TENETvr: Comprehensible Temporal Teleportation in Time-Varying Virtual Environments

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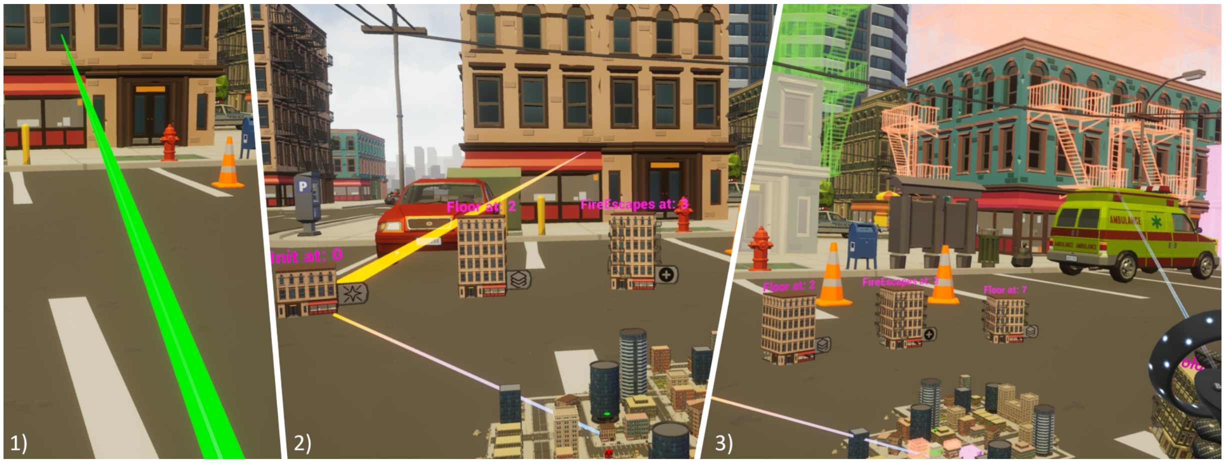

Figure 1: Workflow with our TENETvr navigation technique: 1) The user selects a time object they want to interact with (in our case a building). 2) Key moments are shown, which visualize the changes made to the object over time, above a World in Miniature (WIM) to provide a better overview. The icons next to the building and the text on top specify the type and time of the change. 3) By grabbing a key moment, the user is presented with pre-travel information that visualizes all changes in the environment between the current and target time point. 4) When the grabbed key moment is activated, the time jump gets executed and the virtual environment is updated to the new point in time (not shown here).

Abstract

The iterative design process of virtual environments commonly generates a history of revisions that each represent the state of the scene at a different point in time. Browsing through these discrete time points by common temporal navigation interfaces like time sliders, however, can be inaccurate and lead to an uncomfortably high number of visual changes in a short time. In this paper, we therefore present a novel technique called TENETvr (**T**emporal **E**xploration and **N**avigation in virtual **E**nvironments via **T**eleportation) that allows for efficient teleportation-based travel to time points in which a particular object of interest changed. Unlike previous systems, we suggest that changes affecting other objects in the same time span should also be mediated before the teleport to improve predictability. We therefore propose visualizations for nine different types of additions, property changes, and deletions. In a formal user study with 20 participants, we confirmed that this addition leads to significantly more efficient change detection, lower task loads, and higher usability ratings, therefore reducing temporal disorientation.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Interaction design—Interaction design process and methods—User interface design;

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1 Introduction

A particularly widespread approach to travel through virtual environments in both academic and commercial applications is teleportation, which moves the user instantaneously to a previously indicated location [26]. Travel through time, on the other hand, is mostly done continuously by using a timeline metaphor that allows users to scrub through a recording or revision history of the scene to inspect earlier states [21, 24, 30]. While this metaphor is straightforward and easy to understand, finding specific moments of change related to an object can be challenging [24, 30]. Prior approaches tried to mitigate these effects by, for example, visualizing objects' motion trajectories [21, 24], but these approaches are often not appropriate for discrete changes like additions, property changes, or deletions. Furthermore, in environments with various changing objects, continuous navigation might be confusing when many changes happen at once. Therefore, another common approach is to break down continuous recordings into key moments—points in time when properties of objects of interest changed—to discretely navigate through time by teleporting to them [14, 19, 24, 35]. So far, however, these teleportations happened instantaneously without prior mediation, therefore leading to potential disorientation after arriving at the new time point.

In this paper, we present a temporal navigation technique called **T**emporal **E**xploration and **N**avigation in virtual **E**nvironments via **T**eleportation (TENETvr), which builds on the concept of discretely navigating through the time domain by interacting with key moments of objects of interest. To overcome disorientation, our work draws inspiration from teleportation in the spatial domain, where pre-travel information like a curved ray provide the user with insights about the position they will end up. We adapted this idea for temporal teleportation and suggest different types of temporal pre-travel information that inform the user about the imminent changes to the scene. In a formal user study with 20 participants, we then explored the research question if temporal disorientation can be reduced by adding these forms of pre-travel information to the TENETvr interface. In summary, our work led to the following contributions:

- the derivation and definition of a quality requirement regarding the prevention of *temporal disorientation* based on existing definitions on the prevention of spatial disoirentation
- the introduction of TENETvr, a temporal teleportation interface that enables users to transition to key moments in which an object of interest was altered
- the exemplary realization of temporal pre-travel information for nine different types of scene changes, which are displayed to the user before the scene is transitioned to a new time point
- scientific evidence from a formal user study with 20 participants showing that our temporal pre-travel information led to more efficient change detection, lower task loads, higher usability ratings, and therefore reduced temporal disorientation

Our results underline the importance of temporal pre-travel information and motivate further research on comprehensible navigation techniques through space and time.

2 RELATED WORK

Our navigation techniques for traversing discrete time-varying virtual environments presented in this paper combine prior research results in the realms of both spatial (Sect. 2.1) and temporal (Sect. 2.2) navigation in virtual environments.

2.1 Spatial Navigation in Virtual Environments

Spatial navigation is one of the most fundamental forms of user interaction in virtual reality, which consists of the motor component *travel* and the cognitive component *wayfinding* [5]. A particularly prominent form of travel is teleportation, which builds on the egocentric selection of a new target position by the user before initiating an automatic relocation towards it [26]. It consists of the four phases *Target Specification*, *Pre-Travel Information*, *Transition* and *Post-Travel Feedback* [34]. While it was shown that teleportation can reduce sickness symptoms as opposed to continuous travel for most users [8, 13, 26, 34], some studies criticized teleportation for impairing the users' spatial awareness of the environment [1, 3, 27]. Spatial awareness is an umbrella term that covers a large variety of cognitive constructs on different fidelity levels, starting from mere distance judgments [20] up to the formation of a cognitive map of the environment [6]. These constructs are typically not only influenced by the choice of navigation technique but also by strong interpersonal differences based on age [29], gender [7], and childhood activities [10]. Attempting to isolate the factors that belong to travel techniques, Bowman et al. suggested to focus on "the ability of the user to retain an awareness of her surroundings during and after travel" and therefore the prevention of disorientation as a foundation for more complex spatial tasks [4]. A similar stance was taken by Weissker et al., who suggested that *comprehensible* travel techniques should "foster the awareness of ongoing navigation activities and facilitate the predictability of their consequences" for the involved users [33]. To reduce disorientation during teleportation, prior work has explored the addition of more advanced pre-travel information like portals [12, 22, 31] or preview avatars [9, 16, 32]. In this paper, we suggest adapting the idea of enhancing comprehensibility and thus reducing disorientation for temporal navigation as well.

2.2 Temporal Navigation in Virtual Environments

A prominent use case for temporal navigation is the recording and playback of user interactions within the virtual environment in order to share them with others or re-experience them later on. One of the earliest formal design models in this regard was presented by Greenhalgh et al. in the realm of desktop-based collaborative virtual environments. They suggested so called *temporal links* to embed previous recordings into the current state of the virtual environment and highlighted several temporal, spatial, and presentational properties to adjust their appearance and behavior [15]. For projection-based VR, Kunert et al. presented the metaphor of photoportals that enabled users to capture and replay their 3D-reconstructed avatars and interactions using a tracked camera device [22]. For head-mounted displays (HMDs), the system of Wang et al. allowed users to rewatch their performance in an archery game, where a time slider was available to navigate through the recording. However, it was mentioned that several participants had "issues on navigating to the content they wanted to share efficiently", which motivated the exploration of time-based or location-based markers in future work [30]. Other works observed similar issues and therefore also suggested offering navigational shortcuts to automatically detected key events within a continuous recording [21, 24]. The "Who Put That There" system by Lilija et al. additionally experimented with the idea of directly manipulating objects along their previous movement trajectory to revert the entire scene back in time. Despite taking more time to learn, this interface was appreciated compared to the "less interactive" conventional time slider that often resulted in overshooting [24]. Nevertheless, this approach is less suitable for recordings that involve discrete object changes like additions, property changes, and deletions in scene authoring and versioning systems [19, 35, 36]. To gain a better overview of a time-variant object, Fouché et al. suggested the arrangement of miniature versions of that object's state at different points in time around the user. A user study revealed that this approach provided a better overview of the larger temporal context than a conventional time slider interface [14]. Our technique presented in this paper applies the idea of miniature representations by Fouché et al. to visualize discrete object changes and suggests user-initiated transitions of the entire scene around the user to the time point indicated by one of these miniatures.

2.3 Discussion

Several systems enable users to navigate through spatial recordings in a continuous form using a time slider. However, using these interfaces often comes with accuracy problems when the task is to find certain events in the recording [24, 30]. To overcome this problem, a common approach has been to focus on certain objects of interest by showing their motion trajectories [21] and allow objects to be dragged along them [24]. Motion trajectories, however, are limited to visualizing location changes, and moving through time along them can lead to an uncomfortably high visual flow as all other time-variant objects around the user move as well. Furthermore, discrete events are still easily missed, especially when multiple changes happen in a short amount of time. Another approach is to break down continuous recordings into certain key moments [14, 19, 24, 35]. Up to this point, however, traveling to these key moments is done instantaneously without mediation, which results in many changes happening at once.

The task of forming an understanding of these changes in the time domain is similar to the formation of spatial awareness during conventional teleportation, with the difference that the user has to comprehend environmental changes around them from a static viewpoint instead of understanding an egocentric viewpoint change within a static environment. To formalize this idea, we suggest that travel techniques through time should assist users in the formation of *temporal awareness*, which we define analogously to Bowman et al. as "the ability of the user to retain an awareness of her surroundings during and after travel *to a different time point*" [4]. Also analogously to Bowman et al., we propose using the term *temporal disorientation* as the opposite of temporal awareness.

Since our focus on teleportation-based navigation implies that the actual relocation of the user during travel happens instantaneously, retaining an awareness during travel and therefore supporting temporal awareness requires appropriate mechanisms of either foreshadowing what is going to happen (pre-travel information) or mediating what has happened (post-travel feedback). For spatial teleportation, pre-travel information has been shown to be especially beneficial as it allows users to predict the upcoming relocation and therefore prevent momentary disorientation after the transition [9, 12, 16, 22, 31, 32].

In this paper, we present a first successful solution for preventing temporal disorientation after a teleport through time and motivate the necessity for future research in this area.

3 System Design

We developed a time navigation technique that evolves around selecting objects of interest and interacting with key moments to perform discrete teleportation-based time navigation. To mediate the transition to a new point in time, we also provide meaningful pre-travel information that aims to reduce temporal disorientation. Our technique does not interfere with spatial navigation techniques and can be used alongside them. For our implementation, we used Unreal Engine version 5.1 and an HP Reverb G2 HMD with the included controllers.

3.1 Virtual Environment

We applied our technique within a scene-authoring environment of a virtual city since navigating through different points in time to see how a city evolved would be a realistic use case for example in urban research [11, 25]. The virtual environment consists of a low poly cityscape[1] covering an area of around 300m^2. The city is surrounded by water and features several buildings, parks, and streets. As time-varying objects in our environment, we created different buildings which were parameterized to change their appearance based on the following properties: (1) number of floors given as integer; (2) color given as index of list $[red, green, beige, blue]$; (3) size given as index of list $[small, medium, large]$; (4) fire escape (metal balconies and ladders on the side of the building) given as bool; (5) location given as 3D vector; (6) timestamp the building is initialized given as integer; (7) timestamp the building is deleted given as integer. Furthermore, each building contains a list of changes of the form $\mathbb{C} = \{$property; new value; timestamp$\}$. The list represents changes made to the initial properties of the building and encodes the point in time they will be applied.

3.2 TENETvr

To navigate through time, the user can select an object of interest (in our case a building) via ray-cast, to bring up our proposed TENETvr interface seen in Fig. 2. The interface consists of key moments, that visualize the list of changes applied to the building over time. They are arranged chronologically in a circular manner to provide a better overview and keep the distance to the user equal, which allows for easier grabbing. Below the key moments, a World in Miniature (WIM) provides an exocentric viewpoint of the environment, which allows for a quick overview of the scene. Furthermore, the WIM reflects all changes happening in the environment and also shows the user's current position and orientation. The key moments and WIM always spawn at a fixed position relative to the user's head position and do not adjust their location afterward, allowing the user to get as close to them as they want by moving physically. The central key moment spawns 60 cm horizontally in front of and 20 cm vertically below the user's head, while the circular distance between each key moment is 18 cm. The WIM's center point is 20 cm below the central key moment and has a scaling of 1:800. The rays connect the currently active key moment of the building to its position in the world as well as its counterpart in the WIM. The short text above and the small icons on the side of the building specify the property that changed at the given timestamp.

Figure 2: Our TENETvr interface consists of small versions of the building previously selected at different points in time called key moments. The short text above and the icons on the side of the key moments indicate the property that changed at the given point in time. The rays connect the currently active key moment of the building to its position in the world as well as its counterpart in the WIM.

Analogously to the four-stage classification scheme for spatial teleportation techniques presented by Weissker et al. [34], our temporal teleportation technique can be described as follows: *Target Specification:* by grabbing one of the key moments, the target timestamp is specified; *Pre-Travel Information:* while the key moment is grabbed, the changes that happened between the current and the selected timestamp are visualized, which is further described in Sect. 3.3; *Transition:* when the trigger is pressed while the key moment is held, the environment transitions instantaneously to the new timestamp. This results in an update of the virtual environment to match the selected time point. *Post-Travel Feedback:* after the transition, the rays point to the new active key moment.

3.3 Pre-Travel Information

A core feature that we evaluated in detail in our user study is the addition of meaningful pre-travel information. Based on the list of properties a building can have, as described in Sect. 3.1, we created visualizations for nine different changes that can be applied to a building, which can be seen in Fig. 3: (a) adding floors, visualized by rendering the newly added floors in a transparent green color while (b) removing floors, is rendered in transparent red. Floors are always added or removed between the bottom and top elements of the building; (c) adding and (d) removing of fire escapes is visualized in a similar manner where the fire escapes are rendered in transparent green when they are added and red when removed; (e) changing size is visualized by rendering the whole building in transparent purple; (f) changing color is visualized by rendering the facade of the building in a slightly transparent version of the color it changes to; (g) initializing is visualized by rendering the whole building in transparent gray; (h) deleting is visualized by rendering the whole building in transparent red; and (i) changing location is visualized by rendering a series of arrows from the old to the new location. In addition, the building at the old location is rendered in transparent gray.

Different combinations of changes can also be visualized as seen in Fig. 3 i), which shows the combination of a location change, an

[1] created with the POLYGON-City asset pack by Synty Studios https://syntystore.com/products/polygon-city-pack

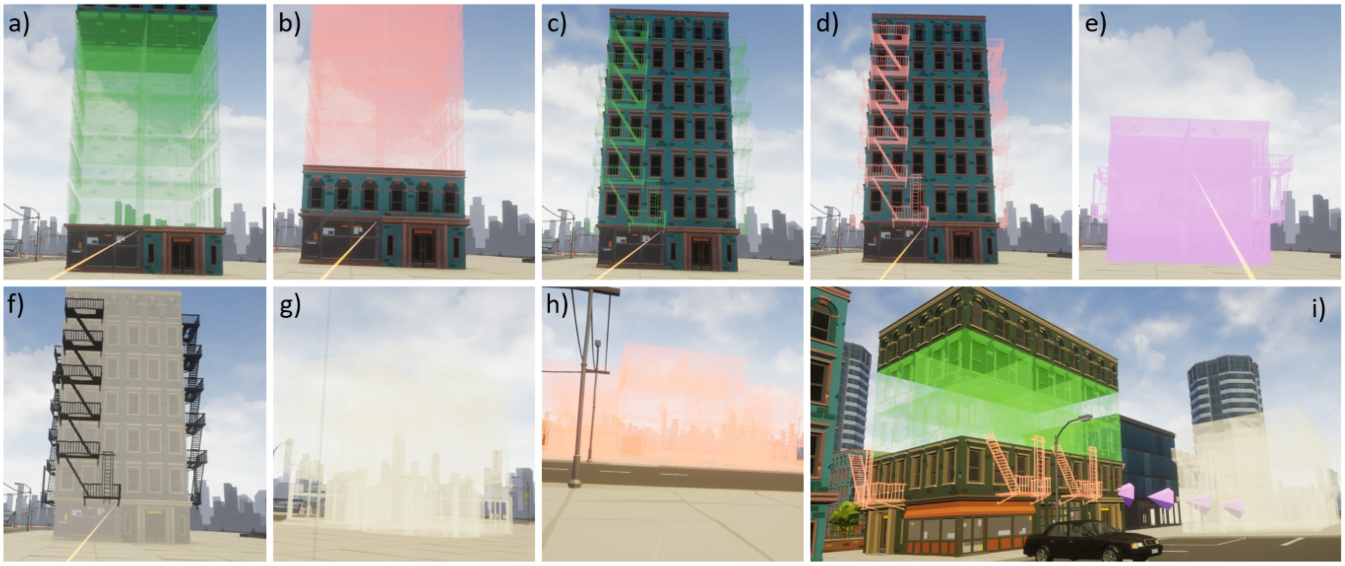

Figure 3: Different visualizations created for our nine different changes: (a) adding and (b) removing floors, (c) adding and (d) removing fire escapes, (e) changing size, (f) changing color, (g) initializing and (h) deleting a building, and (i) changing location. Picture (i) also shows a combination of different changes, in this case changing location, adding floors, and removing fire escapes.

increase in floors, and the removal of fire escapes. Before switching between two time points with TENETvr, the changes of all buildings are highlighted using the described mechanism (pre-travel information) and are also reflected in the WIM. This list is inspired by common changes performed in scene-authoring environments. Adding and removing of fire escapes was chosen as a proxy for adding details to a building. While the TENETvr technique is designed to work with any set of time-varying objects, the pre-travel information presented in this paper is more tailored to the use case of a virtual city model.

4 User Study

In our user study, we were interested in testing the comprehensibility and effectiveness of our pre-travel information as a method to reduce temporal disorientation. Therefore, we conducted a within-subjects user study with one independent variable with two levels. Both conditions use our TENETvr navigation technique, i.e., key moments and WIM are present in both conditions. In condition C_{PTI}, however, the pre-travel information (PTI) is enabled, while in condition C_{Base} it is omitted. Therefore, grabbing a key moment will not lead to any visualizations.

4.1 Hardware Setup and Participants

For our study, we connected an HP Reverb G2 HMD with a tracking area of around $3m^2$ by cable to a PC running Windows 10, which was equipped with an Intel i9-10900X CPU, 32 GB of RAM and an Nvidia RTX 3090 GPU.

We recruited 20 participants (12 male, 8 female) between 19 and 35 ($M = 25.1,\ \sigma = 3.63$) to our VR Lab. Only one user was a first-time VR user while 4, 7, and 8 reported beginner, intermediate, and expert levels (10 users reported their primary use case was research, 9 gaming). All participants successfully completed the user study.

4.2 Task Design

According to the definition of comprehensibility by Weissker et al., which states that navigation techniques should “foster the awareness of ongoing navigation activities and facilitate the predictability of their consequences” [33], the main task of our study was to detect all changes in the environment that happened between two points in time. While we acknowledge that this skill is only a single facet within the complex idea of fostering temporal awareness, this focus gave us controlled insights into the influence of pre-travel information on comprehensibility and therefore on the reduction of temporal disorientation.

To create a controlled and reproducible experimental setup we made some restrictions to the system. Participants were only allowed to select a specific building marked by a green arrow on top to activate the TENETvr interface. In order to do so, they were always positioned directly in front of it without requiring any form of spatial navigation. While the initial appearance and location of the building of interest changed, the list of changes applied to the building stayed the same and consisted of five changes. Because our independent variable is the pre-travel information (the visualizations we created in Sect. 3.3), participants were told to exclude the changes happening to the building they interact with since these changes are also visualized by the key moments. We simplified the interaction by restricting the user to a single time jump from timestamp zero to timestamp seven; therefore, only the respective two key moments were grabbable. The two key moments were also marked by a green arrow to signal the user that these were interactable.

In total, we created 30 tasks with various amounts of changes scattered across the entire environment in different directions relative to the user. Nine tasks contained a single change, one for each type; 10 tasks featured two changes, either distributed over two buildings or combined in a single one; The remaining 11 tasks featured between three to five changes distributed among two to four buildings. In total, 77 changes had to be found (on average 2.57 per task), while each type of change was featured at least eight times.

4.3 Procedure

Upon arriving at our laboratory, participants read the task description, filled out a consent form, and completed a demographics questionnaire. Participants were given an introduction about the TENETvr technique on the PC by the experimenter to get familiar with the buttons and WIM and learned how to perform time jumps by grabbing and activating the key moments. Furthermore, each type of change and the corresponding visualization, i.e., the pre-travel information, was introduced interactively. Next, participants put on the HMD and had a chance to get familiar with the technique before being randomly assigned to one of the two conditions in a counterbalanced fashion. Participants were told that they need to find zero to five changes, so they had a general idea about how long they should search for. After completing two test tasks that featured all nine changes, the first random set of 15 tasks was completed. Afterward, a set of questionnaires was filled out on the PC. The first questionnaire consisted of a single question assessing the users well being ("On a scale from 0–10, 0 being how you felt coming in, 10 is that you want to stop, where are you now?" [2,28]), followed by the Raw TLX to quantify task load [17,18] and the User Experience Questionnaire (UEQ) [23]. After a short break, the procedure was repeated with the other condition, starting again with two test tasks followed by the remaining 15 tasks in random order and the questionnaires.

In the end, participants were asked to specify their preferred condition followed by custom questions about the appearance of the key moments, the usefulness of the WIM, and some free text questions about the pros and cons of the technique, providing us with insights about the TENETvr technique as a whole. The user study took between 45 and 60 minutes to complete, and participants did not receive any form of monetary compensation for taking part in the study.

4.4 Dependent Variables and Hypotheses

To address our research question and measure temporal disorientation, we logged the number of errors made, the time it took the user to find all changes and how many time jumps the user executed. An error point was added when a change was missed or a change was pointed out that was not present. Participants only had to specify the nine different types of changes given in Sect. 3.2, i.e., it was only necessary to point out that floors had been added but not exactly how many. This gave us insights into the user's general understanding of what was happening between two time points. To log task completion time, the timer was started immediately after the participant spawned in front of the building and was stopped manually by the supervisor once participants voiced all the changes they had found and stated that they were done searching. The standard questionnaires after each condition yielded a discomfort score between 0 and 10 and a task load score between 0 and 100, which was derived from the answers of the Raw TLX. Furthermore, the UEQ was filled out after each condition, which results in six scores between -3 and 3 representing the perceived attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty of the technique. To address our research question, we formulated the following hypotheses about our dependent variables before the user study started:

- The number of time jumps (H_1) as well as the task duration (H_2) will be lower in C_{PTI}.
- More changes will be noticed in C_{PTI} (H_3).
- The task load will be lower in C_{PTI} (H_4).
- User experience will be better in C_{PTI} (H_5).

To get additional insights about the technique in general and without formulating explicit hypotheses, we also asked participants about the appearance of the key moments and the usefulness of the WIM. In the end, participants were asked which condition they preferred and what they liked and disliked about the navigation technique.

5 Results

To check if our data was normally distributed, we used Shapiro-Wilk tests and Q-Q Plots to also visually confirm the normal distribution. We rejected the assumption of normality for $p < 0.05$. Both tests confirmed our parameters were normally distributed, with one exception being the *Dependability* score of the UEQ. Therefore, we used paired t-tests to check our hypotheses and a Wilcoxon signed-rank test in the one case where the assumption of normality had to be rejected. The results of the t- and Wilcoxon signed-rank tests were considered significant for $p < 0.05$.

5.1 Logged Data

Fig. 4 shows boxplots illustrating the distribution of the parameters logged during the user study. The average number of time jumps was significantly lower in C_{PTI} ($M = 3.97,\ \sigma = 3.43$) than in C_{Base} ($M = 21.61,\ \sigma = 8.56$) with $t(19) = 11.669,\ p < 0.001,\ d = 2.609$ (large effect), supporting H_1. The mean task completion time given in seconds yielded significantly shorter average values in C_{PTI} ($M = 39.60,\ \sigma = 12.39$) than in C_{Base} ($M = 59.41,\ \sigma = 18.99$) with $t(19) = 5.315,\ p < 0.001,\ d = 1.188$ (large effect), supporting H_2. The mean number of errors in C_{PTI} ($M = 1.55,\ \sigma = 1.00$) was significantly lower than the mean of C_{Base} ($M = 10.40,\ \sigma = 5.75$), with $t(19) = 7.087,\ p < 0.001,\ d = 1.585$ (large effect), indicating that more actions were noticed in C_{PTI} and therefore supporting H_3.

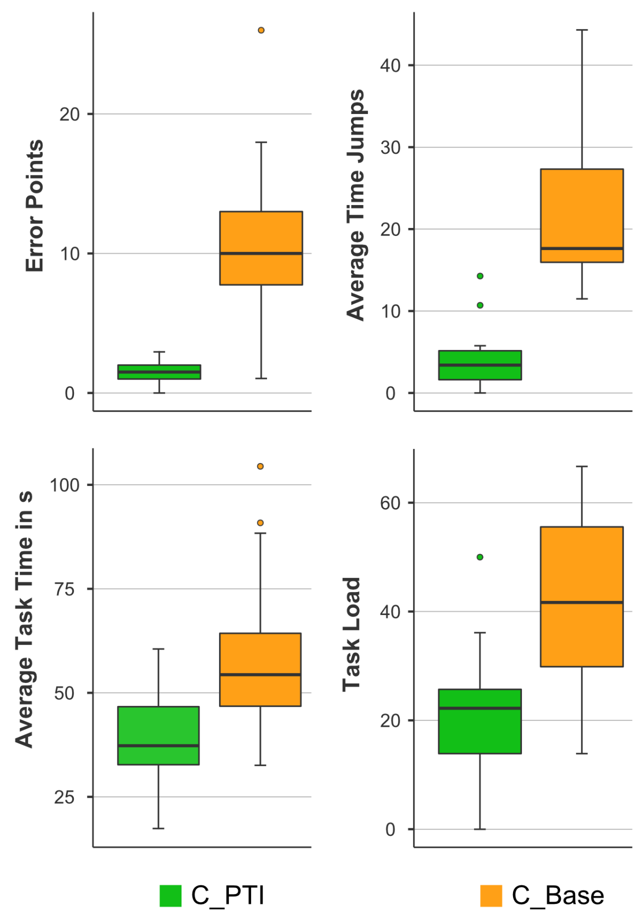

Figure 4: Boxplots illustrating the data distribution of the custom questionnaires (error points, average time jumps and average task time in seconds) as well as the results of the task load questionnaire (Raw TLX) for each condition. Task load scores are given on a scale of 0 to 100, with 100 representing the highest task load.

5.2 Standard Questionnaires

Fig. 4 (bottom right) illustrates the distribution of results from the Raw TLX. On average, these results were significantly lower in C_{PTI} ($M = 21.11,\ \sigma = 11.94$) than in C_{Base} ($M = 41.39,\ \sigma = 15.73$), with $t(19) = 7.317,\ p < 0.001,\ d = 1.636$ (large effect), supporting H_4. The benchmark scores for C_{Base} and C_{PTI} of the UEQ are shown in Fig. 5. Table 1 shows the results of the t-tests for the individual items of the UEQ. Results were significantly higher over all items in C_{PTI}, therefore supporting H_5.

The discomfort score, reported after each condition within a range from 0 to 10, resulted in an average of 3.5 in C_{Base}, with 11 scores being 3 or lower, 6 scores between 4 and 7 while 3 reported 8 or 9. The standard deviation was 2.93. In C_{PTI}, the average score was 1.6, with 10 scores being 2 or lower, 9 at 3 or 4 and one at 5 with a standard deviation of 2.06.

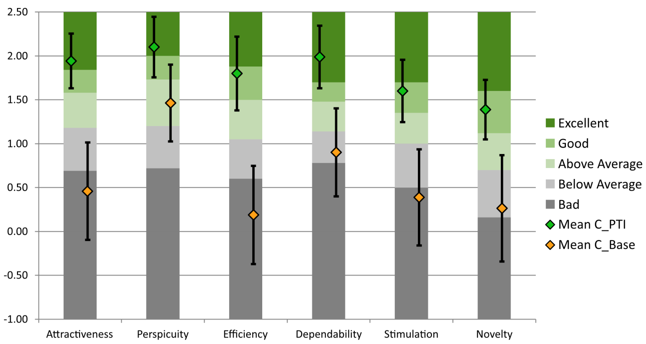

Figure 5: Benchmark scores of the individual items of the User Experience Questionnaire with confidence intervals (confidence level 95%). Diamonds indicate mean values, orange for C_{Base} and green for C_{PTI}.

UEQ Item	Test Statistic	p-Value	Effect Size
Attractiveness	$t(19) = 5.658$,	$p < 0.001$,	$d = 1.265$
Perspicuity	$t(19) = 3.300$,	$p = 0.002$,	$d = 0.738$
Efficiency	$t(19) = 6.809$,	$p < 0.001$,	$d = 1.523$
Dependability	$W = 171$,	$p < 0.001$,	$r = 1.0$
Stimulation	$t(19) = 4.846$,	$p < 0.001$,	$d = 1.084$
Novelty	$t(19) = 4.723$,	$p < 0.001$,	$d = 1.056$

Table 1: t-test results for the individual items of the UEQ. Dependability scores were not normally distributed; therefore, a Wilcoxon signed-rank test was used instead.

5.3 Custom Questionnaires

The average results of our custom questionnaires can be seen in Table 2. The questionnaire consists of questions about the key moments and WIM, and results are given on a 7-point Likert scale. 19 out of the 20 participants stated that they preferred C_{PTI} over C_{Base}.

Item	Mean	Median	Standard Deviation
KM 1	$M = 5.45$	$\overline{M} = 6$	$\sigma = 1.15$
KM 2	$M = 5.95$	$\overline{M} = 6$	$\sigma = 1.15$
WIM 1	$M = 2.35$	$\overline{M} = 2$	$\sigma = 1.57$
WIM 2	$M = 6.70$	$\overline{M} = 7$	$\sigma = 0.57$

Table 2: Average results of our custom questionnaire, given on a 7-point Likert scale, which consisted of the following items: "I liked the way the key moments are represented" (KM1), "I could clearly understand which key moment represented the current state of the building" (KM 2), "Without the WIM, I would have been able to find all differences between the two time points as well." (WIM1), and "The WIM helped me in finding the differences between the two time points." (WIM2).

5.4 Discussion

Overall, our results significantly support our initial hypotheses. While we expected that fewer errors were made in C_{PTI}, a common error in C_{Base} was the misinterpretation of a location change. A lot of participants perceived the location change as a deletion and initialization of a new building; therefore, increasing the number of error points. In C_{PTI}, the color change was often missed since its visualization was not as prominent as others, which participants also stated at the end of the user study. Our initial goal with this visualization was that it is possible to tell to which color the building changes. As a result, it was not possible to render it in a transparent bright color, the way it is done for the other changes. This requires further adaptation in the future. The lower number of time jumps was also expected since jumping back and forth was not necessary to see the changes in C_{PTI}. The task completion time was not only affected by how fast the user found the changes but also by how long the user spent searching for them. In C_{PTI}, changes were not only more easily visible, but the user also had more confidence in stating that he was done searching for them. This also affected the task load score as participants felt more successful and finding the changes was faster and easier in C_{PTI}. If we look at the individual scores of the UEQ, we can see that C_{PTI} performed significantly better than C_{Base} over all items. Only perspicuity was less clear, which might be more affected by the interaction as a whole and less by the pre-travel information.

Looking at the free text fields, asked at the end of the user study, 19 out of 20 participants preferred C_{PTI} and most also additionally reported that they found the WIM very helpful and that the interaction with the key moments was very easy and enjoyable. This is also in line with the results of our custom questionnaires. One participant, however, preferred C_{Base} and stated that the pre-travel information was helpful but "no highlighting was more pleasing to look at". This indicates a possible problem that too many visualizations might clutter the scene; therefore, a good balance has to be found. When users were asked what they disliked about the technique, most stated that it was tiring during C_{Base} to jump back and forth between timestamps as it required a lot of arm movement. This might also be an explanation for the overall higher sickness scores in C_{Base} and additionally affected task load and UEQ scores. Some people would have preferred to be able to move and rescale the WIM to get a better overview. One user stated that in C_{Base} "such fast changes in the environment were a bit uncomfortable. However, with highlighting, the task of identifying changes became much simpler, and I did not feel uncomfortable at all".

In the end, we believe our results showed that adding pre-travel information to teleportation-based temporal navigation techniques can reduce temporal disorientation.

5.5 Limitations

In our user study, a change detection task was used to measure temporal disorientation. As motivated in Sect. 4.2, we believe that this task provides valuable insights into the effectiveness and comprehensibility of pre-travel information in the temporal domain. However, we acknowledge that, analogously to spatial awareness, our definition of temporal awareness is a similarly multi-faceted construct that we have only begun to analyze in this paper.

Furthermore, a comprehensive comparison between TENETvr and other temporal navigation techniques is missing, which would give us more insights into the advantages and disadvantages of teleportation-based time navigation techniques and the suitability of different techniques for different use cases.

While our presented types of pre-travel information were limited in that they were tailored towards changes that can occur to buildings in a virtual city model, the general idea of providing semi-transparent highlights for additions, modifications, and deletions is, despite requiring further analyses, applicable to other use cases as well. While our technique is theoretically not limited by how many changes can happen in the environment, the visualizations might clutter the scene in extreme cases.

Finally, the user study only consisted of 20 participants, was not perfectly gender-balanced, and included solely young adults between 19–35, therefore limiting its generalizability.

6 Conclusion and Future Work

In this paper, we proposed a novel temporal navigation technique called TENETvr that builds on the concept of discrete time navigation via key moments to allow for comprehensible teleportation through the time domain. With our technique, users can grab key moments, which represent points in time when properties of the object have changed, to teleport themselves to them. Furthermore, pre-travel information is shown before the time jump is executed. Our results showed that adding meaningful pre-travel information leads to more efficient change detection, lower task load, and higher usability ratings, therefore reducing temporal disorientation.

As stated in Sect. 5.5, we did not fully investigate the multi-faceted construct of temporal awareness. Therefore, promising avenues for future research include detailed analyses of judging relative temporal distances, estimating one's absolute temporal position within a recording, and the formation of a temporal cognitive map similar to the idea of survey knowledge. We must also further evaluate our technique in different scenarios to test the generalizability of our system and make a comparison to other continuous time navigation techniques.

While we evaluated the general usefulness of pre-travel information, we did not provide a comprehensive comparison of different visualization approaches. The changes could, for example, be animated to also provide feedback about the sequence of changes in the case of multiple changes happening at once.

Overall, our results highlight the importance of adding pre-travel information to temporal teleportation techniques and motivate further research on comprehensible navigation techniques through space and time.

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