ReflectiveSpineVR: An Immersive Spine Surgery Simulation with Interaction History Capabilities

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ABSTRACT

This paper contributes ReflectiveSpineVR, an immersive spine surgery simulation enriched with interaction history capabilities aimed to support effective learning and training. The provided interaction history features are based on a design study we conducted exploring what makes an effective interaction history representation in spatial tasks. Existing surgical simulation systems only provide a crude way to supporting repetitive practice where the simulation needs to be restarted every time. By working closely with medical collaborators and following an iterative process, we present our novel approach to enriching users with nonlinear interaction history capabilities and supporting repetitive practice including how such features were realized in our ReflectiveSpineVR prototype. We conclude the paper with the results of a preliminary evaluation of ReflectiveSpineVR, highlighting the positive feedback regarding our history representation approach and the interface benefits.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**;
• **Applied computing → Interactive learning environments**;
• **Software and its engineering → Virtual worlds training simulations**;

KEYWORDS

Immersive Simulation; Spine Surgery; Interaction History; Education

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1 INTRODUCTION

Virtual reality and immersive simulation systems have been common for supporting learning and training [31]. For the purpose of surgical education, many of the existing immersive simulation systems generally attempt to replicate the actual surgical context and focus on providing accurate implementation of the procedure (e.g., better haptic feedback or improved visualization) [21]. These systems particularly lack the flexibility to supporting repetitive practice, which is essential for developing surgical skills. In other words, the lack of flexible ways to repeat the interaction or part of it during the simulation could impact surgeons' learning and training. Therefore, there is a need to explore innovative repetitive practice capabilities that would better support medical experts while they train and learn about the complex flow of surgical procedures. Ultimately, such repetitive practice capabilities can be further enriched by the integration of intelligent tutoring approaches [30] that guide trainees and inform them of any incorrect behavior.

Many systems today provide support for interaction history by allowing users to roll back and re-try things if the interaction did not work out as expected the first time. Typically, actions are captured in a simple (linear) representation such as a list of history items allowing the user to undo/redo his or her actions, as needed. Such support for interaction history, while common, is not well explored in spatial tasks including immersive simulations. Furthermore, the design of interaction history is mostly limited to capturing linear user actions. Nonlinear history models and branching timelines (e.g., Figure 1) have the potential to preserve different user interaction trajectories over time. On one hand, most of these models are not popular because they are often abstract (e.g., [28] and [33]) , utilizing simple encoding of user actions using text [19] or static image thumbnails (e.g., [6]), and because they require dedicated screen space for their graph/tree representation. On the other hand, few nonlinear branching models are gaining more popularity [10] particularly within non-spatial tasks such as image or text editing scenarios. We think that the flexibility of such nonlinear models deserve further exploration especially within immersive spatial environments. Therefore, we focus on exploring nonlinear interaction history representations in spatial tasks and argue that having improved representations would increase users' awareness and control of their interaction history.

Many tasks are becoming more complex with spatial contexts involving (temporal) interactions that occur within physical or 3D virtual space. Examples of such tasks include walking from one location to another, exploring complex 3D data in immersive environments, designing an artifact, etc. The inherent availability of context space in such tasks affords more freedom when designing interaction, for instance, in collaborative scenarios where sharing space is common and when performing actions that require a large spatial area. Within an immersive mining simulation scenario, for example, a user may explore mining data with the goal of finding an optimal subset of the data. Therefore, the user must try different 3D interactions that filter the data. In such a context, presenting the user's interaction history with either an abstract branching structure or a poorly encoded visualization of history items, similarly to how it is commonly provided in non-spatial scenarios, would limit the user's awareness of his or her interaction history, a limitation that would leave little support for exploration, learning, and creativity. Therefore, it would be important in such immersive spatial environments to capture and present all users' interactions in a flexible way including how users navigate in space, how they manipulate objects, and any gestures/auditory/tactile input.

In this work, we first present a design study we conducted exploring what makes an effective nonlinear interaction history representation in spatial tasks, which we termed ReflectiveHUD (RH). We also propose ReflectiveSpineVR, an immersive spine surgery simulation with interaction history capabilities utilizing novel implementation of the RH representation and following the insight of our design study. Our goal is to assess how expert surgeons react and utilize the ability to control their interaction history and how such flexibility would support repetitive practice. Our prototype utilizes head-mounted display and 3D haptic interfaces and focus on the spatial scenario of back surgery and specifically the task of Pedicle Screw Insertion (PSI). Finally, we report on the preliminary results we gathered from medical experts reflecting on the potential of our prototype for supporting repetitive practice and the value of having effective interaction history features.

The contributions of this paper are as follows:

- The outcome of a design study exploring the potential benefits of using nonlinear interaction history models with insight into the different design variants towards having an effective history representation.
- ReflectiveSpineVR, an immersive 3D spine simulation prototype developed with nonlinear interaction history capabilities allowing surgeons to perform repetitive practice and improve their skills during the procedure of Pedicle Screw Insertion.
- The results of a preliminary evaluation of the developed prototype, highlighting how the participants liked our interaction history approach including reflections on how it could support future design efforts of surgery simulations.

2 RELATED WORK

There is a demand for simulation tools in medical and surgical education [9]. Surgeons not only need effective simulation tools, but they also need flexible interaction capabilities that allow them to repeatedly practice the simulated procedures as needed (e.g., [34] and [3] and [15]). In this regard, it is important to keep history of users' actions allowing them to retrace their steps. However, most prototypes fail this requirement according to Shneiderman [37]. In

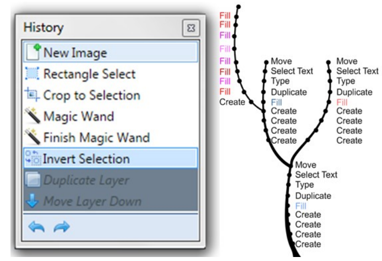

Figure 1: An example of capturing image edits in a linear history list (left), or in a nonlinear branching tree (right)

this section, we overview current surgical simulation and reflect on past work of interaction history management and visualization.

2.1 Surgical Simulation

A recent survey studied the effect of 3D simulation on neurosurgical skill acquisition highlighted that 3D simulation are useful supplement to training programs but stressed the need for improvement in surgical performance to warrant large-scale adoption of the technology [7].

Various computer simulations have been developed for medical and surgical specialties such as general surgery (e.g., [23] and [14]), vascular surgery (e.g., [1]), neurosurgery and critical care medicine (e.g., [29], [42] and [32]). Also, Von Zadow and others have explored how tabletop-based immersive simulations can be beneficial for collaborative medical learning [41]. Ekkelenkamp et al. presented a systematic review of GI endoscopy simulation for learning and training purposes [11]. The authors concluded that the use of validated virtual reality simulators particularly for training novice medical users would accelerate the learning of their skills.

Clearly, effective rendering in surgical simulations is needed. Existing research that relates to such simulation also highlighted the importance of haptic feedback [8]. For instance, needle insertion procedures highlight that having haptic feedback is a major contribution for achieving effective training systems.More recently, the use of 3D printing for supporting surgery has been examined and it has been found that it can ease the difficulty of complex spinal surgery [24]. We acknowledge the importance of haptic feedback and recognize its implementation complexity. We focus in this paper on integrating novel interface elements and interactions that better enable repetitive practice and improves the overall learning experience. In essence, we decided to focus on optimizing the interactive experience because usability and design aspects are often neglected [21].

Immersive simulation systems for training spine surgery including the PSI procedure have been researched from both commercial and academic sources [27]. For instance, Klein and others proposed a CT-based patient-specific simulation for pedicle screw insertion [20]. Alaraj and others have explored the role of virtual and augmented reality spinal simulation utilizing the commercial Immersive Touch simulator for neurosurgical training [2]. More recently, a study investigating the use of patient-specific volume rendering combined with projected fluoroscopy (X-ray) for training junior surgeons about the pedicle screw insertion procedure was conducted

[43]. The authors concluded that it is helpful to support trainees with X-ray projection that can enhance their skills. Our work extends the aforementioned research by focusing on improving usability aspects including how to design and integrate interaction history elements to support novice surgeons while training the spine surgery simulation.

2.2 Interaction History

Interaction history tools have been under research for a while, ranging from supporting basic undo/redo operations, to visualization tools that enable complex nonlinear iterative form of interactions. An excellent survey, by Heer et al. focused on the myriad history tools for supporting analysis, evaluation and communication [18]. The authors presented a design space analysis of interaction histories including the different ways of generating and capturing such interaction histories to visualizing and manipulating them. We follow Heer's design space aiming to improve nonlinear interaction history representations in spatial tasks. Our work focuses on improving nonlinear interaction history representations for spatial tasks following Heer's design space.

Logging interaction history generally requires actions or state modeling. In the first approach, user actions are modeled as commands that follow the Command design pattern [40] and can be applied or inversed as needed. The second approach utilizes application (or object) state that can be saved or restored as needed.

Logging interaction history can be organized linearly as a stack (or list) of history items or nonlinearly as branching structures including trees and graphs. For example, an image editing application may save and organize previous user actions either in a list, or in a tree structure reflecting the image edits as nodes in the tree representation. In this research, we focus on the nonlinear representations particularly within spatial contexts, which afford richness of space that have been underutilized in existing spatial contexts.

Linear history models are common for their simplicity, but oftentimes fail to preserve subsequent user actions after performing an undo. For example, if a user performed an undo operation after 10 steps and decided to return to the sixth step, the subsequent steps (from 7 to 10) are not preserved and the users loses that part of the history. In an attempt to stay away from the seemingly complex nonlinear approaches, existing research attempted to mitigate this issue through The Selective Undo technique [4], which allows users to select and undo only specific operations from the past. Indeed, this technique has been successfully explored in various applications (e.g., [25]). Another approach by Nancel and Cockburn [26] was proposed as a model to clarify possibilities for temporal interactions following the concept of causality enabling applications to combine both the linear and branching approaches. We focus on the nonlinear approach with spatial tasks and attempt to highlight its potential for improving users' awareness of their interaction history.

Most applications of the nonlinear history models are with simple, non-spatial tasks. For instance, image editing applications where a desired image effect can be achieved in different ways, and text editing scenarios that involve multiple users such as the well-known version control systems. We are only aware of one application of nonlinear history models, which is within the gaming industry. For example, Final Fantasy XIII-2 [12] featured, "Gate Matrix", a tree-like visualization that allows the player to jump between different times at the same location or different places at the same time, thus the player follows a branching path to access the different places instead of accessing them linearly. Another game, Tom Clancy's The Division, features Echoes as spatially superimposed 3D holograms of previous actions allowing the player to revisit the past while at certain locations [39]. Also, more recently an interesting research focused on enhancing immersive training by relating memory models to system and representation fidelity [22]. Our work explores people's reaction regarding what makes an effective nonlinear history representation in spatial (practical) tasks such as immersive environments.

Logged history can also be logged locally (for each individual application object) or globally (for all application objects). For instance, an image editing application that enables working with multiple images at the same time may log the user interaction history per image or across all images. The visualization of each logged history item, whether in a list or a tree structure, utilizes descriptive text, an image thumbnail, or both. A web browser may utilize descriptive text for the titles of web pages that have been recently visited [19]. Other research and systems have explored representing each history item as an image thumbnail (e.g., [17] and [6] and [**?**]). To our knowledge, most visualization of interaction history items lack proper visual encoding. While this can be sufficient for simple tasks, we argue that nonlinear representations would benefit from exploring additional visual encodings, and we attempt such exploration in our study.

3 REPRESENTING SPATIAL INTERACTION HISTORY

In this part, we detail the design study we conducted to explore how people perceive (nonlinear) interaction history representations in spatial tasks. Next, we describe how the gained insight informed the design of our prototype.

3.1 Design Study

We conducted a two-part study as a design critique focused on exploring what makes an effective nonlinear interaction history representation in spatial tasks. We explored two conditions in our study, an abstract tree visualization as our baseline condition, and the condition we termed ReflectiveHUD (RH) involving a set of enriched tree-like interaction history visualizations. We conceptualized RH using inspirations from games that explored innovative interaction history representations (e.g., [12] and [39]).

In the first part of the study, we aimed at gathering people's initial reaction to nonlinear interaction history representations. Then, we conducted the second part, utilizing some of the first part's findings, to gather a more focused feedback on the RH condition and explore design variations of the RH representation. In essence, this study aims to inform the design of the RH as a novel nonlinear history representation that captures and presents user's interaction over time. The insight of this study further informs how such history representation may be integrated in immersive simulation.

3.2 Structure

We recruited 6 student participants (1M / 5F) for the first study part and another different 6 participants (4M / 2F) for the second part, all from a local university with background in design, HCI, and visualization. We focused on recruiting participants with specific background to help us improve our ideas with their relevant design and visualization expertise.

Following a within subject design, participants we asked to perform scripted spatial tasks. Initially, the concept of interaction history was introduced through an example of undo/redo within the MS Word application. Following each task, a short interview was conducted to elicit participants' feedback about history representations and their usage in this task. After completing all tasks, a semi-structured interview was conducted to collect how participants perceived the nonlinear interaction history visualization, their feedback on the various design encodings that were explored in the RH representation, and their overall experience. Each Participant was compensated $20 (CAN) for the study session that lasted one hour.

The participants were guided by (either hand- or computer-drawn) paper sketches reflecting specific instructions for each of the study tasks. Additional sketches represented the interaction history at each step of the tasks.

Tasks: We chose simple scenarios reflecting interaction within a variety of spatial contexts. (1) finding a Santa Claus object hidden in the lab space, (2) making a flapping rabbit Origami object , and (3) building a (predesigned) Lego construct. We scripted the tasks to simplify generating content for the history representation.

In the first task, participants were asked to physically walk and search the lab space following the experimenter instructions to fulfill the task to find a Santa object in the lab. At certain (predefined) locations, participants were instructed to change their direction. and continue the searching either to the left or to the right. At each step, an interaction history representation was shown reflecting their search progress so far and the direction changes they made.

The goal of the second task is to build a flapping rabbit Origami. The scripted instructions deliberately involved wrong steps (e.g., incorrect cut, unsuitable choice of colors) and ways to resolve them, allowing participants to rewind time and have another chance to fix the problem.

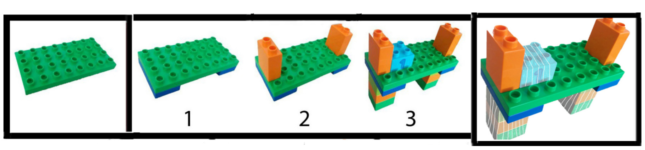

Figure 2: Sketches of the first three steps of the Lego task

In the last task, the user builds a Lego shape and refine the construction by changing his or her mind at certain interaction points. Once the participant realizes that the current progress will not lead to the desired final shape, he or she was guided to roll back and try a different arrangement.

An example of the study sketches highlighting the first three steps of the Lego task (Figure 2). It also shows the associated RH representation when the user performs an undo (reflected by hatched transparency for the Lego parts that were removed after the undo).

The sketches used in the second part of the study aimed to assess different design aspects of the ReflectiveHUD representation including transparency and layout(Figure 3).

In the first part of the study, participants performed all the three tasks. In the second part only the Origami and Lego tasks were considered and the abstract representation was omitted towards our focus on exploring different RH design aspects such as transparency, layout, and arrangement. Figure 3 show an example of design variants that were used with each task.

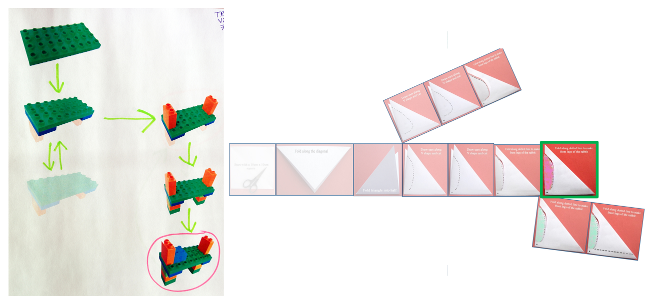

Figure 3: Examples of RH design sketches for the Lego and Origami tasks. (Left: a tree with random layout with transparency only for disregarded paths, Right: a transparency-based visualization showing the main interaction branch as always expanding horizontally to the right with disregarded branches fanning out over time)

3.3 Results & Discussion

We analyzed the gathered data to understand how participants perceived the nonlinear interaction history representations, and what are their preferences on the RH design variants we explored.

All but two participants responded with "Agree" on a 7-point Likert scale to the statement *"I found the RH representation to be usable for being aware of my interaction over time"*, with the remaining two participants responding with "Strongly Agree" to that statement.

Our content analysis of the data revolved around the following themes, which we argue are important aspects for future design efforts of interaction history representations in spatial tasks: nonlinearity, spatiality, node representation, node connectivity, and usability & usefulness.

NonLinearity: All participants found RH nonlinear history representations to be useful and preferred them to the abstract one (or the simple undo/redo). They reasoned that the nonlinear one preserves previous alternative interactions, and provides a clear idea of what have been tried before. The subjective comment from P2, for instance, highlights that, *"I like that it preserves several paths you have tried so that you can clearly switch between three or four different ways of doing the same thing, and choose one that works best". "I like the possibilities you get with the nonlinear because you can try out several different branches and continue through the one you want. I like that it preserves several paths that you have tried* *so that you can very clearly essentially switch between three or four different ways of doing the same thing, and choose the one that works best"*. Participants also mentioned other reasons for favoring the nonlinear approach as it: (1) better informs users' understanding of their interaction behavior, (2) simplifies how the interaction history is preserved, and (3) provides freedom for choosing where to jump back in time, without the need to manually trace back the interaction path by performing a sequence of undo(s).

An interesting reflection from one of the participants hinted at the potential of sharing the RH representation with others. That participant gave an example of a teacher who asks a group of students to do some task while logging their interaction history. Then, all the captured interactions are combined in a bigger nonlinear tree, allowing the differences among students' interactions to be quickly identified and all interaction trajectories that led to failure can be re-explained.

Spatiality: During the first part of this design critique, two out of six participants specifically linked the choice of the history representation to the simplicity/complexity of the task and of one's workflow. In this regard, P3 expressed that the *"Usefulness [of the RH] may not be clear for simple applications, but it is more effective for engineering and modeling"*. Along the same line, P6 expressed, *"this [RH] representation is better for navigation tasks and for being oriented in space, while the abstract graph is better for less spatial tasks like planning things"*.

Node Representation: We gathered participants' feedback on the tree nodes' representation. Only two participants reported that it might be enough to use descriptive text and no visuals especially if the task is non-visual or if the task's real estate is limited. In contrast, most participants favored a more visual history especially if the task is visual, highlighting that it is simpler to understand and act as memory triggers for recalling previous user interactions. As P5 commented, *"It is [the RH representation] illustrative of what the actions actually were as opposed to, just maybe, basic node names, so it was easier to recall what the actions were, as well as at a glance see the overall path or the different pathways you took"*. In this regard, the visual nodes are simpler to understand and act as memory triggers for recalling previous user interactions, which is aligned with the comment of P6: *"I prefer [nodes with] graphics because it more easy to follow the history, and you don't have to recreate the history in mind since it is there"*.

Beyond having a 2D image-based node representation, an animated (3D) node could be more helpful. This insight is in line with the feedback we received from most participants who highlighted the value of animation to show what has changed, especially in 3D spatial scenarios wherein just having static image thumbnails may be less expressive. In this regard, P6 stated, *"Yes, it makes sense to use 3D [nodes] because while with the images it may be easy to spot things, some 3D models can be complex and you would need to rotate to see the different part of it, which you can't do with the images"*.

Transparency can be applied to tree nodes (and branches) to simplify reading the tree and to hint at the temporality of user's actions. However, we didn't receive conclusive feedback regarding the usage of transparency. Most participants understood that making disregarded branches (or nodes) transparent reflects that they are gone and that it is not possible to interact with them anymore. Furthermore, many participants suggested applying transparency to the design of nodes with a constant value and to not dynamically fade it over time. As P2, for instance, described it, *"I like the transparency but I like it as a clue that you are not here anymore ... When I see transparency fading, i see that I cannot go back to that point any more"*. Alternatively, P3 suggested to vary the effect of time on nodes with a gray-scale rendering to avoid confusion, leaving recent nodes vivid and with older ones losing color, so it is easier to see what have been done. This effect is only about making history nodes less colorful, and not to be confused with the design that intends to make some of the user interface elements disabled by graying them out. In essence, most participants agreed that transparency could be helpful, but stressed that it should be carefully utilized (e.g., by applying it consistently to nodes as opposed to having it fade over time).

We envision flexible RH representation that adapts to immersive environments with the rich variety of sensory elements that may exist (e.g., visual, sound, tactile). We gathered participants' thoughts on whether it would be useful for the RH node representation to include logging of such additional sensory elements. While many participants found it difficult to imagine integrating additional sensory information in the node representation, almost half of them stated that it could work especially in complex simulation environments. They stressed, however, that it should be dependent on the task to avoid confusion, and that the designer should be selective or at least eliminate such information that would not be helpful. The following comment of P3 is among those who favored the idea, *"So you are basically planning to capture the whole experience ultimately ... I would say I do not see it being done any other way."*

Some participants raised a concern for nonlinear tree-like representations as they get very big while logging many actions. We argue that almost all history representations, whether linear or not, would be less usable if many user actions were logged. We believe that, in many scenarios, only subset of user's actions need to be saved as most people care about specific interaction moments or only the recent ones. In scenarios where large interaction history is logged, some techniques can be used to simplify this issue including combining certain nodes/branches, utilizing transparency, and providing search/filter capabilities.

Node Connectivity: Different rendering styles exist to connect tree nodes including explicit lines (e.g., solid, dotted) with varying thickness as well as with the option of directly attaching nodes to each other without any lines at all.

Participants' opinions on line connectivity varied. Only two found lines unnecessary as they can get in the way and that the sequence of history nodes is still clear without them. The remaining participants, however, preferred having line connectivity especially if the representation layout would change dramatically. They added that lines should be dotted, thinner, or transparent for disregarded branches and should be solid, opaque, or thicker for the active path. In this regard, P6 said, *"Lines should be dotted for the path that you skipped and strong one for the current path, because here you would have a clear visualization of where you are. And you have to have lines [between nodes]"*.

Some participants mentioned that line segments should be directed (with arrows) for clarity and to guide the layout especially if the representation does not have implicit arrangement (e.g., root's location is not fixed). Tagging nodes can also simplify the lack of implicit arrangement (e.g., with text that indicates event ordering).

Usability & Usefulness: All participants agreed on the usefulness and usability of the RH representation, especially with correct encoding. As P4 puts it, *"It is useful to see the task context during temporal interaction. With the abstract [graph], it is hard to remember what all these actions were"*. Another participant highlighted that correct visual encoding is important to the usefulness of representation (e.g., careful choice of colors, size, layout, and transparency). Interestingly, P1 mentioned surgical simulation as a scenario that could benefit from the RH representation where doctors can try actions while maintaining awareness of the things that could go wrong, ultimately to enhance their learning. Finally, intuitive interaction with the RH representation is needed for better usability. Most participants mentioned that they would prefer having flexibility when interacting with the RH representation (e.g., the ability to change its location, zoom it, or save/restore it as needed).

Preference for the ReflectiveHUD Design Variants: We report participants' feedback of the second part of the study concerning the explored RH design variants. For the Lego task, 4 out of 6 participants preferred the RH design with transparency for the disregarded nodes/branches as it gives better impression of time, and for clarity. For the RH variants used with the Origami task, 4 out of 6 participants preferred a tree-like organized structure as P4 puts it: *"Using the column/row format [of this RH design] is less cluttered. I like the more structured approach as it is clear and easier to go back in time [with it] especially if it is animated and balanced"*. The other two participants favored the other RH variant utilizing gradual transparency and a horizontal main thread, due to its utility for conserving space with its straight (horizontal) path.

Some participants also provided suggestions that are applicable to all design variants of the RH representation. For instance, P4 suggested collapsing the less important tree nodes to avoid having a gigantic tree representation over time. He or she also added that textual tags can be integrated with graphical nodes, but it does not need to be included with all nodes to help conserving real estate (e.g., the context space).

4 APPLYING REFLECTIVE-HUD IN SIMULATION

Based on the insight from our previous design study, we explored preliminary implementation of the RH representation within a spatial immersive surgical simulation prototype, which we named ReflectiveSpineVR. The developed prototype intuitively integrates interaction history capabilities that support repetitive practice aiming to contribute better training and learning (Figure 4). We argue that the RH representation can be applied to various immersive contexts beyond our surgical simulation scenario, especially those that are spatially rich and which potentially benefit from logging user actions over time.

ReflectiveSpineVR focuses on simulating the procedure of pedicle screw insertion and supports visualization of the spine and its context utilizing fully immersive rendering and 3D haptic interface capabilities. The virtual reality simulated context consists of a semi-realistic replica of the surgical operating room (OR), which was developed following consultations with our medical expert collaborators (Figure 5).

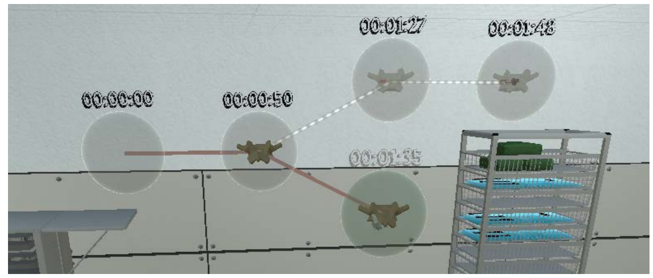

Figure 4: A view of our prototype showing the Reflective-HUD tree floating in the virtual 3D space.

4.1 Design

Prior to integrating the RH representation within ReflectiveSpineVR, we discussed the findings of the design study with our medical collaborators. We followed a participatory design approach [36] wherein the medical experts participated and agreed on how the history should be visualized. The design process was iterative and continuously guided by feedback from our medical expert collaborators.

We made various decisions when designing the RH visualization. First, and because of the spatial richness of this context, we decided to visualize the RH representation as a floating tree in the 3D simulated space allowing the user to look and interact with it as needed. The position of the root node is always fixed within the 3D virtual space, but it can be customized as needed.

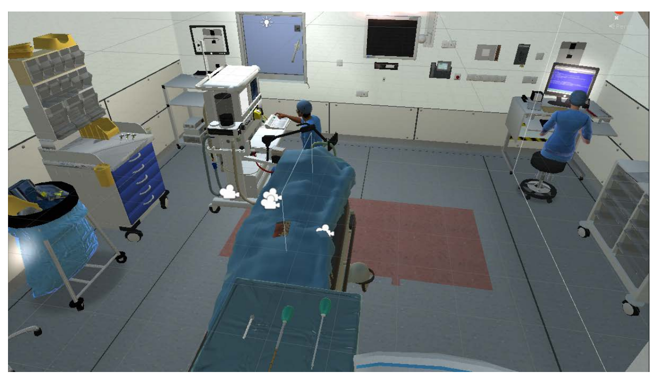

Figure 5: The immersive surgical simulation context resembling a replica of an actual operating room.

Animation was a key part of the RH representation. For instance, when a new node is added, the tree layout is animated to make room for the new node, so that the tree presentation is always balanced and optimizes the view estate. It is worth noting that this animation only affects the surrounding nodes (e.g., sibling, parent, children) of the one being added to avoid confusing the user, which might happen when the whole tree layout is manipulated.

We represented each node in the RH visualization as a semi-transparent 3D bubble. The inside of each bubble reflects a preview of the logged user action saved as a snapshot of what occurred at that moment. In our simulation, for instance, if the user interacts with a specific spine vertebra by drilling its bone, this action including the modified object will be cloned inside the transparent RH bubble (Figure 6). For clarity purposes and due to the similarity of some user actions, supplementary textual tags may be beneficial. In this regard, we render 3D text that is displayed above each tree node, which by default reflects the time of the action that occurred but it can be customized as needed (e.g., the name of each spine level). We also decided to vary the rendering of the currently selected/highlighted bubble, by making it slightly bigger than other nodes, tint it with different color, and highlight its textual tag. Finally, we decided to automatically re-orient each bubble's content to always face the camera, which would make it easier to see the 3D content inside the tree nodes. An alternative approach would be to allow the user to explicitly manipulate each bubble's content, but this idea merits itself as an interesting future work.

We decided to connect the nodes in the active path (from the root of the tree to current node) using solid lines while rendering the disregarded paths (the previously tried paths) using dotted lines. Furthermore, the active path connections were colored dark red while the inactive paths were white (Figure 4). In essence, the goal of this design is to quickly hint the user at the current temporal interaction thread and distinguish it from other (disregarded) history paths.

We utilized a haptic hand controller to enable interaction both with the virtual patient and the tree presentation. In particular, we designed a tree-interaction mode, which the user activates by a specific button on the haptic arm. In this mode, a virtual ray is displayed from the user's eye allowing the user to point at and interact with the tree nodes. The user, then, can use other buttons in the haptic controller to restore the simulation to a particular selected node.

When a user decides to jump back in time to a particular node in the RH tree, we activate a transitioning effect by blurring the camera's rendering, animating its field of view, and by presenting everything in grayscale. Also, a sound effect is employed, hinting to the user that he or she is travelling through time. It is worth noting that we have experimented with a variety of other effects before reaching a final decision for the aforementioned transitioning effect.

In essence, the design of the RH representation within our simulation prototype enable users to save their interaction progress and to jump back in time to a previously saved snapshot, effectively resetting the simulation to that moment.

4.2 Hardware and software

ReflectiveSpineVR supports 3D stereoscopic rendering as well as auditory and haptic feedback for user interaction. We used Unity3D as our prototyping environment with the Oculus Rift [13] CV1 and the Touch Stylus [38] hand controller for supporting haptic feedback. The Touch Stylus was integrated using a Unity plug-in that utilized the well-known OpenHaptics library [16].

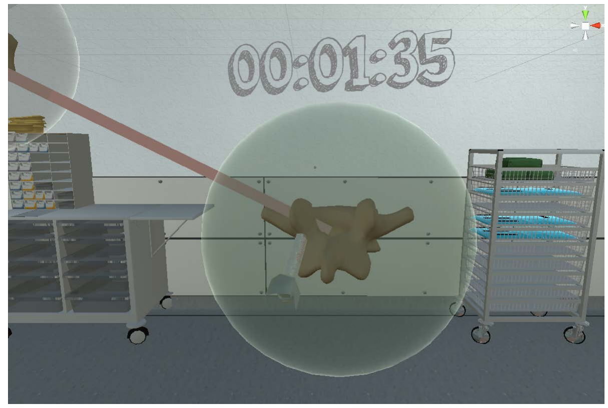

Figure 6: A ReflectiveHUD tree node tagged by action time, and shows a spine vertebrae with a screw inserted in it.

Our simulated virtual world included a semi-realistic representation of an actual surgical operating room (OR) including 3D patient model lying on a table and variety of medical devices and tools (Figure 5). During the simulation, a pulsing OR sound is continuously playing in the background as a way to increase the level of immersion. To simplify user interaction with the medical tools and the RH tree representation, we utilized the RayCasting interaction technique [5]. In this regard, we render a selection sphere guided by user's head that is only visible when the user looks at specific areas (e.g., the table that contain the surgical tools). Once the user's look direction hits an interactable object (e.g., one of the surgical tools) within the immersive environment, that objected will be rendering temporarily bigger to afford interaction (as shown in Figure 7).

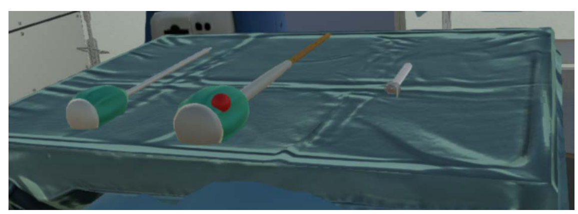

Figure 7: A surgical tool is rendered slightly bigger when the user looks at it using his or her look direction.

5 EVALUATION

We conducted a preliminary evaluation, gathering feedback on how our participants perceived the RH representation and the overall immersive experience. We hypothesized that our temporospatial RH representation would be effective for raising awareness of oneself interaction history within immersive simulation, and would support repetitive practice and the overall learning experience. Our participants experienced the simulation of a simplified surgical task augmented by our implementation of the RH representation. All the recruited medical residents and surgeons provided positive feedback about the immersive simulation and the RH representation, highlighting its potential for supporting repetitive practice and medical education especially for novice people.

5.1 Participants

We recruited 6 medical participants (5 M / 1 F) of varying expertise (junior and senior residents and surgeons) who tried the simulation and provided feedback. We acknowledge the difficulty in recruiting large number of subject matter experts who are often busy or unavailable for such studies, and highlight that we managed to recruit participants representing more than half of the existing residency program.

5.2 Study Design & Procedure

We had two pilots in addition to our study participants; one with a surgeon staff member and the other with a junior resident. The outcome of these pilots contributed to improving our simulation prototype prior to conducting our study.

At the beginning of each study session, participants were introduced to the concept of interaction history and the ability to manipulate it using Microsoft Word. Afterwards, participants received training of the simulation and its usage including how to utilize the RH history representation. Then, each participant was asked to use the immersive simulation by following a scripted PSI task.

After going through the immersive experience, each participant completed the iGroup presence questionnaire (IPQ) [35], which we choose because its definition of presence corresponds with our own; the subjective sense of being in a virtual environment. Examples of the IPQ items are: *"I felt like I was just perceiving pictures"*, *"In the computer generated world I had a sense of "being there"*, and *"I still paid attention to the real environment"*. Each of the 14 IPQ items follows a 7-point scale resulting in potential presence values between 14 (minimum) and 98 (maximum). Finally, the participants completed a short usability survey (5 questions) and a post-study interview (7 questions) after the IPQ questionnaire.

In this last part, participants rated their satisfaction with the simulator and reported their perception of the simulation's features/limitations including how realistic the visual/haptic feedback aspects were. Our participants also commented on different aspects that relate to the RH history representation including their preference of the RH approach versus the linear history model and how they perceive the value of RH for supporting repetitive learning. The duration of each study session lasted less than one hour.

The scripted task used in this study utilized the simulation environment to educate users about the task of pedicle screw insertion. Each participant was asked to imagine himself/herself as a junior/novice medical student who knows very little about the procedure of pedicle screw insertion, and that he or she is doing it for the first time. In this regard, the simulation task involved the core procedure steps (e.g., identifying a landmark, drilling a pilot hole, and inserting the screw) as well as few additional steps reflecting the unexpected threads where things could go wrong (e.g., having less optimal landmark placement, touching the nerve, or making a breach by going through the bone).

6 RESULTS & DISCUSSION

Our prototype went through multiple iterations guided by feedback from our medical collaborators. The integrated interaction history features in our prototype enable surgical trainees, especially the novice ones, to learn about and repeatedly practice the PSI task. As one of the medical participants stated, *"The ability to try a step in a vertebrae multiple times was really valuable for mastering [this skill] especially at my current novice level"* [P5]. Such a feedback reflects on the RH potential of supporting repetitive practice and skill training, enriching the overall learning experience.

In this part, we report the study results of how our participants perceived the immersive environment and their reaction to the RH visualization.

6.1 Presence

Our participants have positively experienced our immersive simulation, and this insight is supported by IPQ presence questionnaire results and the qualitative responses received. As we only had a relatively small sample size of participants, we refrain from making any statistical significance claims.

We analyzed the presence data in two ways. First, we calculated an overall score for each participant as shown in Figure 8. This result highlights that all participants felt somehow present within our immersive simulation (Mean score = 64, STD = 4.7). Second, we attempted to group the data from all participants for each of the unique IPQ items, reflecting on the testing of general and spatial presence, the experienced realism and how each participant felt involved within the immersive environment (Figure 9). While this result highlights that our participants experienced less simulation realism, we argue that it may be because they expected better haptic feedback, which was not the case in this simulation since our focus was on the interaction history capabilities.

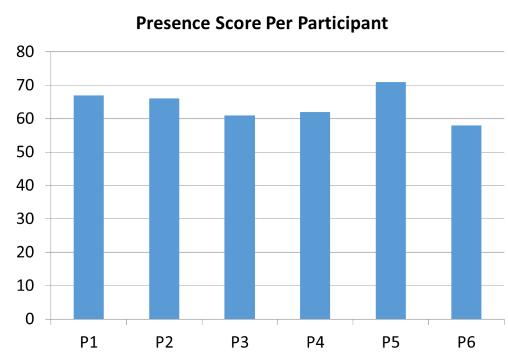

Figure 8: Presence scores per participant combining all the IPQ questionnaire items.

We received many subjective comments from almost all participants highlighting how they liked the immersive environment. For instance, P1 expressed, *"The ability to be immersed in the virtual world significantly adds to the learning experience"*. Another participant, P4, commented on how our virtual world simulated the real experience well, when he or she said: *"I like placing the fluoro [x-ray] in a place as where you can see it in the operating room when you look up, so that by having the tree next to it, kind of adding to that hub of accessory of information in front of you; it is less distracting. I do not foresee in better position"*.

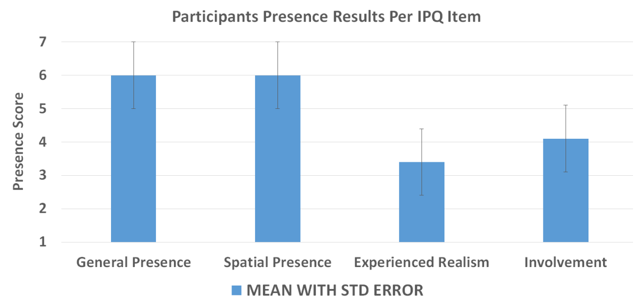

Figure 9: The Mean of IPQ Presence results grouped per category for all participants

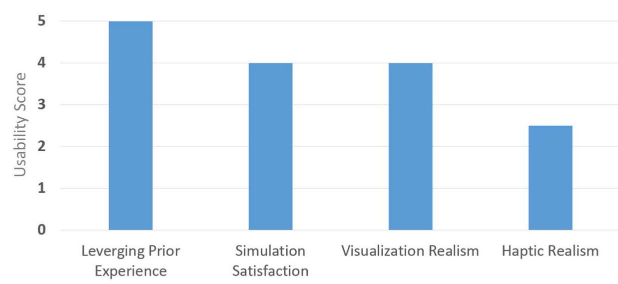

Figure 10: Participants' usability responses for our prototype (higher is better)

6.2 Simulator's Usability

All participants reported high satisfaction with our simulation, found its visualization to be quite realistic, and liked its simple interaction (Figure 10). This is supported by the received feedback. As P5 puts it, *"The interface of the system is very easy to use and is user friendly"*. Similarly, P6 expressed, *"The re-do part [of the RH] was easy to access and do"*.

All participants were able to effectively interact with our simulation and the RH representation. For instance, P1, commented on using one's head to interact, *"I think the way you have it is very intuitive and I was able to learn rapidly with minimal instruction"*. We also received positive feedback with regards to our visualization. For instance, as P6 puts it, *"The feedback of imaging from the computer were extremely useful to see where the screws were put"*. More specifically, for example, our choice of rendering the RH branches as dotted/solid paths seems to make sense. The example comment from P5 reflects that when he or she said, *"it was cool, very intuitive, and yea it just made the tree very useful"*.

We also received feedback about the simulator's limitations and suggestions for improvement. Examples of refinement include better descriptive text for tagging the tree nodes and considering ways to handle quickly growing tree branches. For instance, P5 expressed, *"You may have tree very long, say you are not doing like a three-step operation, but the full thing [with more steps and repeatedly with multiple screws], you may have to come up with some way to collapse and expand the branches"*. The key limitation we received relates to the haptic feedback that seemed less realistic. For instance, P1 expressed, *"The haptic feedback is good, but if people were to use it to improve their skills then it needs to be more realistic"*. Indeed, we did not focus on having accurate haptic feedback on our implementation since it would require complex integration that is beyond the focus of this research. This concern of the poor haptic feedback can be mitigated in future work either by improving the haptic implementation or by using better haptic devices.

6.3 History Representation

Our participants reacted positively to the interaction history feature we integrated. Two third of participants responded with "Strongly Agree" to the following statement, *"I found the history representation to be useful for being aware of my interaction within the simulation"*. The remaining answered with "Agree", using the 7-point Likert scale we used.

Many of the qualitative feedback we received support our history representation. First, with regards to supporting temporal interaction, P5 stated, *"I think this [RH] more flexible, if you instead of inserting screw in 3 steps, it is 10 steps, it would take 10 clicks to go back to the beginning of the whole sequence, whereas with this [approach] you can pick exactly how far you want to go back in one click"*. Along the same line, P6 said, *"I prefer the one that you made [over a simple undo] because it is more visual and because we are doing a simulation for something actually visual"*.

Many of our participants highlighted the potential value of the RH representation for supporting planning and learning. As one participant said, *"I think this [RH] is better [than a simple undo] because it gives me the ability to review what I did wrong ... If I make multiple attempts, just the simple linear undo/redo won't give me the chance to branch and see what I did before. So, from a learning perspective, this is definitely more useful"*. Similarly, P1 stated, *"I think the trajectory planning [for the screw insertion task] is quite good with this tree"*. Along the same line, P4 stated, *"I think the nonlinear way presented in this simulation is definitely superior [to a simple undo], especially with pedicle screw [task]"*. These comments reflect on how the "non-linearity" inherent in the RH representation has the potential to support learning.

Finally, we present two interesting comments of how the RH representation can be shared with others and how it is perceived as potential addition to surgical simulation. First, P5 mentioned how RH may be used to reinforce learning at situations of failure, by stating, *"In terms of learning, it is interesting, cause it is like a lot of your previous steps, so if you landmarked poorly and you saved [your progress with the RH] after your landmarked, your teacher can come by [look at your interaction tree] and show you where the thing that made everything else goes off"*. P4 who tried other simulators commented saying, *"I think this tree addition is very big asset because in the other ones you have to restart from scratch, and for me one of the important aspects of learning is the fact you can use sub-optimal placement of your screws and then learn how the different trajectory may affect your outcome whereas in other simulations if you put that ill-position landmark you have got one shot of trying to fix it, or you would have to restart the simulation trying to get better at the same ill-positioned before you can give it a go. I think you learn a lot more form that instead of trying to do the full thing from scratch"*.

7 CONCLUSION & FUTURE WORK

We proposed ReflectiveSpineVR, an immersive 3D spine simulation enriched with interaction history capabilities to enable repetitive practice and aid education of surgical procedures. The conception and integration of our interaction history representation were guided by the insight we gained from a design study we conducted prior to developing ReflectiveSpineVR. Also, our research process involved collaboration with medical experts through various iterations to meet their expectations and needs. We presented a preliminary evaluation highlighting the potential benefits of integrating spatial interaction history representations in an immersive surgical simulation environment.

ReflectiveSpineVR is the first immersive prototype where we explored our interaction history ideas, and we are still improving it. We are considering the feedback we received to refine our implementation. This includes changing the representation of specific tree branches to be more compact once the tree grow beyond certain limit to simplify its exploration. Also, we plan to integrate our interaction history representation into other immersive simulation scenarios with formal studies, aiming to confirm its value for supporting temporal interaction for simulation-based education.

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REFERENCES

[1] R Aggarwal, SA Black, JR Hance, A Darzi, and NJW Cheshire. 2006. Virtual reality simulation training can improve inexperienced surgeons' endovascular skills. *European Journal of Vascular and Endovascular Surgery* 31, 6 (2006), 588–593.

[2] Ali Alaraj, Fady T Charbel, Daniel Birk, and et al. Tobin, Mathew. 2013. Role of cranial and spinal virtual and augmented reality simulation using immersive touch modules in neurosurgical training. *Neurosurgery* 72, 0 1 (2013), 115.

[3] S Barry Issenberg and et al. Mcgaghie, William C. 2005. Features and uses of high-fidelity medical simulations that lead to effective learning: a BEME systematic review. *Med. teacher* 27, 1 (2005), 10–28.

[4] Thomas Berlage. 1994. A selective undo mechanism for graphical user interfaces based on command objects. *Trans. on Comp.-Human Inter.* 1, 3 (1994), 269–294.

[5] Doug Bowman and et al. Kruijff, Ernst. 2004. *3D User Interfaces: Theory and Practice, CourseSmart eTextbook.* Addison-Wesley.

[6] Hsiang-Ting Chen and et al. Wei, Li-Yi. 2011. Nonlinear revision control for images. In *ACM Transactions on Graphics*, Vol. 30. 105.

[7] et al. Clark, Anna. 2017. The Effect of 3-Dimensional Simulation on Neurosurgical Skill Acquisition and Surgical Performance: A Review of the Literature. *Surgical Education* (2017).

[8] Timothy R Coles, Dwight Meglan, and Nigel W John. 2011. The role of haptics in medical training simulators: a survey of the state of the art. *IEEE Transactions on Haptics* 4, 1 (2011), 51–66.

[9] David A Cook and et al. Hamstra, Stanley J. 2013. Comparative effectiveness of instructional design features in simulation-based education: systematic review and meta-analysis. *Medical teacher* 35, 1 (2013), e867–e898.

[10] Mark Derthick and Steven F Roth. 2001. Enhancing data exploration with a branching history of user operations. *Knowledge-Based Sys.* 14, 1 (2001), 65–74.

[11] Vivian E Ekkelenkamp, Arjun D Koch, Robert A de Man, and Ernst J Kuipers. 2016. Training and competence assessment in GI endoscopy: a systematic review. *Gut* 65, 4 (2016), 607–615.

[12] Square Enix. 2017. Final Fantasy XIII-2. (2017). Retrieved Mar 13, 2017 from http://www.finalfantasy13-2game.com/

[13] Facebook. 2017. Oculus Rift: A well known head-mounted display. (2017). Retrieved Jan 17, 2017 from https://www.oculus.com/rift/

[14] Jonas Forsslund, Eva-Lotta Sallnas, and Karl-Johan Palmerius. 2009. A user-centered designed FOSS implementation of bone surgery simulations. In *Euro-Haptics conf. on Haptic Interfaces for Virtual Environment and Teleoperator Systems.* IEEE, 391–392.

[15] Anthony G Gallagher and et al. Ritter, E Matt. 2005. Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training. *Annals of surgery* 241, 2 (2005), 364–372.

[16] GeoMagic. 2017. The OpenHaptics toolkit enables haptic support through variety of haptic devices. (2017). Retrieved April 12, 2017 from http://www.geomagic.com/en/products/open-haptics/overview

[17] Tovi Grossman, Justin Matejka, and George Fitzmaurice. 2010. Chronicle: capture, exploration, and playback of document workflow histories. In *VRST*. ACM, 143–152.

[18] Jeffrey Heer, Jock Mackinlay, Chris Stolte, and Maneesh Agrawala. 2008. Graphical histories for visualization: Supporting analysis, communication, and evaluation. *IEEE TVCG* 14, 6 (2008).

[19] Shaun Kaasten and Saul Greenberg. 2001. Integrating back, history and bookmarks in web browsers. In *CHI'01 EA*. ACM, 379–380.

[20] Shawn Klein, Cari M Whyne, Raphael Rush, and Howard J Ginsberg. 2009. CT-based patient-specific simulation software for pedicle screw insertion. *Clinical Spine Surgery* 22, 7 (2009), 502–506.

[21] Elspeth M McDougall. 2007. Validation of surgical simulators. *Endourology* 21, 3 (2007), 244–247.

[22] Ryan P McMahan and Nicolas S Herrera. 2016. AFFECT: Altered-Fidelity Framework for Enhancing Cognition and Training. *Frontiers in ICT* 3 (2016), 29.

[23] Christine Mégard, Florian Gosselin, Sylvain Bouchigny, Fabien Ferlay, and Farid Taha. 2009. User-centered design of a maxillo-facial surgery training platform. In *The 16th ACM VRST*. 265–266.

[24] et al. Mobbs, Ralph J. 2017. The utility of 3D printing for surgical planning and patient-specific implant design for complex spinal pathologies: case report. *Neurosurgery: Spine* (2017), 1–6.

[25] Brad A Myers and et al. Lai, Ashley. 2015. Selective undo support for painting applications. In *CHI*. ACM, 4227–4236.

[26] Mathieu Nancel and Andy Cockburn. 2014. Causality: A conceptual model of interaction history. In *CHI*. ACM, 1777–1786.

[27] William Nash, Roland Walker, Jonathan Lucas, and Adil Ajuied. 2017. Seminal papers in spinal surgery. *Orthopaedics and Trauma* (2017).

[28] James O'Brien and Marc Shapiro. 2004. Undo for anyone, anywhere, anytime. In *ACM SIGOPS European 11th workshop*. 31.

[29] Panayiotis E Pelargos and et al. Nagasawa, Daniel T. 2017. Utilizing virtual and augmented reality for educational and clinical enhancements in neurosurgery. *Clinical Neuroscience* 35 (2017), 1–4.

[30] Martha C Polson and J Jeffrey Richardson. 2013. *Foundations of intelligent tutoring systems.* Psychology Press.

[31] Joseph Psotka. 1995. Immersive training systems: Virtual reality and education and training. *Instructional science* 23, 5-6 (1995), 405–431.

[32] Reva Ramlogan and et al. Niazi, Ahtsham U. 2017. A Virtual Reality Simulation Model of Spinal Ultrasound: Role in Teaching Spinal Sonoanatomy. *Regional anesthesia and pain medicine* 42, 2 (2017), 217–222.

[33] Mark O Riedl and Robert Michael Young. 2006. From linear story generation to branching story graphs. *IEEE CGA* 26, 3 (2006), 23–31.

[34] Kneebone RL. 2009. Practice, rehearsal, and performance: An approach for simulation-based surgical and procedure training. *JAMA* 302, 12 (2009), 1336–1338.

[35] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The experience of presence: Factor analytic insights. *Presence: Teleoperators and virtual environments* 10, 3 (2001), 266–281.

[36] Douglas Schuler and Aki Namioka. 1993. *Participatory design: Principles and practices.* CRC Press.

[37] Ben Shneiderman. 1996. The eyes have it: A task by data type taxonomy for information visualizations. In *IEEE Visual Languages*. 336–343.

[38] 3D Systems. 2017. Touch Stylus: a haptic 3D stylus. (2017). Retrieved Jan 23, 2017 from https://www.3dsystems.com/shop/touch

[39] Ubisoft. 2017. Tom Clancy's The Division Game (ECHO). (2017). Retrieved Feb 21, 2017 from http://division.zone/echo/

[40] John Vlissides, Richard Helm, Ralph Johnson, and Erich Gamma. 1995. Design patterns: Elements of reusable object-oriented software. *Reading: Addison-Wesley* 49, 120 (1995), 11.

[41] Ulrich Von Zadow and et al. Buron, Sandra. 2013. SimMed: combining simulation and interactive tabletops for medical education. In *CHI*. ACM, 1469–1478.

[42] James B Walker, Eddie Perkins, and H Louis Harkey. 2009. A novel simulation model for minimally invasive spine surgery. *Neurosurgery* 65, 6 (2009), 188–195.

[43] Liangbi Xiang and et al. Zhou, Yue. 2015. Significance of preoperative planning simulator for junior surgeons training of pedicle screw insertion. *spinal disorders & techniques* 28, 1 (2015), E25–E29.