Experiencing an Invisible World War I Battlefield Through Narrative-Driven Redirected Walking in Virtual Reality

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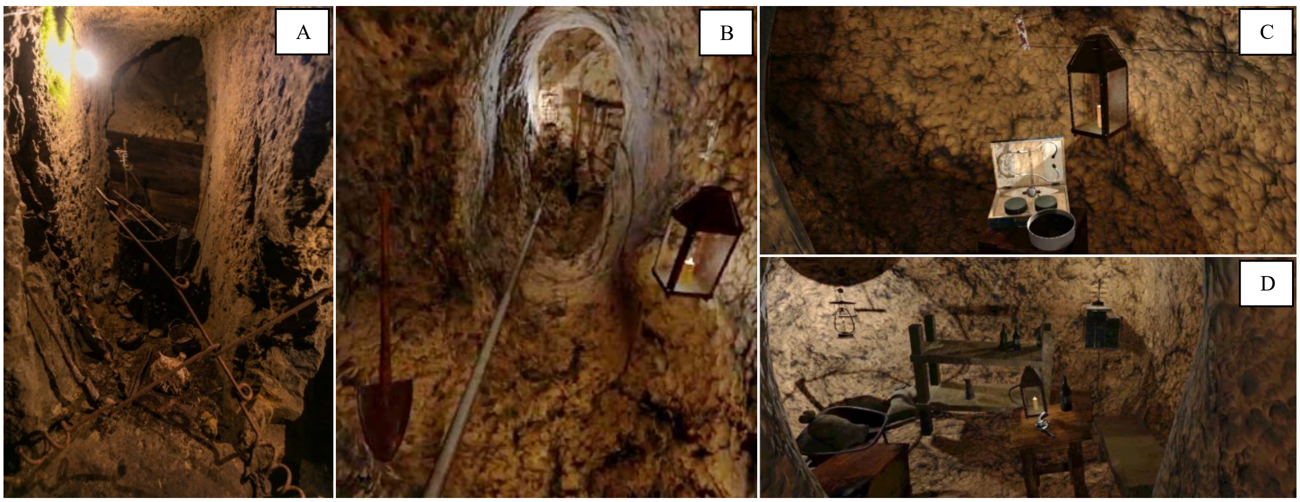

Figure 1: A. Photograph of actual Vauquois tunnel; B. VR re-creation of the tunnel; C. A corner that connected two adjacent segments of the tunnel, which served as the "redirection zone" where re-orientation was applied; D. A room in the tunnel where soldiers used to sleep

Abstract

Redirected walking techniques have the potential to provide natural locomotion while users experience large virtual environments. However, when using redirected walking in small physical workspaces, disruptive overt resets are often required. We describe the design of an educational virtual reality experience in which users physically walk through virtual tunnels representative of the World War I battle of Vauquois. Walking in only a 15- by 5-foot tracked space, users are redirected through subtle, narrative-driven resets to walk through a tunnel nearly 50 feet in length. This work contributes approaches and lessons that can be used to provide a seamless and natural virtual reality walking experience in highly constrained physical spaces.

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1 Introduction

Natural walking is an optimal way for users to experience and explore a wide variety of virtual worlds. Walking does not have to be learned or explained; it enhances the sense of presence [18]; and it improves users' spatial understanding [2, 14]. These benefits in turn may have a positive effect on learning in educational virtual environments [10]. However, most interesting virtual worlds are larger than the typical tracking workspace provided by room-scale or even more advanced virtual reality (VR) tracking systems.

To maintain the benefits of real walking within the constraints of real-world tracking workspaces, the concept of redirected walking (RDW) has been proposed and explored extensively in recent years [11, 12, 16]. Unfortunately, seamless RDW usually can be achieved only in workspaces larger than typical room-scale VR setups [4, 13]. In room-scale VR, specialized redirection algorithms with limited applicability have been proposed, such as using a strictly pre-defined path, or more disruptive and overt techniques must be used to "reset" the user's orientation so that she walks back into the workspace [7, 19, 20].

In our work, we explore the idea that resets can be embedded into the narrative of the VR experience, so that they not only allow the user to continue walking in the virtual environment but also enhance the experience itself. We present the design of an educational VR application with the goal of letting users experience some of the horrific conditions faced by soldiers in World War I. In particular, the experience puts users in a tunnel representative of the Battle of Vauquois. Our system design allows users to physically walk through a tunnel nearly 50 feet in length, but only requires an exhibition space of approximately 15×5 feet. We discuss the lessons learned from this narrative-driven redirection approach, and how it can be applied to other settings for a seamless and natural walking experience in VR.

2 Related Work

Razzaque et al. first introduced the concept of RDW [11, 12]. It reorients and/or repositions the user to confine his movement to the physical space while he is walking through a larger virtual scene. A key element of RDW is to make such manipulation unnoticeable, so that users perceive themselves as walking normally. Follow-up studies have shown that a fairly large physical space is needed to effectively hide this redirection from the user, although the exact threshold value of this size might depend on the estimation method and the specific design of the redirection algorithm [4, 7, 13]. Recently, Langbehn et al. presented an undetectable RDW technique for room-scale VR using bent paths, but the approach was limited to strictly pre-defined paths [7]. Suma et al. demonstrated that infinite walking could potentially be supported using a 6m by 6m physical space with intelligent algorithms, but more evidence is needed to validate the effectiveness of this approach [15].

Since the original RDW work, rich variations of this method have been proposed. Hodgson et al. compared different steering strategies of RDW algorithms [5]. Suma et al. proposed a taxonomy for all RDW methods based on three criteria: whether the redirection is based on reorientation or repositioning, whether the redirection is presented as subtle change or overt alteration, and whether the redirection is actuated continuously or as a discrete event [16]. Our technique resets the user's orientation at each joint of the tunnel, which fits the reorientation, subtle, and discrete categories.

Related to our approach, Williams et al. tested several straight-forward realizations of redirected walking based on resetting the user's position or orientation: When the user approached the boundaries of the physical space, the viewpoint of the virtual environment was frozen and she was explicitly asked to step back or turn around. They also presented a method called "2:1 turn," in which the user was asked to turn around by 180 degrees while the viewpoint in virtual world was rotated by 360 degrees. After one of these resetting actions, she could walk further in the virtual world while in reality she was moving back to the physical space [19]. To alleviate the disruption introduced by the brute force reset, Yu et al. proposed to incorporate these resetting actions into the virtual scene itself by applying metaphors such as "bookshelf" or "bird." In their method, a bookshelf could virtually rotate the user into another room and a bird could carry her into another section of the scene while she stood still in reality [20]. All these approaches employ overt redirection that explicitly resets the orientation or position, while our approach tries to keep the subtle reorientation unnoticeable.

Similar to our method, subtle reorientation could be applied to hide the manipulation from the user. Suma et al. proposed to alter the virtual environment by leveraging "change blindness", a phenomenon that people might fail to notice the change of virtual scene when it happens outside one's field of view [17]. This approach relied on modifying the virtual scene itself instead of just changing the position and/or orientation of the viewpoint, which might not be desirable in certain situations. Peck et al. used a visual distractor to draw the user's attention while manipulating the viewpoint's rotation [9]. Similarly, Neth et al. proposed to use virtual characters in the scene to affect the user's walking path [8]. However, the distractors or virtual characters in these techniques are added to the virtual environment and might be incompatible with the virtual world's context (thus, Suma et al. categorized visual distractor as overt redirection instead of subtle) [16]. On the other hand, Grechkin et al. emphasized that redirection techniques could be integrated into the virtual world itself, which is similar to our design goal [3]. They proposed the concept of adding a secondary target that was consistent with the narrative, in order to seamlessly manipulate the user's travel path. Our method provides a concrete example of embedding redirection into the narrative, which not only allows physical walking through the entire virtual environment, but also enhances the educational experience.

Previous research has shown successful examples of applying RDW in a domain-specific application. The "Arch-explore" system was one such example, in which redirection was applied when transitioning between rooms in an architectural walk-through experience [1]. Closer to our perspective in focusing on a historical site, the "Bema" system created a VR experience of "ancient political assemblies at the hill of the Pnyx", in which architectural modeling and crowd simulation of high fidelity were used to support experiential analysis of mass gatherings at that specific historical phase [6].

3 Recreating a World War I site in VR

3.1 The Hill of Vauquois

The rural village of Vauquois sat atop a gentle hill in rural France, 155 miles to the northeast of Paris. The village dates to the early medieval period, and prior to World War I was a small, quiet village of fewer than 200 residents. Because of its location and topography, Vauquois became an important strategic location for both the German and French armies. The hill of Vauquois provided an ideal position for the German Army to observe the French fortress-city of Verdun and control vital transportation routes in the area.

The four years of fighting from 1914 to 1918 at Vauquois represent the full spectrum of combat in World War I, from street fighting, to the development and use of trenches and underground shelters, culminating in a war conducted entirely underground through the extensive use of mining and tunnel warfare. Other sites along the Western Front saw mining used for attack, but Vauquois is unique in the extent of the mining and the fact that both armies attacked and counterattacked one another underground in one location for over three straight years. Vauquois was essentially two underground cities connected through subterranean combat.

Today, there is no hilltop village of Vauquois. What remains are two hills instead of one, with massive craters, that 100 years later are still over 60 meters deep in places. Below the surface, tens of kilometers of tunnels remain, including barracks, command posts,

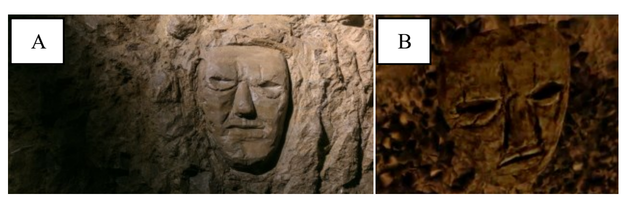

Figure 2: A. Carvings on the wall in the real Vauquois tunnel; B. The re-creation in the VR scene.

power generation rooms, attack tunnels, hospitals, chapels and more. A photo taken in one of the tunnels can be seen in Figure 1A. Today, mining tools, weapons (such as rifles, pistols, and hand grenades), heaters, ventilation equipment, rail lines, and personal items (such as bedding, tables, and eating utensils), still remain in the tunnels. Most human of the items left behind are the carvings made by the soldiers to honor friends and loved ones, or mock feared generals (Figure 2).

Visiting the site itself presents challenges in terms of not only its geographic isolation but in its challenging terrain. Visiting the underground aspects of the site is only possible for those who are not only able-bodied but also adventuresome and comfortable in dark, confined spaces. But Vauquois is a well-preserved representation of the futility of war and the deadlock that typified combat in World War I, while also offering a unique view on types of combat seldom thought of by anyone not intimately knowledgeable of World War I history. The team wanted to create a high-quality representation of Vauquois that could be experienced by anyone, anywhere.

3.2 Data Capture

The field team employed a terrestrial LIDAR (Light Detection And Ranging) unit (FARO scanner) as well as photogrammetry both above and below ground to acquire the data needed to create the virtual environment representation. Over a six-day period, we scanned three different tunnels with multiple entrances from both the German and French sides including above ground entrances and side trails. Over 381 LIDAR scans were taken. We also utilized a photogrammetry process based on thousands of photos taken with an SLR camera for difficult tunnels where the scanner could not reach because of small crawl spaces or difficult ground surfaces.

Both photogrammetry and laser scanning generate a 3D point cloud. Multiple point clouds from both techniques were combined (by matching at least three points from adjacent scans) to create a detailed and accurate structure of the tunnels and trenches. It took over four months to create the combined file, which had a size of 210 GB and over 3.5 billion points.

As part of data collection at the site, we also took hundreds of photos of items we wanted to create 3D models of in the future; including carvings, listening devices, lanterns, electrical switches, bedding, tables, and cutlery. Finally, multiple audio recordings of not only ambient sound in the tunnels, but also oral histories by local historians were collected.

3.3 3D Modeling

Knowing the project was going to be used in VR, the modeling team had to balance realism and real-time rendering requirements. We used game modeling techniques to reduce the models' size and weight. We created low-polygon geometry and placed normal, specular and diffuse maps on each object to create a realistic illusion of the space without slowing down the frame rate.

For the VR tunnel experience, we had to find a part of the actual tunnel that was relatively straight. Then we processed the point cloud data of that section into a dense mesh. The team then cleaned up the surface of this heavy mesh and retopologized it into a low-polygon structure. Using ZBrush software, we baked the dense mesh onto the low-poly mesh, creating a normal map. This produced 4K maps to use in the game engine. The scanner yielded poor RGB data for the wall surface, but we were able to use photos taken by team members to create the texture of the tunnel interiors. Using Zbrush and UV software, we were able to create a 4K texture map without seams to be used in the game engine.

We also modeled over 40 props to be used in the VR space. Many of these were hand modeled in Maya and ZBrush and textured in Photoshop. Some objects took up to 12 hours each to hand model.

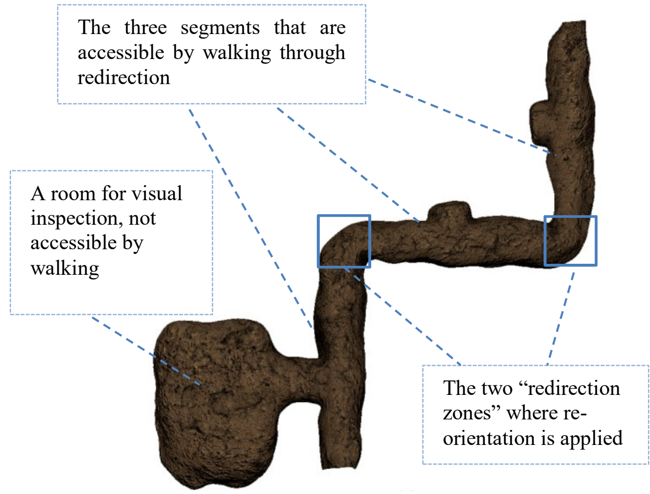

Figure 3: Overview of the virtual tunnel layout. The tunnel comprised three straight segments connected by 90-degree turns.

4 NARRATIVE-DRIVEN REDIRECTED WALKING

4.1 Experience Goals and Design Constraints

The overall goal of this VR experience was to create a convincing illusion of walking through the tunnels of Vauquois and ultimately to gain a sense of what life was like for the people who lived and fought there. The hope was to provide this feeling through as natural an experience as possible, with the narrative elements and objects telling the story, and the physical movement conveying some sense of the confining space and elaborate network of mines navigated daily by the soldiers who lived there. Educational information should, in our view, be naturally conveyed through the realistic feeling of being placed in an authentic site of history.

The experience was designed to open up opportunities to develop a sense of place and perspective regarding the day to day experiences of soldiers (and civilians) during World War I, and to

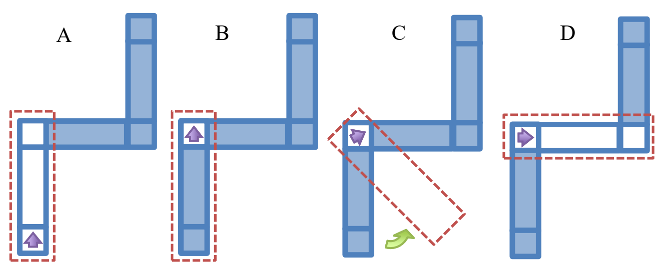

Figure 4: The reorientation process. The dotted red rectangle represents the physical space, while the shading of each tunnel region marks whether it is lighted. A. The user is facing a new segment that is lighted up and accessible by walking; B. After she enters the redirection zone, all other regions' lights are turned off, so she needs to inspect the surrounding environment and search for the light switch; C. As she turns her head, the entire virtual world is rotating around the center of redirection zone relative to the real world; D. After the redirection is done, the next segment is aligned with the physical space and lights are turned on for this new area.

provide participants, who had minimal knowledge of World War I, insights into its impact and effects on French citizens and the practice of warfare.

Our redirected walking design needed to serve these goals by meeting two requirements. First, introducing any overt disruption that might cause a break in presence was likely to be undesirable. The redirection needed to be seamlessly embedded into a continuous narrative and the virtual environment itself. Second, objects in the scene should not deviate too much from historical facts, so we had little freedom in adding metaphors that might facilitate redirection, such as vehicles or spinning bookshelves [20].

More design constraints came from the real-world setting of the exhibition. We only had a small and narrow physical space to create the entire walk-through experience (15 feet by 5 feet). The width of this real world space roughly matched the width of the tunnel itself, but the length was only enough to cover a very small segment of it. Meanwhile, we were expecting dozens of visitors to go through this demo in one day, so completion time needed to be fairly short for each individual.

4.2 Reorientation Technique

Redirected walking techniques create walkable space beyond physical constraints by manipulating the mapping between the physical and virtual worlds. In our case, we were facing a severe spatial constraint—the width of the narrow workspace, which was only around 5 feet. Since the virtual tunnel was also thin and had a similar width as the physical space, aligning one small segment of the virtual tunnel with this physical corridor was the natural choice of mapping. Following this idea, we first broke the tunnel into multiple segments, each having the same size and shape as the tracking space. This facilitated a naïve 1:1 mapping between one such segment and the physical space, so that the user could naturally walk through this part of the tunnel using real walking without any redirection.

Now it was the redirection technique's job to enable walking beyond one such segment. The goal was essentially to make the user walk back-and-forth within the tracked area while creating the illusion that he was traversing multiple segments that composed the entire tunnel. Note that this is very similar to the fire-drill task in the original RDW paper, in which the user was to walk in a zig-zag pattern through several line segments connected by waypoints in the virtual world while walking back-and-forth in the smaller physical space [12]. However, we had a more severe design constraint because of the five-foot width of the workspace—this space was so narrow that the user could easily walk out of it with one or two steps. Any mapping that misaligned the physical space with the virtual tunnel segment, even for a short period of time, would risk the user walking into the boundary. Thus, Razzaque's algorithm [5] was incompatible with our setup, as their technique redirected the user continuously and dynamically during walking. It relied on the fact that even though the user might deviate from the ideal path, the algorithm would redirect him back in the next few steps. In fact, Razzaque et, al. explicitly mentioned that they had to increase the width of the tracking area from 3m to 4m to prevent the algorithm from failing [12].

Figure 5: A. View as the user approaches the first redirection zone. The virtual tunnel continues around the corner to the right, but that next segment is dark until the reset has been completed; B. User reaching with a virtual hand to turn on the lights in the next tunnel segment.

Our solution was to separate walking from redirection: a reset event that re-oriented the user was created at each joint that connected the current and next segments. The goal was to make the user stop at this joint and physically turn back (by 180 degrees) to the tracking space while convincing him that he was about to walk further into the next segment of the virtual tunnel. After each redirection event, the next segment was required to be aligned with the physical tracking space, so the entire new segment became walkable. By repeating this walk-reset-walk pattern, the user was always prepared to enter the new segment; thus, a tunnel that was much longer than the physical workspace could be traversed by walking.

Because we intended to make this reset event subtle and unnoticeable, it was desirable to keep the rotational gain small. With this in mind, the segments of tunnel were connected with 90-degree turns rather than as a straight line (Figure 3 and 4). Using this design, only 90 degrees of added rotation was required to make the user face the next segment in the virtual tunnel (a 90-degree virtual turn) while turning back to tracking space in reality (a 180-degree physical turn), instead of 180 degrees of added rotation if the tunnel was entirely straight.

A square shaped "redirection zone" was created at each joint corner connecting two segments, as shown in Figures 3 and 4. Once the user entered this zone, the entire virtual environment needed to rotate around the center of the redirection zone. After 90 degrees of such rotation, the new segment would be aligned with the physical space, marking the completion of the reset event (Figure 4). Note that since the redirection zone was pretty small, the user was always standing roughly at the pivot point of rotation during the reset event.

The key issue now was how this extra rotation should be applied over time. To determine this function, we drew inspiration from the original RDW paper, in which the maximum of the following three components was used as the basis of rotational gain [12]:

(a) A small, fixed amount of baseline rotation that was constantly applied
(b) A component of rotation based on the user's walking speed;
(c) A rotation that was proportional to the user's angular velocity when turning her head.

Among these three, (b) was not applicable in our case, since our intention was to separate re-orientation and walking. We tested (a) and (c), both combined and individually, with lab visitors and among ourselves, and collected informal feedback. What we found was that (a) always made the re-orientation very noticeable, as most users reported that the rotational distortion became especially obvious when their heads stayed still while the world was slowly rotating. Using (c) alone, on the other hand, didn't suffer from this issue and was perceived as much less noticeable. Based on these observations, we decided to use a rotation that was applied only while the user's head was turning in the redirection zone, with a rotational speed proportional to the speed of the head's yaw rotation.

Next, we needed to determine the actual value of this turning speed. Making this rotation too fast would, obviously, make the reorientation very noticeable, while making it too slow would require too much head turning to complete one reset event. Based on empirical tests with a range of values, we found that Equation (1) provided a good balance between keeping the manipulation subtle while demanding a reasonable amount of head rotation.

$$r = 0.1 \times |y| \tag{1}$$

In this equation, r was the amount of rotation applied for reorientation during every frame update, and y was the amount of head yaw in that same frame. Note that r was always in the direction the world needed to rotate to align the next segment of the tunnel with the tracking space, while y could be in either direction. Thus, when the user turned her head in one direction, the rotation would appear to be amplified by 10%, while in the other direction the rotation would appear to be scaled down by 10%.

4.3 Embedding Reorientation into the Narrative

Two requirements needed to be fulfilled during the reset event before moving on to the next segment:

(a) Once the user has entered the redirection zone, he must not exit it before the reorientation is completed.

(b) 90 degrees of added rotation needs to be applied in order to align the next segment with the tracking space. This requires the user's head to accumulate 900 degrees of yaw according to (1).

A naïve solution to (a) would be adding barriers (e.g. walls, obstacles) in the scene to stop the user from exiting the zone. However, these barriers would need to be dynamic (e.g., the obstacle between the redirection zone and the next tunnel segment should be removed once the reset was done). Such moving barriers would not be historically accurate. We also considered adding explicit visual or auditory instructions to regulate the user's movement during the walk-reset-walk process. This was not desirable either, as it could introduce disruptions to the otherwise seamless VR experience.

To fulfill requirement (a) without breaking the environment or the flow, we decided to constrain the user's movement by manipulating the lighting—to stop the user from entering a certain region, we took advantage of people's natural impulse to not walk into a dark, unknown space by turning off all the lights in that area. Compared to the previously mentioned two solutions, turning the lights on and off was more consistent with the historical context, as the tunnels were indeed illuminated by sometimes unreliable man-made lighting systems.

The manipulation of lighting was designed in the following way: the new tunnel segment beyond the corner was initially unlit and almost completely dark, and the previous segment immediately grew dark once the user entered the corner for redirection (see Figure 4, A and B and Figure 5A). This effectively stopped the user from stepping into the unwanted areas. Only after the needed rotation had been accumulated would it be possible to light up the new area, while the previous segment would always stay dark. This naturally guided the user to walk into the lit, new segment that was by then mapped to the tracking space, as shown in Figure 4, C and D.

In order to accumulate 900 degrees of rotation (requirement b), we had to motivate the user to keep turning her head. The first solution we considered was adding an animated item that drew the user's attention, like a visual distractor [9]. Again, it was difficult to design this type of distraction without breaking the authenticity of the scene or the intended narrative.

Another way to encourage someone to turn her head was to give her something to search for, as one would have to look left and right in order to locate an object that was difficult to spot. We found this idea particularly appealing: by asking the user to search for a hidden light switch, we could integrate this motivation for head turning into the lighting mechanism mentioned above.

First, the user was verbally informed beforehand that there would be dark hallways and that she would need to find a light switch at each corner in order to continue. When she entered the redirection zone, the lights in the previous segment were turned off automatically, while the lights in the next segment would need to be turned on manually with a light switch. This switch was initially invisible, encouraging users to turn their heads repeatedly searching for it. Once the user had accrued enough added rotation, it was made visible, but was deliberately placed in a location that would be difficult to spot initially (e.g., a dark corner much lower than eye-level). In this way, the user would be less surprised to see it. Instead, she would be likely to believe that the switch had always been there and that she couldn't find it because she didn't look carefully enough in the first place. The user could then reach out with a tracked handheld controller, represented as a virtual disembodied hand, to touch the light switch and turn on the lights of the next tunnel segment (Figure 5B). In case the user couldn't find the light switch even after the redirection had been completed, the lights in the next hallway were automatically turned on after five seconds as a fail-safe solution to let the user continue with the experience.

To further help the user accumulate enough rotation naturally, two additional narrative-driven tools were implemented:

- The redirection zone was filled with artifacts of historical value as shown in Figure 1C and Figure 5A, specifically designed to encourage users to stop and look around, causing them to stay within the redirection zone and rotate their head repeatedly.
- An audio clip of narration was played to direct the user's interest to those objects, again, to encourage her to stay there and look from various angles.

Note that the light switches were not actually present in the historical site. Instead, they were tools to facilitate the redirection technique. However, the entire lighting mechanism was seamlessly embedded as part of the narrative, and it didn't break the fundamental authenticity of the virtual environment. Furthermore, the light switch task not only stopped users and encouraged them to turn their heads, but also made the VR experience more interactive. Users were not simply viewing the virtual tunnel passively; they took on a more active role in the exploration. We expected this narrative element to further increase user engagement and plausibility of the virtual environment.

4.4 Implementation

The system hardware was built around the HTC Vive head-mounted display. The Vive was used because it provided the ability to track the user in the entirety of the available 15'x5' exhibition space. Two Vive lighthouses were placed on either end of the tracking area, approximately 15' apart and 9' above the floor. Users wore an MSI VR One backpack computer which drove the simulation and connected to the Vive HMD. All cables were connected directly to the backpack, allowing the user to walk untethered through the tracking area (and potentially out of it). A docent walked next to each user to ensure they did not leave the tracking area, and to answer questions if necessary.

The virtual experience was rendered in the Unity game engine. The textured models of the tunnel and interior props were each imported into Unity separately, as well as audio files with narration and sound effects, and an equirectangular image captured outside the exit of the actual tunnel. In Unity, the assets were arranged inside the tunnel to create a scene reminiscent of what the tunnel might have looked like during active use in the war, and to facilitate narrative-driven reorientation. Reorientation was implemented in Unity scripting to control the virtual camera assets and interface with the HTC Vive system software.

At the midpoint of the first hallway, there was a connected side room approximately 6'x10' which soldiers used as a sleeping quarters (Figure 1D). In the virtual re-creation of the room, it was filled with a bunk bed, food sacks, lanterns, a gun, and several other props. It was included to give the sense that soldiers lived in the tunnels, rather than treating it as a transient space. However, the room was outside the usable tracking area. To discourage users from exploring the room and walking out of the tracking area, the virtual doorway was blocked with pipes, crates, and shovels.

Atmospheric lighting and sound effects were added to increase immersion. Virtual lights were added inside props of candles and lanterns. The lights flickered and occasionally dimmed in order to create the sense of real light sources in the tunnel. Field recordings of ambient sound recorded at Vauquois could be heard, layered with foley sounds of distant explosions and dripping water. A recording of footstep sounds on rock was played when the user's movement delta was high enough to indicate probable walking. In two areas of the tunnel, the user's presence triggered an explosion event designed to represent a mortar shell exploding directly above the tunnel, with a loud boom, shaking of the virtual camera, and a dust and rock particle effect coming from the ceiling directly above the user's perspective. Short voiceover clips were triggered as the user walked the tunnel, describing what he was seeing and how soldiers described their experience in the tunnels during the war.

5 Observations

The project was exhibited at the Institute for Creativity, Arts and Technology (ICAT) of Virginia Tech during the "ICAT Day" event in Spring 2017, in which collaborative interdisciplinary research projects were demonstrated to the public. The VR experience was a component of a larger exhibit that included a large physical diorama of Vauquois Hill upon which animation and maps of the site were projected, surrounded by a 32-foot cylindrical screen displaying 360-degree video of Vauquois along with period photographs and documents as well as photos taken during the team's field work. The VR demo ran for 2 hours and 45 minutes, and dozens of visitors experienced it.

Our observations indicated that the VR experience as a whole was very effective. Users' behavior was indicative of a strong sense of presence. For example, many users ducked their heads to avoid the low ceilings of the virtual tunnel, and they often stopped and exclaimed verbally when the simulated mortar shell exploded, dropping rock and dust. We asked several visitors about their impressions of the experience and about what they learned. Responses included:

- *I think the VR exhibit kind of gave me a better sense of what ... the underground warfare was like, how terrible and cramped and miserable that was.*
- *I thought the use of the virtual reality was really unique and really inventive and really made it a very immersive experience and made the history really come alive.*
- *I think in the history classes I have taken ... you don't really think as much about the people that were there and you don't really think about the human aspect of it, because it is not presented to you in a human way, it is presented to you as facts and figures and dates ... I loved that I walked in and I felt like I could have kept walking. I am definitely somebody who ... was very bored by history, because it was so unreachable. And so feeling like you could kinda touch it made it all the more interesting.*
- *When you are able to use technology and bring the lived experiences of soldiers into the classroom, to give it context, it makes history much more meaningful.*

As for the redirection technique, it appeared to be effective in these respects:

- The users were effectively stopped from trying to continue through the tunnel or going back to the previous region when they reached the redirection zone. They found it natural to stop and look for the light switches, and no one tried to enter the dark areas.
- Users were generally interested in the objects placed in the redirection zone along with the audio introduction of these items. Most of them were willing to spend a little extra time there inspecting the environment while looking for the light switch, which helped to accumulate enough head rotation in a reasonable amount of time.
- For those who spotted the light switch soon after enough head rotation had been accrued, the experience worked as we intended—they could interact with the light switch and naturally continue to the new regions seamlessly.
- Many expressed amazement that they could have walked so far in virtual reality when they later understood the path they had walked in physical space.

For some of the users, the experience didn't work completely as expected, which indicated the drawbacks of our approach:

- Some couldn't locate the light switch in time, and the lights in the new region were still turned on as a fail-safe measure (as mentioned in Section 4.3). This introduced some confusion, as they were expecting to manually turn on those lights. Most of these users explicitly asked whether they should keep walking to this new area even though they had not used the switch.
- The rotational distortion was not unnoticeable for all users. Specifically, some reported that they felt something strange happened in the redirection zones. Among these users, some explicitly told us that they considered that to be a system error from the instability of the equipment (e.g., tracking errors). These cases indicated that it might be necessary to improve the design of the reset event itself and/or the empirically determined function (1) in computing the rotational gain over time.

6 Conclusions and Future Work

Motivated by a large interdisciplinary history education project, we have developed a unique VR application allowing users to experience what it was like to be a soldier in the underground tunnel warfare of World War I. The unique feature of this experience is the use of subtle redirection in a very small physical workspace to enable natural walking through a lengthy virtual tunnel. We have explored how narrative cues and embedding the redirection into the story can make redirection less noticeable and actually enhance the user's experience. The design of this application contributes ideas and principles for naturally stopping the user at the boundary of the physical workspace, providing a search task consistent with the narrative that requires the user to turn her head back and forth, applying subtle rotation gains during the search task that reorient the user toward the workspace, and employing visual effects that naturally tell the user when she can start walking again. In addition, the application is an exemplar of a high-quality, multi-sensory VR experience that can enhance engagement, presence, and learning about history.

In the future, we plan to continue this work in these directions:

- Evaluation: we hope to systematically evaluate our narrative-driven redirection approaches to understand how often they are detected, how they affect users' perception of space, and how often they can be applied without becoming tedious to the user. We also hope to examine potential learning gains with our system in a deeper way.

- Improvement of the technique: We would like to explore new approaches that can either enhance the current lighting-based manipulation and/or introduce other techniques that could be embedded in the environment and narrative. For example, combining narrative-driven resets with continuous RDW techniques to enable longer walking experiences could be interesting (if the tracking area is slightly larger).
- More applications: We will explore similar methods of inserting redirection into the narratives of VR experiences set in other contexts.

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