Improving Spatial Orientation in Immersive Environments

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ABSTRACT

In this paper, we present a comparative evaluation of three different approaches to improving users' spatial awareness in virtual reality environments, and consequently their user experience and productivity. Using a scientific visualization task, we test the performance of 21 participants to navigate around a virtual immersive environment. Our results suggest that using landmarks, a 3D minimap, and waypoint navigation all contribute to improved spatial orientation, while the macroscopic view of the environment provided by the 3D minimap has the greatest positive impact on spatial orientation. Users also prefer the 3D minimap for usability and immersion by a wide margin over the other techniques.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Scientific visualization**; **User studies**;

KEYWORDS

Immersive virtual environments, spatial orientation, presence, virtual reality, locomotion, scientific visualization

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1 INTRODUCTION

As Virtual Reality (VR) finds ever-growing adoption across many fields, including biomedical imaging [30], scientific visualization [5, 8, 32] and education [20, 34], the importance of communicating information clearly and maintaining a positive user experience remains paramount. Spatial orientation, defined as the user's knowledge of their location and orientation within the environment [13], is tied to both of these. Disorientation, on the other hand, both interrupts the exchange of information and degrades the quality of the user experience with symptoms of VR sickness [6, 18].

Our Immersive Virtual Environment (IVE) consists of a model of a tokamak thermonuclear fusion reactor wherein users can navigate and experience fast-moving particle simulation data. It is designed to fit the parameters of the ITER project (Fig. 1a) [1]. Rendering and shaping flexibility is limited in scientific VR applications, such as those that use 3D voxel or particle simulation data, because the environment must faithfully reflect the data or risk misinforming the user. Since the environment is modeled to represent a particular tokamak design specification and is a major component of the visualization, it would be inappropriate to apply any techniques to improve users' sense of presence and spatial reasoning within the environment that assume the environment is malleable in its representation.

This kind of environment typically lacks the necessary visual cues to be conducive to maintaining spatial orientation when moving around inside the virtual space, thus making it more difficult for users to complete data analysis or other complex actions. In the case of the tokamak (Figure 1), the toroidal structure's radial symmetry makes it impossible to distinguish one side of the environment from the other without some kind of external assistance.

We implement and evaluate three separate approaches for improving spatial orientation of users in such an IVE. The first is to add artificial landmarks (i.e. visual cues indicating cardinal directions) to the IVE to provide a clear sense of direction and position. We intend to increase and maintain spatial orientation by allowing users to associate their position in an otherwise directionless space. The second is a 3D minimap, also known as a world in miniature (WIM), that presents a smaller, semitransparent replica of the environment with the user's position marked with an indicator. The minimap follows the user's controller and updates in real time to show movement history, providing an external perspective that would be otherwise unavailable to the user. The last approach we evaluate is an improved locomotion technique designed specifically for navigating environments with a greater degree of freedom. This technique, called waypoint navigation, provides waypoints to mark the history of users' movement, with the intent of improving spatial orientation by clarifying how the user has moved around the environment.

Our work's primary contribution is a comparison between these three improvements (enumerated above) to immersive environments and user interactions within such environments. We perform a quantitative evaluation of each technique in a within-subject design user study with 21 participants. The results of the study provide significant evidence that while all of the techniques are significantly beneficial to users, the 3D minimap stands out as the strongest among them. The waypoint navigation performs similarly well, but is less robust. We found landmarks to be less effective overall than the others. By improving IVEs, especially for data analysis purposes, we open new doors to new possibilities for immersive scientific visualization and immersive data analysis. Scientists and analysts alike may find it increasingly convenient and efficient to

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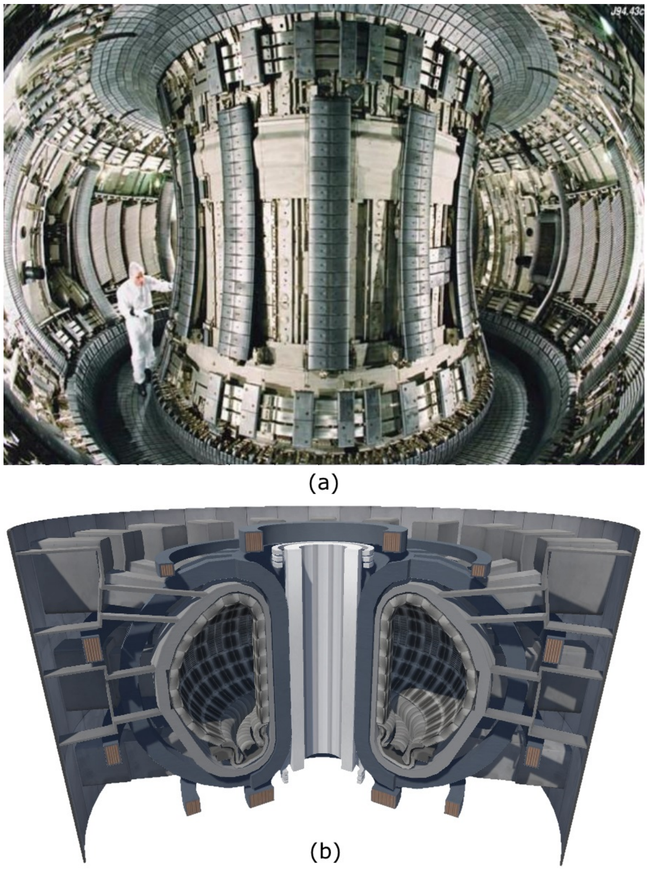

Figure 1: Tokamak Fusion Reactor. (a) an internal view of JET, an ITER-like tokamak [9, 23]. (b) a cross section view of our virtual tokamak that users can explore with a virtual reality HMD.

work in virtual environments as more of the issues, such as weak spatial orientation, are mitigated and improved upon.

2 RELATED WORK

Though it is expanding, the use of virtual reality for scientific visualization and data analysis is still limited. This may contribute to the small number of comparative studies focused on solving common problems for immersive scientific visualization.

The concept of spatial orientation in virtual immersive environments has been explored with a variety of experiments, with many focusing on the effects and effectiveness of navigation techniques [2, 4, 11, 25]. Recently, additional efforts have been put into improving spatial orientation specifically through IVE modifications and improvements [15, 21]. Others have evaluated the impact of external factors, such as viewing conditions [17] and the transition between real and virtual [31]. None of these, however, attempt to use a scientific visualization environment or an environment that does not restrict navigation to a single plane in their evaluation.

Evaluating spatial orientation has been approached in several ways. Some studies employ memory tests, such as those performed by Mania et al. [17]. A far larger number employ a variety navigation tasks. Such a task typically includes a few core components, i.e. a certain amount of distance to travel, a required change in direction, and varying target visibility [3]. Our tasks follow these guidelines, as one of them (navigation task) requires users to navigate around an obstacle and find a certain unmarked location. The other (particle tour task) is a variation of the spatial orientation task used by Nguyen-Vo et al. [19] which takes the core concept of tracking environment interactions and applies it in a way that makes sense for our scientific visualization environment. Nguyen-Vo et al. task their users with touching a number of concealed balls by observing boxes from a certain angle. The important feature that we use from this work is that the interactive objects do not show any sign that they have been touched, thus requiring users to navigate the environment efficiently to avoid repetitively touching the same object. A detailed description of the tasks used in our study can be found in Section 5.2.

Teleportation has been established as user-friendly navigation technique with minimal effort and learning required to use effectively [4]. However, disorientation during navigation is more prevalent with teleportation compared to other techniques [13]. Due to disorientation concerns, preference is sometimes shown to alternative navigation methods, such as redirected walking [22], which has been studied in terms of its effects on spatial orientation by Suma et al. [29].

As another solution to disorientation, node-based navigation techniques have been implemented and evaluated in the past, including the very recent work by Habgood et al. [11], from which our implementation draws inspiration. Their work evaluates a form of navigation that uses rapid, continuous movement between predefined nodes, exhibiting improved accessibility and reduced instances of VR sickness. We use the concept of nodes (renamed to waypoints) but remove the restriction of placement, allowing waypoints to be placed in predefined locations but also at user-defined locations using controls within the IVE. We also employ continuous movement, but replace the linear function of position with a sigmoidal one.

Worlds in miniature (WIMs) [28] have been used extensively in virtual environments for both traditional media and virtual reality [7, 14]. While they may be implemented for a number of reasons, their use for providing spatial orientation in virtual spaces is proven [14, 33].

A recent publication by Usher et al. [30] uses a WIM in a VR neuron-tracing application to allow users to determine which subsection of a larger volume they are currently rendering. Usher et al. implemented their WIM primarily to serve as a spatial anchor, and did not study the effects of the WIM on users' spatial orientation. Their WIM did not represent the user's position within the space, beyond a large bounding box which represented a subsection of the rendered volume. The 3D minimap implemented in this work builds on this by rendering additional information beyond the environmental features, including user position and path history.

Landmarks have been shown by Riecke et al. [24] to assist users of immersive environments to maintain effortless spatial orientation through "automatic and obligatory spatial updating" (p.299). Riecke et al. compared an environment with landmarks to one devoid of any identifiably unique features and conclude that the visual cues provided by the landmarks are capable of significantly improving spatial orientation. Gao et al. also investigated the use of landmarks for learning in immersive environments, finding that artificial landmarks improve both spatial learning and recall with memory-based tasks [10]. The limited application and variability of landmarks may contribute to the scarcity of further evaluation and improvement to this particular technique.

3 TECHNIQUE DESIGNS

The need for an improved navigation design arose when originally creating our immersive Tokamak demonstration environment, in which experienced users frequently became lost or did not believe that the original teleportation implementation had, in fact, taken them to where they had indicated with the control. This was due to several design flaws of the original teleportation mechanic, which teleported the user instantly with no indication of where the user was going or where they had been after the initial jump. Our response was an iterative process that led us to our current design which contains several notable and adaptations combined from recent research [11, 25] to function optimally in terms of reducing disorientation and VR sickness. The original teleportation implementation, which only moves the user instantaneously to a point in the 3D environment where they are aiming with the controller, is used as the default navigation method for the comparative evaluation.

3.1 Base Design

Each of the following sections describe the designs that we compare in this work. To provide context, we compare them also against a ‘default environment’ which is the simplest implementation of necessary features required to complete the tasks provided in our user study. The base design uses a ’point-and-click’ style teleportation and provides no other tools to assist users in navigating or orienting themselves in the environment.

The user can always walk around within the tracked space, however the tracked space is much smaller than the environment, thus the user needs a way to move the tracked space within the environment. The teleportation uses a controller to project a beam in the direction of movement, and will teleport the tracked space by a set distance in that direction when they press the controller’s trigger. The beam will stop if it hits an object, and has a max distance that it will project if it does not hit any object. Users can adjust this distance by moving their finger up or down on the controller’s touch sensitive pad. This allows users to teleport into any space (within the environment’s boundaries) even if it is not adjacent to a solid surface. The navigation techniques used in this work all prioritize allowing users to move anywhere in the environment and view it from any angle.

3.2 Waypoint Navigation

Countless improvements have been proposed to improve immersive locomotion techniques in some respects, yet solutions remain imperfect. Our waypoint-based navigation system is based on work by Habgood et al. [11], but is modified from their design to allow free movement between user-defined waypoints instead of limited movement between predefined locations.

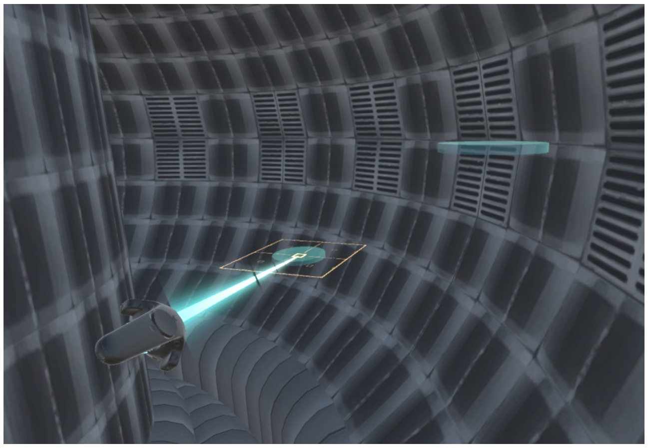

Figure 2: Waypoint-Based Navigation allows the user to create waypoints (or nodes) with a single button press, and allows easier movement between waypoints with snap-aiming.

3.2.1 Waypoints. The current implementation of waypoint navigation allows users to move quickly to specific marked locations in the environment which can be either predefined or user-defined during runtime. While this functionality is partly inspired by Habgood et al. [11], our system differs in that we allow users to create their own network of waypoints, instead of only allowing a pre-defined set of nodes to act as waypoints. As they travel around the environment, a user may look back to see where they have been and instead of seeing nothing they will see a node, or waypoint, indicating their last position. This provides reference to the user of relative position in the environment, which in turn allows the user to spend less time having to think about where they are, and more on what is around them.

3.2.2 Sigmoidal Continuous Movement. A major difference between a typical basic virtual reality teleporter and our design is that the user is translated continuously toward the destination over the course of a fraction of a second. This may seem counterintuitive, as common belief would indicate any form of uncontrolled continuous movement in an IVE is likely to cause increased effects of VR sickness, but this is not the case as indicated by recent research by Habgood et al. (2018) in accessible VR locomotion techniques [11]. To avoid VR sickness effects, our movement is carefully tailored to feel natural, and occur only when the user performs a specific action that would logically cause such movement. To achieve a ‘natural’ feeling, we avoid sudden or abrupt movements by using a Sigmoidal curve to accelerate the user into the transition and decelerate them out of it. The curve follows the form of:

$$position(t) = \frac{1}{1 + e^{-at+b}} \tag{1}$$

where a and b are positive constant values used to appropriately shift the domain of t. This fraction of a second spent moving towards the destination of a movement action allows users to verify that the direction they are going is the one they specified, and gives some estimation of how far away it is, as well. This is not unlike the

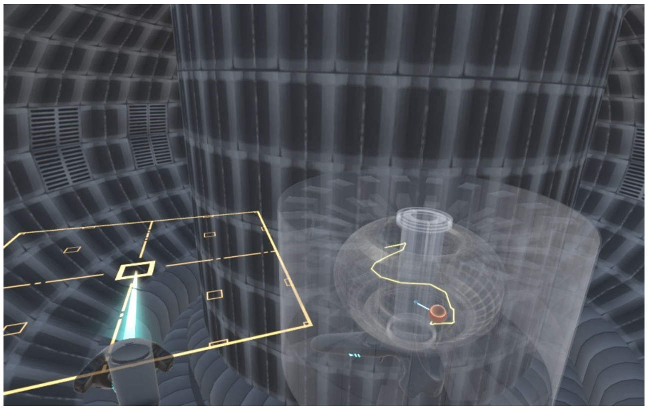

Figure 3: The 3D minimap shows the user's current position (orange sphere), their movement history (yellow polyline), and projected navigation direction (blue sphere and line) all within a transparent model of the environment.

velocity curve used by Mackinlay et al. to provide better control in virtual 3D workspaces [16], which used a logarithmic scale to allow fast movement while far from a point of interest, and slow controlled movement while near it. In our implementation, the teleportation endpoints can be considered as points of interest, while the space in between is not and can be travelled through quickly.

3.2.3 Charging. The last modification we have added is a charging mechanic. When the user aims the control and presses the button to indicate the target destination, they are required to hold the button until the beam indicating the direction becomes 'charged,' which takes approximately a quarter of a second with our implementation. A charged beam is indicated by being wider and brighter to the user, and the press-and-hold design is used to improve the user experience of navigating in two ways. First, it prevents accidental double-presses, where the user may unintentionally move twice, which is a fairly disorienting and unpleasant experience. Second, it provides time, even if only a little, for the user to consider where the navigation tool is actually pointing, as opposed to just aiming it a general direction and going there. This split second of delay provides an affordance to users, and is intended to be short enough that it does not distract or frustrate the user, but still enhance the user's memory and awareness of their position in the environment.

3.3 3D Minimap

We use a 'minimap' attached to one of the user's controllers within the IVE to display the user's relative position within the environment. Unlike a typical map, however, our minimap is not a plane but a volume. As can be seen in Figure 3, the 3D minimap is simply a partially opaque model of the entire explorable space, with a fully opaque sphere marking the user's position. The sphere leaves behind a bright trail when the user moves a significant distance in the environment, as through any navigation tool, so that the user can clearly and unambiguously see their history of movement in the environment. Additionally, a smaller sphere marks the location that the user would teleport to if they chose to do so at that moment.

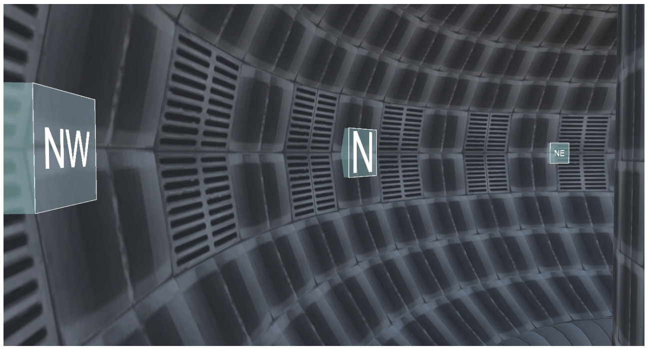

Figure 4: The otherwise radially-symmetric walls have eight markers on the cardinal and intermediate directions, referred to here as landmarks.

While the 3D minimap does move with the user, it does not rotate with them, instead it always maintains the same orientation as the environment itself. This is critical for the behavior of the minimap, since the user's ability to glean information from it is directly tied to its spatial relation to the larger version of the virtual environment. This way, for example, if the user's location is marked on the left side (relative to the user) of the minimap, then the user knows that they are also on the left side of the immersive environment.

A similar but not identical minimap concept was implemented by Usher et al. [30] for a Neuron Tracing application. While the general purpose of indicating a specific location in the environment is the same, our implementation is tailored to a user-centric view. That is, in place of information relevant to the task within the minimap's volume, we display the user's position, their indicated direction and past locations. This helps compensate for weaknesses in other aspects of the environment, such as in navigation, where users might have increased difficulty tracking their relative position during and after moving.

3.4 Landmarks

Our approach to solving the issue of user disorientation in isotropic, non-unique or non-oriented environments is to provide markers, or landmarks, that have a static absolute position (Figure 4). With these, users are able to mentally reason about the environment as being located relative to a landmark near them. Some environments based on scientific visualizations, such as medical fMRI data, have key features (body parts, bones, etc.) that could be labeled and used as landmarks [8]. Our environment, however is almost completely radially symmetric and isotropic, so there are no inherent features to use as landmarks for the user. To overcome this, we assign directions at 45° angles, i.e North, West, South, East, and their intermediate complements, starting from an arbitrary location. While using arbitrarily placed landmarks is not ideal, since they may give the user an impression of knowing something about the environment that is not actually an inherent feature of the environment, they still serve the same purpose of providing an 'anchor' for users to consider orient themselves against.

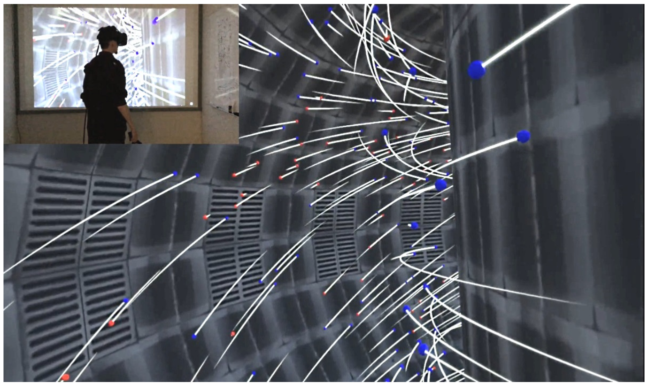

Figure 5: An image captured from a user standing inside the virtual Tokamak, with spheres (approx. 0.1m diameter) representing individual particles colored based on a useful classification: 'trapped' vs. 'passing.'

4 TOKAMAK IMMERSIVE ENVIRONMENT

Our environment consists of a 3D model of a tokamak thermonuclear fusion reactor, shown in Figure 5, that uses spheres to visualize the trajectories of a subset of particles from a simulated version of this tokamak reactor design. The trajectories can be analyzed to classify particles as either 'trapped' or 'passing,' an important distinction for experts [12]. The environment can be used to visualize several aspects of fusion data, including magnetic fields and particle trajectories [26, 27].This IVE shares a number of features in common with immersive scientific visualizations of 3D time-variant data. Namely, the environment is difficult to modify without obscuring or changing the information communicated by the visualization, and it is common to become disoriented or lost in the environment.

This IVE was designed with scientific data analysis performed by particle physics experts in mind [26]. However, this work does not focus on the real-world scientific applications of the IVE, but instead uses it as a basis for investigating spatial orientation in a more general sense. The tokamak IVE serves as an interesting application that presents several challenges to traditional spatial orientation techniques. Navigation in IVEs, for instance, now also has to allow vertical movement instead of just movement on one surface. As mentioned before, the tokamak has perfect radial symmetry, making it impossible to tell one section from another without an extra cue provided by the application. The toroidal shape also means that a large portion of the environment is occluded by the inner boundary, restricting the amount of information visible from any location in the environment. Each of our implemented techniques for improving spatial awareness attempts to directly or indirectly solve one or more of these issues. For instance, the continuous movement of Waypoint Navigation is intended to help users maintain orientation while translating with three degrees of freedom. Landmarks are intended to break up the symmetry of the otherwise plain environment, and the 3D Minimap renders walls with transparency in an attempt to circumvent the occlusion problem.

5 USER STUDY

Our goal with this work is to investigate the impacts of and compare several common VR navigation and presence techniques in immersive scientific visualization environments. To this end, we performed a user study with 21 participants, each given two tasks to perform with each of the various implemented spatial orientation improvement techniques within the Tokamak environment.

5.1 Experiment Design

Our study is designed as a within-subjects experiment, with each user completing two tasks within each of the four environment conditions:

C1: Default Environment
C2: Landmarks
C3: 3D Minimap
C4: Waypoint Navigation

For each environment condition, participants complete two tasks and answer several questions concerning the difficulty of the tasks and relative user experience. Every environment uses the same base tokamak model. Moreover, every environment *except* C4 uses an instant teleportation implementation.

5.2 Tasks

We used two tasks in the study:

T1: Reach a destination. Participants are placed at a predetermined location in the environment and instructed to move as close to exactly 180° around the center of the toroidal environment as possible, maintaining nearly the same distance from the center of the environment as well as the same height.
T2: Tour the dataset. Participants are placed in the environment with eight static particles and given unlimited time to interact with each particle once by touching it with one of the controllers.

For T1, we record the distance between the participant's final location and the destination. The participant is not shown any indication of where the destination is; they are required to complete the task using only their knowledge of the starting location and visual cues in the environment. For T2, we record the time required for the participant to interact with each particle. When the participant interacts with a particle in T2, it becomes highlighted for one second before returning to normal, with no indication to the participant that it has been previously activated. Additionally, we record the route each participant takes for both tasks, including total number of movements and distance of each movement. Time to completion for both tasks is measured from when the environment begins rendering to when the user announces that they have completed the task to the best of their ability.

After completing the experiment, the participant is asked several questions pertaining to the relative difficulty and confidence of each permutation of task and environment condition. Each participant is also asked to comment freely and compare the various implemented environment conditions.

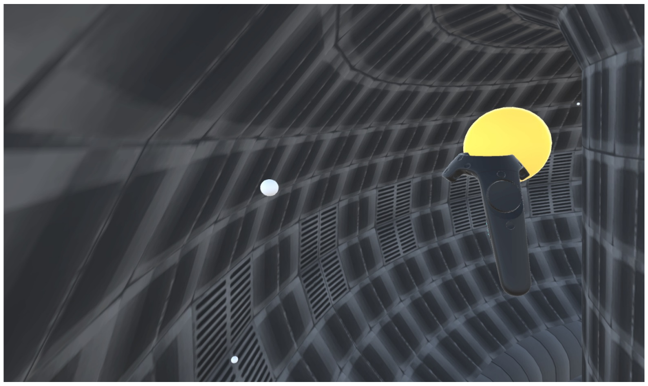

Figure 6: For the purposes of this study, particle spheres are rendered yellow while being touched by a controller, and white otherwise. This color change signifies an interaction that can be related to a real application, such as getting detailed information about the particle or classifying it.

5.3 Participants

We recruited 21 participants (17 male and 4 female) for our user study. The mean age of participants was 26.95 ($SD = 4.92$), ranging from 21 to 39 years. Fourteen (66.67%) participants had used a head-mounted display (HMD) before the study, and every participant was familiar with the concept of VR and had some notion of the current state of VR technology. Twelve (57.14%) had interacted with scientific simulation data in the past, while four (19.04%) said they knew nothing about such data and had no experience with it.

Eight participants have normal vision, or corrected vision without glasses (i.e. contact lenses). Thirteen participants wore glasses. While twelve of them used the HMD with glasses, one did not. This participant was only nearsighted, for which we compensated by adjusting the focal distance of the HMD.

Each participant completed the study in about 45 minutes, including HMD adjustment, training, the experiment, and questionnaires.

5.4 Implementation

Participants used the HTC Vive HMD, and were instructed to stand in the middle of the room-scale environment at the start of each task. The HTC Vive HMD splits 2160 × 1200 px (1080 × 1200 px per eye) OLED display with a 90Hz refresh rate. The environment was rendered using a desktop computer with an Intel i7 6900K CPU and dual (SLI enabled) NVIDIA GTX 1080 graphics cards. The environment was consistently rendered at 90 frames per second.

The tracked physical space measures 3.0 meters by 3.1 meters. The virtual space is a toroid with an inner radius of 8.75m, an outer radius of 18.0m and a maximum internal height of 18.0m. The boundaries of the tokamak are opaque and the inner wall occludes the user's view of the opposite side of the environment from where the user is standing.

5.5 Procedure

After ensuring participants are aware of possible VR/HMD issues, such as sickness or disorientation, we adjust the HMD interpupillary distance (IPD) for each participant. Participants are allowed as much time as necessary to ensure the HMD was fit as comfortably as possible and without issue. None of the participants experienced any issue with the HMD.

5.5.1 *Training.*

Each participant receives training on how to interface with the immersive environment using the HMD and hand-held controllers. We provide a simple explanation of the environment and the dataset being visualized within. We give each participant 10-15 minutes to learn the controls necessary to complete the tasks and become familiar with the immersive environment. Additionally, each task is preceded by a sample task to prepare the participant. No results are gathered during the participant training phase of the experiment.

5.5.2 *Experiment.*

The order of tasks is constant for each participant, always progressing in order from T1 to T2 in each environment condition before moving on to the next condition. The order of conditions is counter-balanced with a Latin-square design to mitigate learning effects. T2 requires a separate particle set for each environment condition to prevent participants from learning particle locations and relying on memory instead of spatial orientation. The order of particle sets is the same for each participant, such that each particle set is counter-balanced with each environment. This accounts for any differences in difficulty between particle sets.

Participants are encouraged to take a short rest between tasks, for as long as they need. Between each task, the environment is fully reset and participants are re-oriented to the starting position and direction in the middle of the physical room-scale space.

5.6 Hypotheses

We expected the following results from our user study:

H1: For all tasks, the default condition (C1) will perform worst in terms of both completion time and correctness rate.
H2: For the navigation task (T1), the landmark condition (C2) will perform best overall.
H3: For the particle tour task (T2), the waypoint navigation condition (C4) will perform best overall.
H4: Participants will prefer the 3D minimap condition (C3) for usability.

5.7 Results

Overall, C1 performs worse than all the other conditions (C2, C3, C4) in correctness rate for both tasks, worse in completion time for T2, and never outperforms the other conditions, confirming H1. C2 did not outperform C3 in terms of correctness rate in T1, refuting H2. C4 had the highest correctness rate in T2, confirming H3. Finally, most participants prefer C3 overall, confirming H4.

5.7.1 *Task Completion Time.*

On average, T1 took 62.33s ($SD = 42.63$) and T2 took 143.15s ($SD = 51.89$) for participants to complete.

The mean completion times for T1 are shown in Fig. 7a to be 64.26s ($SD = 60.27$) for C1, 48.45s ($SD = 27.24$) for C2, 64.08s ($SD = 32.34$) for C3, and 72.52s ($SD = 42.46$) for C4. Completion time does not vary significantly with each of the four conditions ($p > 0.05$, $\varepsilon = 0.642$, ANOVA with Greenhouse-Geisser correction).

The mean completion times for T2 are shown in Fig. 7e to be 146.69s ($SD = 58.79$) for C1, 138.88s ($SD = 48.23$) for C2, 154.30s ($SD = 53.95$) for C3, and 132.74s ($SD = 46.96$) for C4. A repeated

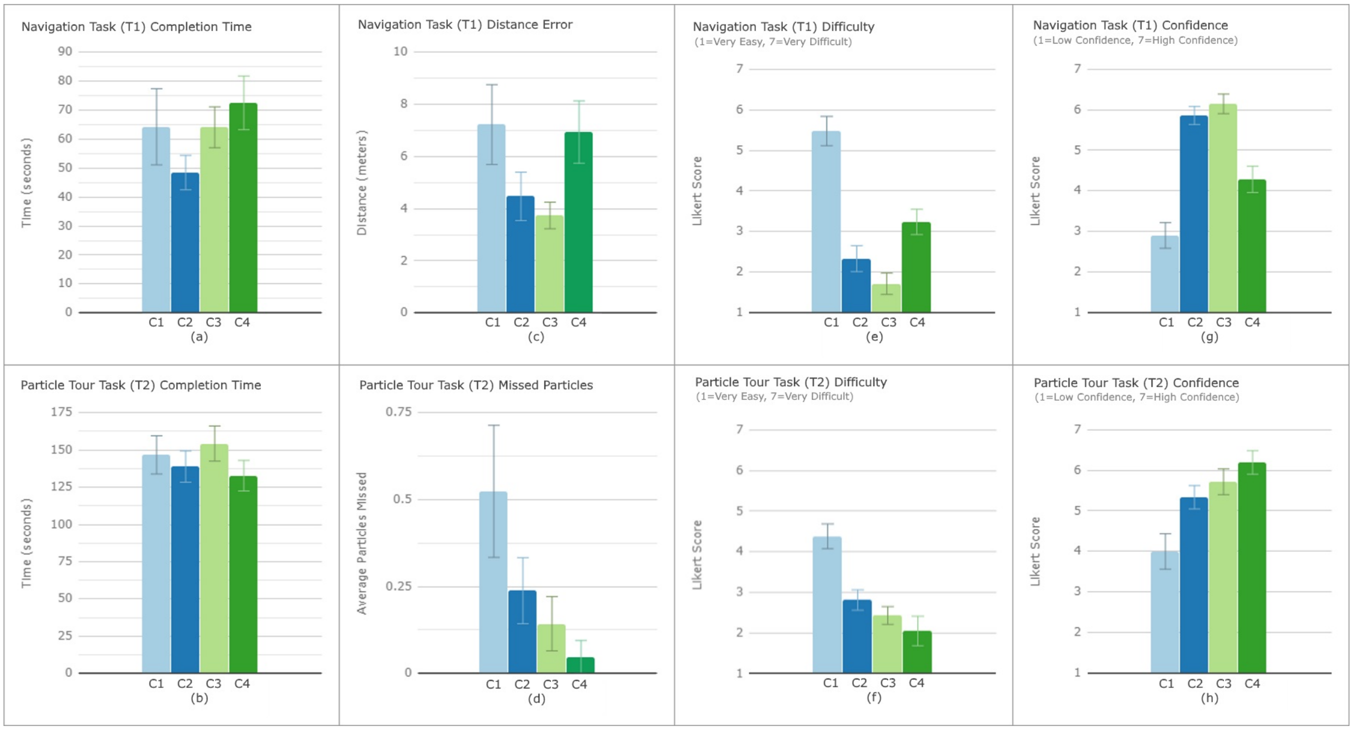

Figure 7: Results of the experiment. (a) through (d) show T1 results, including task completion time, user error (measured by distance from correct position), user rated difficulty and user rated confidence, respectively. (e) through (h) show the same details for T2, where user error is instead measured by number of missed particles.

measures ANOVA shows a significant effect of environment condition on task completion time ($F_{3,60} = 4.42, p < 0.01$). Post-hoc t-tests using Bonferroni correction indicate that C4 is significantly faster than both C1 ($p < 0.05$) and C3 ($p < 0.01$), and C2 is significantly faster than C3 ($p < 0.05$).

5.7.2 *Correctness Rate.* On average, participants were off-target in T1 by 5.59m ($SD = 5.21$), and missed 0.24 particles ($SD = 0.55$) in T2.

The mean distance-from-target for T1 is shown in Fig. 7b to be 7.22m ($SD = 7.02$) for C1, 4.47m ($SD = 4.26$) for C2, 3.74m ($SD = 2.33$) for C3, and 6.94m ($SD = 5.48$) for C4. A repeated measures ANOVA with Greenhouse-Geisser correction ($\varepsilon = 0.550$) shows a significant effect of environment condition on correctness in T1 ($F_{3,60} = 3.88, p < 0.05$). Post-hoc t-tests using Bonferroni correction indicate that C2 is better than C1 ($p < 0.05$) and C4 ($p < 0.05$), C3 is better than C1 ($p < 0.05$) and C4 ($p < 0.01$).

The mean number of missed particles is shown in Fig. 7f to be 0.524 ($SD = 0.873$) in C1, 0.238 ($SD = 0.436$) in C2, 0.143 ($SD = 0.359$) in C3, and 0.048 ($SD = 0.218$) in C4. A repeated measures ANOVA with Greenhouse-Geisser correction ($\varepsilon = 0.504$) shows a significant effect of environment condition on correctness rate in T2 ($F_{3,60} = 3.86, p < 0.05$). Post-hoc t-tests using Bonferroni correction indicate that C4 had significantly fewer missed particles than C1 ($p < 0.05$).

5.7.3 *User Feedback.* Participants were surveyed after the trials to gather feedback concerning the relative difficulty and confidence of each task and each environment condition, using Likert scales ranging from 1-7. For the first question, 1 means that the task is very easy, and 7 means that the task is very hard. For the second question, 1 means that the participant have little to no confidence in their performance, while 7 means that they have extreme confidence. With a total of four questions (2 tasks × 2 subjects), we used Friedman tests (non-parametric alternative to one-way repeated measures ANOVA) to individually establish that the environment conditions had a significant effect on participants' responses ($p < 0.0001$ for all four tests). Our post-hoc analysis consists of pairwise Wilcoxon Signed-Rank tests with Bonferroni correction for each question, the major findings of which are shown below.

We found that for both tasks, users found the task to be most difficult with C1 relative to the other conditions ($p_{c2} < 0.001, p_{c3} < 0.001, p_{c4} < 0.01$), as portrayed in Fig. 7c and 7g for T1 and T2, respectively. Additionally, C3 is easier than C4 ($p < 0.05$), but only significantly easier for T1.

Similarly, for both tasks (Fig. 7d and 7h), users were least confident in their performance in C1 relative to the other conditions ($p_{c2} < 0.05, p_{c3} < 0.05, p_{c4} < 0.05$). Moreover, for T1 only, users had little confidence in their performance in C4 compared to both C2 ($p < 0.01$) and C3 ($p < 0.05$).

Users also answered several qualitative questions concerning each environment condition in general. In response to being asked which environment was most preferable and why, none of the participants answered with C1, while 76.2% of participants answered with C3, with a variety of comments listed below in order of prevalence:

- "The ability to see the overall structure is helpful."
- "The path history helped me remember."
- "The minimap is most convenient because it is attached to the controller."

Fewer participants (14.3%) answered with C4 and fewer still (9.5%) with C2, for reasons such as:

- "The continuous movement (with C4) was much less disorienting than the normal teleportation."
- "I can choose what locations to mark with waypoints."
- "The landmarks are easier to see and remember than waypoints."
- "The landmarks are more accurate and quicker to interpret than the minimap."

Participants also had criticism for each of the techniques, mainly:

- "The lack of history information with landmarks makes it less effective."
- "The waypoints don't help when something is in the way, blocking the view."
- "The waypoints can be inconvenient to place, it is sometimes too much to do or keep track of."
- "The minimap can get cluttered after awhile because the history never goes away."

Five participants also mentioned that their ideal interface would employ several of the implemented environment conditions, either C3 with C2, C3 with C4, or all three. Many of the participants also expressed a sense of enjoyment and fascination when first using the 3D minimap. At no point did any participants mention experiencing any form of VR-induced nausea, dizziness or discomfort beyond perspiration from extended HMD use.

6 DISCUSSION

The results of the user study consistently indicate that the three implemented techniques (C2, C3, C4) are better than the unchanged environment (C1) for both tasks. For the navigation task (T1) specifically, the 3D minimap (C3) is significantly more accurate with better user experience and confidence than the other techniques. Landmarks, despite getting fairly lackluster feedback from users, performs nearly as well in terms of accuracy, but is less useful for the particle tour task (T2). When it comes to T2, however, it is waypoint navigation (C4) that shines above the rest in both *task completion time* and *correctness rate*.

The two tasks favored different conditions for both *task completion time* and *correctness rate*, which highlights the impact of occlusion in the environment. The inability of users to see and move through the middle of the environment, due to the nature of the tasks, affects T1 more than T2. The navigation task is an abosulute navigation task that uses the immutable environment itself as a reference. The particle tour task, on the other hand, is a dynamic navigation exercise, requiring users to orient themselves relative to mutable objects (particles) in the environment. During the navigation task, users were unable to see where they had started once they were near the correct location, and were thus limited in how much they could improve their accuracy, as shown by the inferiority of the default condition (C1) and waypoint navigation (C4) in the navigation task (T1). Waypoint navigation did, however, provide the shortest *task completion time* and highest *correctness rate* in the particle tour task (T2). The high *correctness rate* can be attributed to the strategy that 19 (90.5%) participants used, where they would leave a waypoint at each particle to indicate that they had interacted with it. Thus, most users were able to identify quickly which particle they missed if they made it around the environment without interacting with all eight, and were more confident that they had completed the task correctly. In essence, the dynamic and flexible nature of the waypoints was very efficient for the dynamic task. The active interaction of placing a waypoint with the control may also improve spatial memory compared to the passive interactions of the other techniques.

The lack of significant improvement in accuracy for the navigation task (T1) with the waypoint navigation (C4) reveals two important findings. First, the concept of waypoints is highly subject to occlusion, and thus does not help users orient themselves when the environment contains significant opaque boundaries. As a consequence, some users pointed out that placing waypoints becomes "a waste of time." Second, the continuous movement and charging features of waypoint navigation were not sufficient to improve spatial orientation with any significance. Users did, however, prefer continuous over instantaneous movement because it felt more natural. Due to their compatible nature, we believe waypoint navigation can be integrated with the 3D minimap to provide the best aspects of each, and the investigation and refinement of this combined technique is a likely next step in the progression of this direction of research. For instance, the ability to place waypoints and have them appear in both the virtual environment and the minimap representation could be a powerful combination. Additionally, it would reduce the need for the path history trail in the minimap which occaisonally became too cluttered to read effectively. And it would also give users the sigmoidal continuous movement that feels less unnatural and disorienting.

The landmarks (C2) performed sufficiently to improve spatial orientation above the baseline (C1); however, C2 did not perform as well in either task in terms of *correctness rate*. Landmarks are a simple solution that require little effort to implement, and little effort on the part of users to use them in navigation. Their lack of additional function compared to the other two conditions, particularly the concept of a navigation history, means that they are less effective overall for improving spatial orientation. We suspect the generally passive nature of landmarks also contributes to users not gaining as much from them. Moreover, using artificial landmarks borders on acceptability for our IVE and other immersive scientific visualization environments. This is due to the possibility of creating false association between arbitrary positions in the environment and meaningful data analysis. Users could mistakenly modify their analysis due to a perceived correlation between a landmark and the data when none exists. For example, the North marker in the environment has no meaning, but it does draw the attention of users, which may cause them to coincidentally pay more attention to data near the landmark compared to data that is not near a landmark. Proximity to a landmark, however, is not an important data feature.

Such an illusory correlation would be a negative impact that far outweighs the spatial orientation benefits of using artificial landmarks in IVEs of this class. This makes landmarks the only technique (of the three investigated in this study) that has the potential to be more detrimental than beneficial.

Despite slowing users down to some degree, the 3D minimap (C3) provided users with a better overall sense of their position in then environment, which in turn had a strong effect on spatial awareness as reflected in the improved *correctness rate* in both tasks. Additionally, the majority of users preferred C3 overall and users that suggested combining multiple techniques always included C3, indicating that it is the most robust technique. It was interesting to observe how differently users interacted with the 3D minimap, with some manipulated it to view every angle and line up the perfect trajectory for the navigation task, while others glanced at it only occasionally to glean quick spatial information with minimal effort. The flexibility in its usage appears to be a major factor in the technique's success across a diverse set of users and navigation strategies. For this reason in addition to the significant performance increase, we think the minimap has the widest applicability for immersive scientific visualization and data analysis. In fact, the minimap does not rely on any assumptions about the environment beyond that the objects in the environment can be represented in a transparent material. Thus, it should be transferable to most IVEs, even those that are not closed systems such as the tokamak model.

7 CONCLUSION AND FUTURE WORK

While minimaps, navigation techniques and artificial landmarks have all been implemented and proven effective in the past, this work is the first to compare them in an immersive scientific visualization virtual environment. The results of the user study show that continuous movement combined with the ability to actively mark locations in the environment (i.e. waypoint navigation) has the highest potential but also a greater weakness to complexity in the structure of the environment. The 3D minimap performs similarly but without the drawback of being stymied by walls, making it more robust for a wider variety of environments, and a better candidate overall for improving spatial orientation. Artificial landmarks, while still significantly better than nothing, are the least effective of the implemented techniques. Additionally, landmarks should be as meaningful as possible, and not positioned or referenced arbitrarily due to its potential to confound data analysis in IVEs.

Our work evaluates only a limited selection of techniques in a specific use-case, but illuminates a key concept of spatial awareness in general. That is, navigation history (a core component of the 3D minimap and waypoint navigation) has a significant positive impact on users' ability to know their position in an immersive virtual environment. Also, different types of navigation requirements, described in this work as 'absolute' and 'dynamic,' should be considered when choosing how to address spatial orientation in virtual environments. Dynamic tasks and environments call for dynamic improvements, such as waypoint navigation, while absolute tasks are better suited to the static displays of the minimap and landmarks.

The next steps to expand the scope of this work can follow several different directions from here. One is to refine and improve upon these techniques with the insights from this evaluation, to further reduce the prevalence of disorientation in IVEs. Another direction is to design and implement techniques in a larger variety of environments to expand the significance of this work to more general solutions. Additionally, with respect to the application context of non-unique environments, it may be interesting to see how some of these techniques can improve navigation in real-world environments with augmented reality technologies. Consider the example of providing visitors at a large airport with AR glasses that could show them a WIM of the entire facility. We hope our findings will encourage others to test more improvements for scientific visualization in virtual reality to continue pushing it toward the forefront of modern visualization technology, providing scientists with better tools for analyzing and interacting with complex multi-dimensional data.

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REFERENCES

[1] Bernard Bigot. 2017. ITER: A unique international collaboration to harness the power of the stars. *Comptes Rendus Physique* 18, 7-8 (2017), 367–371.

[2] Doug A Bowman, David Koller, and Larry F Hodges. 1997. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Virtual Reality (VR 1997)*. IEEE, 45–52.

[3] Doug A Bowman, David Koller, and Larry F Hodges. 1998. A methodology for the evaluation of travel techniques for immersive virtual environments. *IEEE Virtual reality (VR)* 3, 2 (1998), 120–131.

[4] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point & Teleport Locomotion Technique for Virtual Reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '16)*. ACM, 205–216.

[5] Steve Bryson. 1996. Virtual Reality in Scientific Visualization. *Commun. ACM* 39, 5 (1996), 62–71.

[6] Sue VG Cobb, Sarah Nichols, Amanda Ramsey, and John R Wilson. 1999. Virtual reality-induced symptoms and effects (VRISE). *Presence: Teleoperators & Virtual Environments* 8, 2 (1999), 169–186.

[7] Dane Coffey, Nicholas Malbraaten, Trung Bao Le, Iman Borazjani, Fotis Sotiropoulos, Arthur G Erdman, and Daniel F Keefe. 2012. Interactive Slice WIM: Navigating and Interrogating Volume Data Sets Using a Multisurface, Multitouch VR Interface. *IEEE Transactions on Visualization and Computer Graphics (TVCG)* 18, 10 (2012), 1614–1626.

[8] Michael de Ridder, Younhyun Jung, Robin Huang, Jinman Kim, and David Dagan Feng. 2015. Exploration of virtual and augmented reality for visual analytics and 3d volume rendering of functional magnetic resonance imaging (fMRI) data. In *Big Data Visual Analytics (BDVA 2015)*. IEEE, 1–8.

[9] EUROfusion. 2011. JET Tokamak. https://www.euro-fusion.org/news/detail/the-virtual-vessel-with-plasma/. (2011). Accessed: 2018-06-30.

[10] BoYu Gao, HyungSeok Kim, Byungmoon Kim, and Jee-In Kim. 2018. Artificial Landmarks to Facilitate Spatial Learning and Recalling for Curved Visual Wall Layout in Virtual Reality. In *International Conference on Big Data and Smart Computing (BigComp 2018)*. IEEE, 475–482.

[11] Jacob Habgood, David Moore, David Wilson, and Sergio Alapont. 2018. Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique. *IEEE Virtual Reality (VR)* (2018).

[12] Robert Hager and CS Chang. 2016. Gyrokinetic neoclassical study of the bootstrap current in the tokamak edge pedestal with fully non-linear Coulomb collisions. *Physics of Plasmas* 23, 4 (2016), 042503.

[13] Regis Kopper, Tao Ni, Doug A Bowman, and Marcio Pinho. 2006. Design and evaluation of navigation techniques for multiscale virtual environments. In *Virtual Reality (VR 2006)*. IEEE, 175–182.

[14] Yinggang Li, Chi-Wing Fu, and Andrew Hanson. 2006. Scalable WIM: Effective exploration in large-scale astrophysical environments. *IEEE Transactions on Visualization and Computer Graphics (TVCG)* 12, 5 (2006), 1005–1012.

[15] Hai-Ning Liang, Feiyu Lu, Yuwei Shi, Vijayakumar Nanjappan, and Konstantinos Papangelis. 2018. Evaluating the effects of collaboration and competition in navigation tasks and spatial knowledge acquisition within virtual reality environments. *Future Generation Computer Systems* (2018).

[16] Jock D Mackinlay, Stuart K Card, and George G. Robertson. 1990. Rapid Controlled Movement Through a Virtual 3D Workspace. *SIGGRAPH Comput. Graph.* 24, 4 (1990), 171–176.

[17] Katerina Mania, Shahrul Badariah, Matthew Coxon, and Phil Watten. 2010. Cognitive transfer of spatial awareness states from immersive virtual environments to reality. *ACM Transactions on Applied Perception (TAP)* 7, 2 (2010), 9.

[18] Michael E McCauley and Thomas J Sharkey. 1992. Cybersickness: Perception of self-motion in virtual environments. *Presence: Teleoperators & Virtual Environments* 1, 3 (1992), 311–318.

[19] Thinh Nguyen-Vo, Bernhard E Riecke, and Wolfgang Stuerzlinger. 2018. Simulated Reference Frame: A Cost-Effective Solution to Improve Spatial Orientation in VR. *IEEE Virtual Reality (VR)* (2018).

[20] Iulian Radu, Erica Southgate, Francisco Ortega, and Shamus Smith. 2017. Summary: 2017 IEEE virtual reality second workshop on K-12 embodied learning through Virtual & Augmented Reality (KELVAR). In *Virtual Reality Workshop on K-12 Embodied Learning through Virtual & Augmented Reality (KELVAR 2017)*. IEEE, 1–2.

[21] Eric D Ragan, Siroberto Scerbo, Felipe Bacim, and Doug A Bowman. 2017. Amplified head rotation in virtual reality and the effects on 3d search, training transfer, and spatial orientation. *IEEE transactions on visualization and computer graphics (TVCG)* 23, 8 (2017), 1880–1895.

[22] Sharif Razzaque, Zachariah Kohn, and Mary C Whitton. 2001. Redirected walking. In *Proceedings of EUROGRAPHICS (short presentation)*, Vol. 9. 105–106.

[23] Paul-Henri Rebut. 2017. The Joint European Torus (JET). *The European Physical Journal H* (2017), 1–39.

[24] Bernhard E Riecke, Douglas W Cunningham, and Heinrich H Bülthoff. 2007. Spatial updating in virtual reality: the sufficiency of visual information. *Psychological research* 71, 3 (2007), 298–313.

[25] Bhuvaneswari Sarupuri, Simon Hoermann, Frank Steinicke, and Robert W Lindeman. 2017. Triggerwalking: a biomechanically-inspired locomotion user interface for efficient realistic virtual walking. In *Proceedings of the 5th Symposium on Spatial User Interaction*. ACM, 138–147.

[26] Franz Sauer, Yubo Zhang, Weixing Wang, Stéphane Ethier, and Kwan-Liu Ma. 2016. Visualization Techniques for Studying Large-Scale Flow Fields from Fusion Simulations. *Computing in Science Engineering* 18, 2 (2016), 68–77.

[27] G Schussman, Kwan-Liu Ma, D Schissel, and T Evans. 2000. Visualizing DIII-D Tokamak magnetic field lines. In *Proceedings Visualization 2000. VIS 2000 (Cat. No.00CH37145)*. 501–504.

[28] Richard Stoakley, Matthew J. Conway, and Randy Pausch. 1995. Virtual Reality on a WIM: Interactive Worlds in Miniature. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '95)*. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 265–272.

[29] Evan A Suma, David M Krum, Samantha Finkelstein, and Mark Bolas. 2011. Effects of Redirection on Spatial Orientation in Real and Virtual environments. In *Symposium on 3D User Interfaces (3DUI 2011)*. IEEE, 35–38.

[30] Will Usher, Pavol Klacansky, Frederick Federer, Peer-Timo Bremer, Aaron Knoll, Jeff Yarch, Alessandra Angelucci, and Valerio Pascucci. 2018. A virtual reality visualization tool for neuron tracing. *IEEE transactions on visualization and computer graphics* 24, 1 (2018), 994–1003.

[31] Dimitar Valkov and Steffen Flagge. 2017. Smooth immersion: the benefits of making the transition to virtual environments a continuous process. In *Proceedings of the 5th Symposium on Spatial User Interaction*. ACM, 12–19.

[32] Andries Van Dam, Andrew S Forsberg, David H Laidlaw, Joseph J LaViola, and Rosemary M Simpson. 2000. Immersive VR for scientific visualization: A progress report. *IEEE Computer Graphics and Applications* 20, 6 (2000), 26–52.

[33] Chadwick A Wingrave, Yonca Haciahmetoglu, and Doug A Bowman. 2006. Overcoming world in miniature limitations by a scaled and scrolling WIM. In *Symposium on 3D User Interfaces (3DUI 2006)*. IEEE, 11–16.

[34] Michael Zyda. 2005. From visual simulation to virtual reality to games. *Computer* 38, 9 (2005), 25–32.