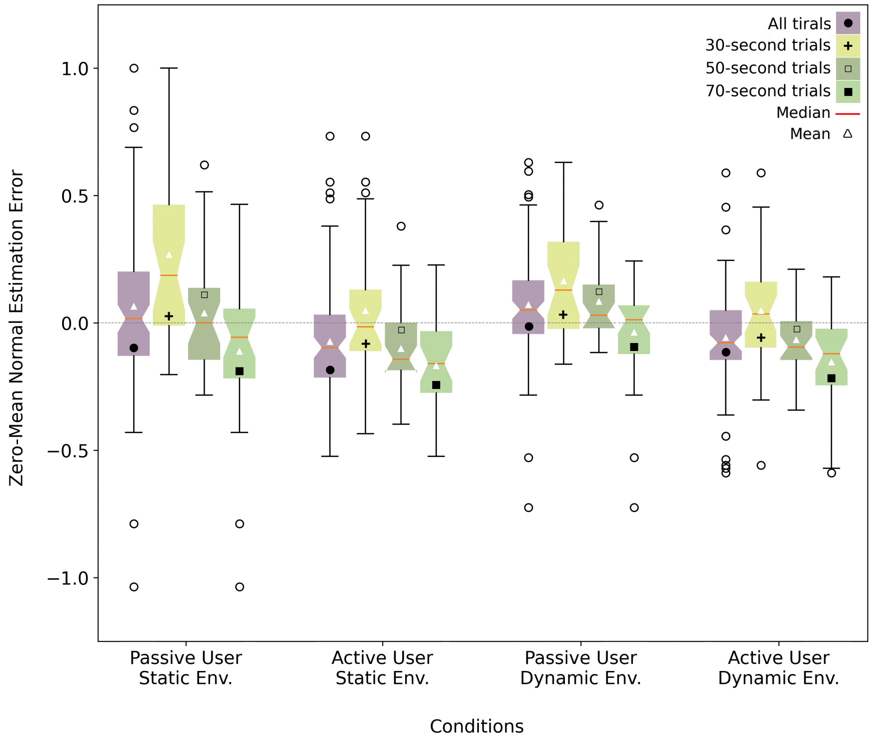

Figure 6: Zero-mean of normal duration estimation errors, grouped by conditions.

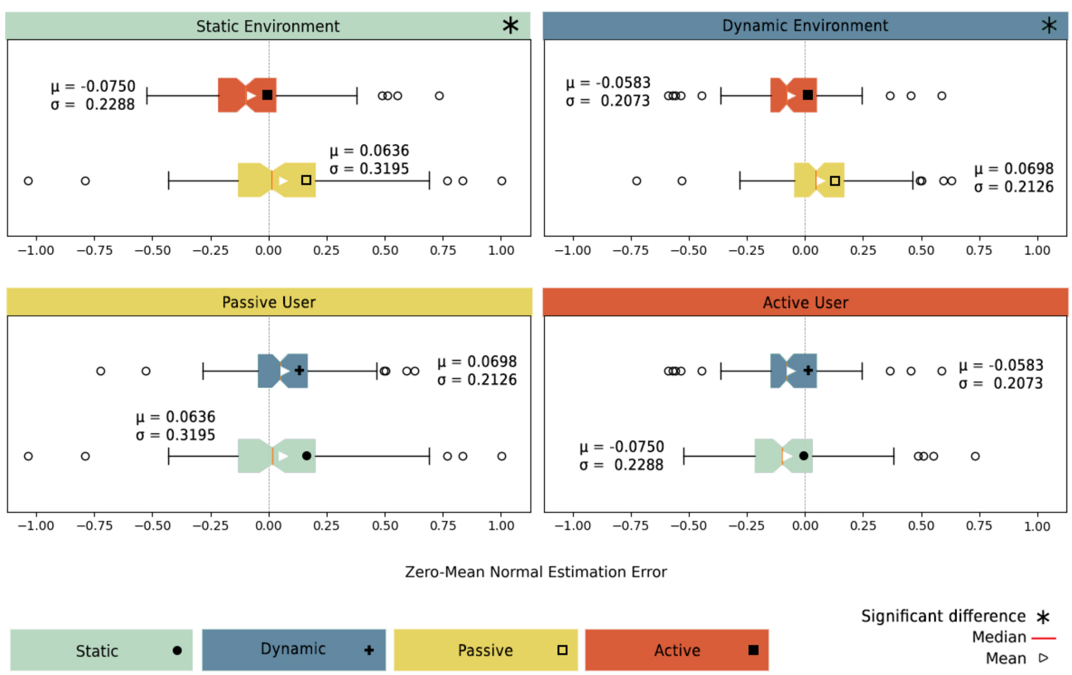

Figure 7: Pairwise comparisons of parameters in different experimental conditions.

Table 2: Results of RM-ANOVA on ZM-NEE values for experimental parameters grouped by trial duration

	All trials		30-sec trials		50-sec trials		70-sec trials	
Parameter	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
dynamism	0.3198	0.5761	1.0254	0.3196	2.1827	0.1504	1.7603	0.1949
engagement	44.9322	**<.0001**	17.9251	**0.0002**	22.0180	**0.0001**	4.3237	**0.0465**
dynamism:engagement	0.0344	0.8542	1.2309	0.2764	0.0251	0.8753	0.5787	0.4530

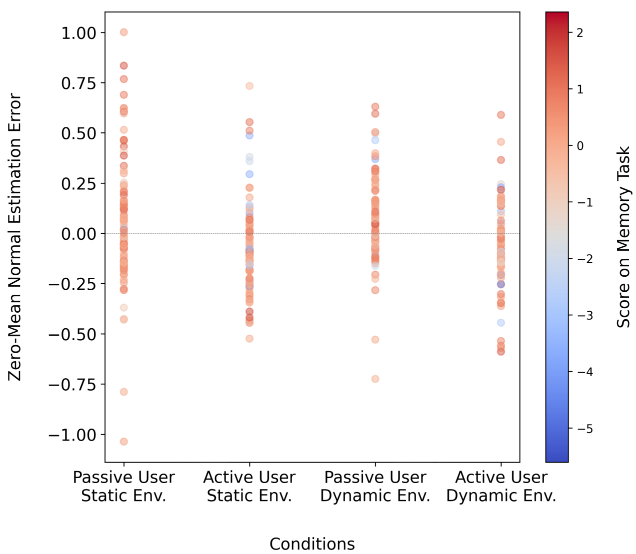

Figure 8: Performance on the memory task, grouped by conditions.

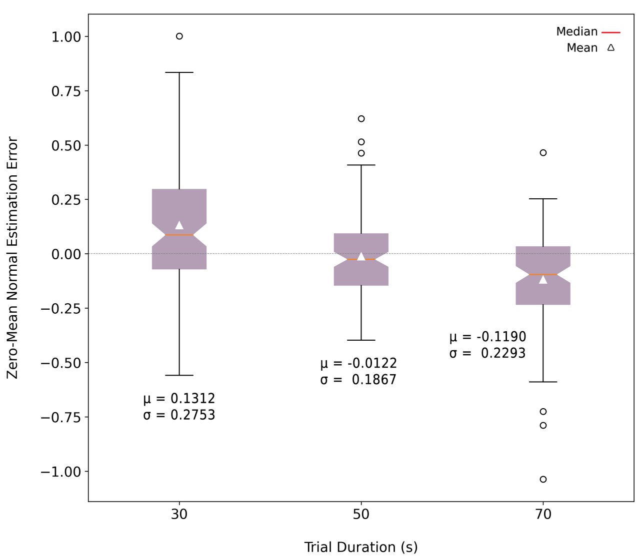

Figure 9: Zero-mean of normal duration estimation errors, grouped by trial duration.

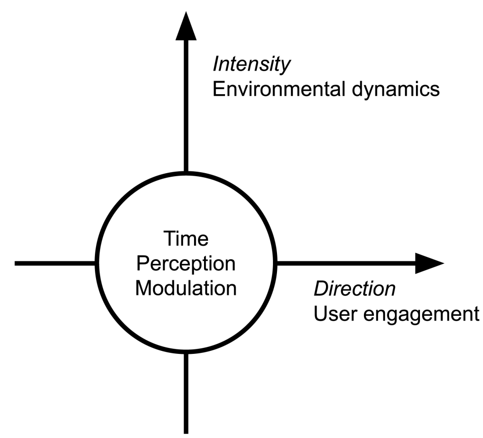

Figure 10: Time perception in VR can be modulated along two axes; *direction*: time passes fast or slowly, and *intensity*: time passes slightly fast/slowly or very fast/slowly.

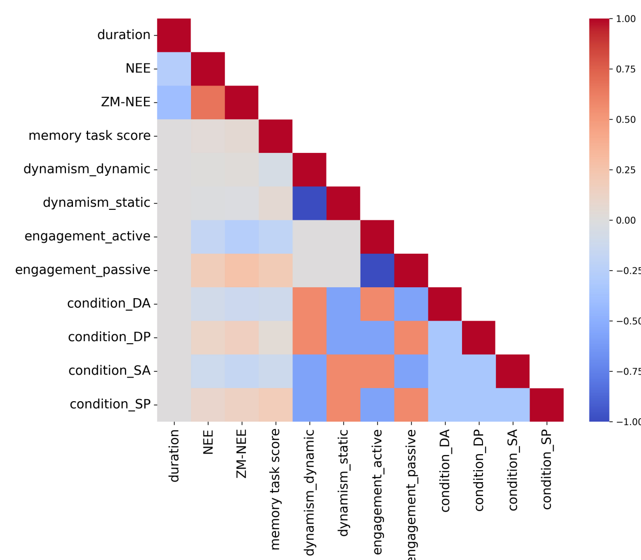

Figure 11: Study parameters and results correlation matrix.

to skew the study's results. This is also confirmed by Figure 8 which shows an even distribution of lower scores across both the negative (underestimation) and positive (overestimation) ranges of ZM-NEE axis, and Figure 11 which does not indicate a correlation between performance on the memory task and ZM-NEE. However, we observed two significant contrasts between the conditions regarding the score on the memory task: DA-SP and SA-SP. Both contrasts are also among the significant cases of shifting time perception (Table 1). This demonstrates the importance of having a well-defined monitoring system along with time perception modulation to ensure no undesired side effects on user performance or well-being.

Further analyses of the results grouped by trial duration indicate the findings are independent of both the time spent in the virtual environments and the specific location within the environment (Table 2 and Figure 6). However, even after normalizing to account for varying duration of trials, we notice a significant negative correlation between the duration and estimation errors (Figure 9). This observation is consistent with the literature on time perception, which states shorter intervals are typically overestimated, while longer intervals tend to be underestimated, which is in line with the literature [6, 14, 29]. Furthermore, we also observe a general tendency to underestimate the trial duration, which is usually attributed to VR's general effect on time perception (Figure 6).

Overall, the findings support our hypothesis that user engagement and environmental dynamics can modulate users' perception of time. The correlation between user engagement and perceived duration is negative, significant, and independent, while the effect of environmental dynamics is limited and vague in direction, serving as a complementary factor that can intensify the impact of user engagement. However, these findings sharply contrast with those of Read et al. [30, 31]. The results of their work indicate that user interaction with the environment does not affect the judgment of duration, while a more complex and dynamic environment tends to distort perceived duration. Nonetheless, general literature on time perception backs the idea that any processes that consume attentional resources contract perceived duration [12, 15, 19, 29]. Thus, in our case, significant underestimation of duration due to goal-driven engagement with the virtual environment seems natural and anticipated.

On the other hand, in our experiment, environmental dynamics played its most significant role when coupling with the passive user, in contrast with an active user in a static environment. This observation is also consistent with the existing literature on time perception. It is often reported that receiving visual information can expand the experienced time, and the vividness of visual input is positively correlated with the perceived duration [23, 37, 50]. Matthews and Meck [23] frame this phenomenon as the *the ease of extracting information from the stimulus*, covering not only syntactical features like magnitude and salient color of stimuli, but also semantic aspects such as simplicity and authenticity. In our dynamic environment, ambient sound, animated objects, and the natural user position and FoV contribute to the realism of the environment and consequently, to its *perceptual vividness* [23], thereby expanding the perceived duration compared to the static environment.

4.1 Future Work and Limitations

This study is a starting point, offering a framework and perspective for future, more in-depth research. Several aspects of this work could benefit from further investigation and improvement. For example, future work could investigate the influence of specific features of each condition, such as spatial ambient sound in the dynamic environment or the limited field of view in the static environment, separately. Another approach involves surveying participants on their experience of presence or detachment to validate the effective implementation of the intended effects within the virtual environments. Finally, less than 27% of the sample population for this study identified themselves as women, which biases the dataset towards males. A balanced distribution of gender could produce more reliable findings in terms of generalizability.

5 CONCLUSION

Based on our findings, a user actively engaged in the virtual environment experiences a compression of time. On the other hand, an observer within a dynamic virtual environment perceives an expansion of time. These findings, combined with the unprecedented opportunities offered by multisensory VR technology helps us develop more effective and intelligent user interfaces. We can explore the trade-off between the *interactor* and *observer* roles in user status. For example, when making time-sensitive decisions, reducing interaction with the environment will shift the user's role to that of an observer, thereby alleviating time pressure that could eventually improve performance. Similarly, reducing interaction could help gamers become more aware of elapsed time and mitigate or possibily prevent game addiction. On the other hand, a more engaging virtual environment can shorten perceived duration, which can be leveraged in designing unpleasant yet unavoidable experiences, such as chemotherapy (see Schneider et al. [33]).

However, the growing trend of perception research in VR needs to naturalize a VR perspective and exercise caution in interpreting the results through VR concepts and terminology. VR is not a simple tool in the social science lab; it is an entire laboratory.

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