

Supporting Anatomy Education with a 3D Puzzle in a Virtual Reality Environment - Results from a Pilot Study

Daniel Pohlandt
daniel.pohlandt@googlemail.com
Otto-von-Guericke University
Magdeburg
Magdeburg, Germany

Bernhard Preim
preim@isg.cs.uni-magdeburg.de
Visualization Group,
Otto-von-Guericke University
Magdeburg
Magdeburg, Germany

Patrick Saalfeld
saalfeld@isg.cs.uni-magdeburg.de
Visualization Group,
Otto-von-Guericke University
Magdeburg
Magdeburg, Germany

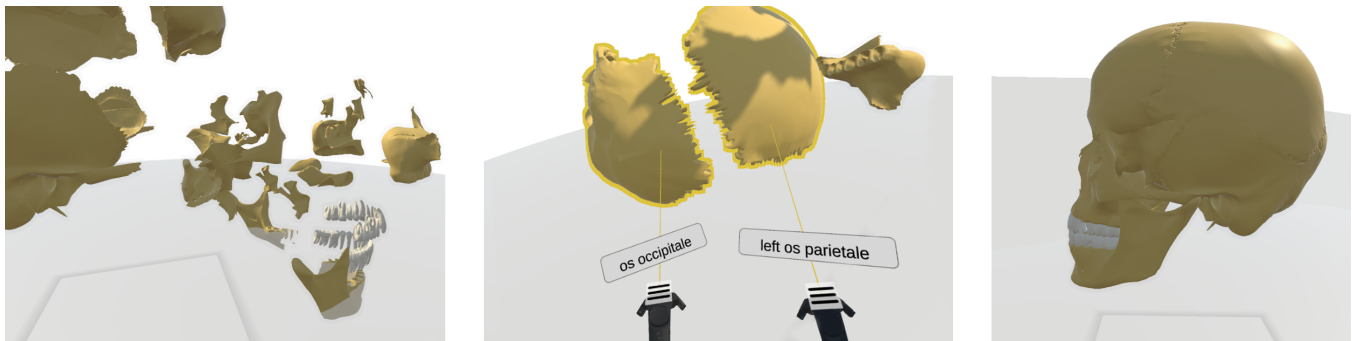


Figure 1: By puzzling anatomical parts, the user learns about their names and spatial orientation.

ABSTRACT

We designed an immersive VR system to support the imagination of complex anatomical structures. By solving a 3D puzzle of anatomical models, medical students learn names and spatial relations. The approach is proposed as a supplement to the work with traditional human body donors. To meet the needs of medical students and satisfy the different stages of learning, the approach contains different modes that help the student to gather and review medical knowledge. Additionally, different feedback mechanisms that support the student with the puzzle task are proposed. The concept is realized as a prototype application using the HTC Vive and the Unity game engine. This prototype is evaluated in a pilot study, where we investigate the general usefulness as well as the feedback mechanisms. The results suggest that a 3D puzzle in a fully immersive virtual reality environment can be a valuable extension to traditional teaching methods in the medical curriculum. Regarding the feedback, it is clear that a combination of vibrotactile feedback and a ghost copy approach are most promising.

CCS CONCEPTS

• **General and reference**; • **Human-centered computing** → **Virtual reality**; *Interaction devices*; *Interaction design*; *Visualization*; *User studies*; • **Applied computing** → **Interactive learning environments**; *Life and medical sciences*; *E-learning*;

KEYWORDS

Virtual Reality, 3D Puzzle, Anatomy Education

ACM Reference Format:

Daniel Pohlandt, Bernhard Preim, and Patrick Saalfeld. 2019. Supporting Anatomy Education with a 3D Puzzle in a Virtual Reality Environment - Results from a Pilot Study. In *Mensch und Computer 2019 (MuC '19)*, September 8–11, 2019, Hamburg, Germany. ACM, New York, NY, USA, 11 pages. <https://doi.org/10.1145/3340764.3340792>

1 INTRODUCTION

Learning often involves the understanding of complex spatial relations. Engineers need to know where parts of a machine are situated even if they are not visible from the outside. This especially applies to the most complex “machine” known to mankind: the human body. In both fields of application, it is essential to learn and understand the position of even the tiniest part of a system. Traditionally, learning is based on abstract visualizations in anatomy atlases and real life models. These methods lack interactivity. An *active* type of learning has the highest potential to result in a sustainable knowledge gain [25]. Therefore, watching, e.g., a video sequence of an anatomical region passively can only be a good starting point. For a deeper understanding, however, the video has to be complemented with more involving types of learning. As an example, Jang et al. [13] highlight an additional learning effect

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

MuC '19, September 8–11, 2019, Hamburg, Germany

© 2019 Association for Computing Machinery.

ACM ISBN 978-1-4503-7198-8/19/09...\$15.00

<https://doi.org/10.1145/3340764.3340792>

during the interactive manipulation of 3D content in comparison to viewing video sequences showing the same content. This is due to the phenomenon of *embodied cognition*, which occurs during the activation of perceptual and motor systems [7].

Learning the human anatomy strongly benefits from realistic anatomical data and interactive feedback. For this purpose, a 3D puzzle metaphor has been introduced [26, 28]. With the rise of high-quality virtual reality headsets, such as *Oculus Rift* and *HTC Vive*, immersive virtual reality applications are a reasonable extension to provide a proper learning experience [35]. In this context, a 3D puzzle is a suitable metaphor since it uses simple real-world concepts and extends them with powerful information visualization tools [17]. In our work, we aim to investigate how the 3D puzzle metaphor can be applied to an immersive virtual reality environment. As a research goal, we investigate the usefulness and usability of different feedback mechanisms as these should support students in solving the puzzle.

2 BACKGROUND & RELATED WORK

This section briefly outlines the basics of anatomical teaching and the part that computer technologies take in it. Further, we discuss the 3D puzzle metaphor, which is the foundation for the work at hand.

2.1 Educational Background

For the development of virtual learning environments, pedagogical aspects have to be considered in the design phase to maximize the learning outcome [9]. Dave Meier divides the process of learning into four indispensable phases that need to be covered until a skill can be considered learned [18]. These phases comprise: **Preparation**: The first phase consists of arousing interest in a new skill or new knowledge. This interest can either be sparked by external stimuli or the realization that something new can be learned as current knowledge is not sufficient. **Presentation**: This phase covers the encountering of the new knowledge or skill. All necessary and relevant details need to be provided and thoroughly examined. It is crucial to understand that this phase takes a different amount of time for each individual and might need different strategies for different learners. **Practice**: After encountering the new knowledge or skill it is necessary to integrate it. This is usually realized by repeating and rehearsing it without the aids that were used in the presentation phase. The previous phase and this phase are often alternated multiple times. **Performance**: The final phase is the application of the new knowledge or skill into a new environment. Even though the situation might be different from the presentation or practice phase, the learner is able to apply gained knowledge. In every educational environment these phases are covered and each student needs to go through them over time. As for anatomy education, it usually takes years for some skills or knowledge to reach the final phase. Anatomical knowledge is the basic prerequisite for understanding clinical problems and therefore a fundamental component of medical education.

2.2 Virtual Anatomy Education

Over the years, a vast amount of computer-aided approaches have been introduced with the goal to improve and supplement traditional learning environments. *Computer-aided Learning Applications* range from widespread medical databases [34] to interactive 3D anatomy atlases [38]. The pioneering work in 3D anatomy teaching is the highly acclaimed *VOXEL-MAN* [12], initially presented in 1986. Based on the *Visible Human* [1] datasets the *VOXEL-MAN* presents the human anatomy in an interactive three-dimensional environment. Spatial information can be gathered by inspecting every detail of the model from different angles. It is further possible to remove parts of the model, which is similar to a real dissection. Symbolic information is provided by labels and detailed descriptions of each structure. Approaches like this are oriented towards an atlas metaphor. A similar example is the *Zoom Illustrator*, which presents an extension to fisheye views to explore three-dimensional anatomy models [24]. The software provides a close relationship between images and associated text by influencing the appearance of each other with respective interactions. More recently, web-based tools such as *OsteoScope*¹ or *Online Anatomical Human* have already been introduced for anatomy education [8, 15, 33]. Based on real human anatomy, students can use these applications to freely interact with 2D or 3D views of medical image data. Applications like that can be used by potentially large numbers of learners worldwide, at any time, either in private or in classrooms. Especially tools that are based on WebGL, such as the *LiverAnatomyExplorer* or *Open Anatomy Browser*, are suitable for a wide audience as they present high-quality 3D renderings on portable devices such as smartphones or tablets [2, 11]. It has been shown that students would appreciate more freedom to interact with 3D anatomy models in anatomy education [23]. An extensive survey on virtual human anatomy education systems was given by Preim and Saalfeld [25].

2.3 3D Puzzle Metaphor

Especially assembling and disassembling of anatomical models by themselves is desirable [27]. This led to the introduction of a 3D puzzle metaphor for learning spatial relations of anatomical structures [28] on a desktop system. From an educational point of view, solving a puzzle is related to constructivist learning theory, where learning happens through an experiential process [20]. Adding this *playful* component into an educational environment does indeed improve the user's understanding of spatial relations from 3D illustrations [26]. Their interactive 3D visualization allowed users to work with the foot anatomy with functions related to labeling and exploded views. Realizing this concept in an immersive virtual environment is even more compelling, as single puzzle pieces can be investigated in more detail and positioned with more control. A semi-immersive realization of their concept has already been done in 2008, but unfortunately an informative evaluation was not given [29]. In engineering environments, similar concepts have already been introduced [14] and it has been proven that such approaches are at no disadvantage to traditional methods and it is promising to pursue more research [35]. Furthermore, a more realistic representation of 3D models is possible, which can result in

¹<http://taxonstudios.com/index.php/portfolio/osteoscope/> (Accessed: 12.03.2019)

a deeper understanding of spatial properties of anatomical regions. Another 3D puzzle to help students learn the anatomy of various organs and systems was presented by Messier et al. [19]. In an initial comparative study, they compared three display paradigms (2D monitor, stereo monitor and Oculus Rift) and two input devices (space mouse and standard keyboard). The most recent prototype containing a 3D puzzle metaphor was presented by Seo et al. [30]. In their *Anatomy Builder VR* application, users are limited to construct the skeletal canine anatomy. The user takes virtual bones out of a bone box, containing models of scanned real bones. After that, the user can suspend bones in place by placing it in an “anti-gravity” field. This is repeated until the skeleton is assembled to the user’s satisfaction. They performed a comparative study with their virtual bone box and a real one. The participants found the VR application considerably more enjoyable than the traditional bone box.

Compared to the previous work, we evolved the 3D puzzle metaphor further by giving students and teachers more possibilities for manipulation and guidance. Furthermore, our application is not restricted to an anatomical region. By giving feedback about how accurate pieces are positioned, users have the possibility to correct the position and orientation of puzzle pieces immediately.

3 A FULLY IMMERSIVE VR APPROACH FOR INTERACTIVE LEARNING

The proposed concept for an educational scenario is built on the constructivist learning theory and the work from Ritter et al.’s 3D puzzle metaphor described in the previous section. Their ideas are transferred into a fully immersive virtual reality environment with focus on various anatomical structures. Basically, in such an environment the user is presented with a scattered 3D anatomy model and then solves the task of correctly putting all pieces together, equivalent to a real world jigsaw puzzle. While doing so, learning the names and spatial relations of each structure is essential (see Figure 1).

3.1 Requirements Analysis

Our requirement analysis is based on an analysis of publications related to VR-based education and discussions with two experienced anatomy lecturers in a joint “virtual anatomy” research project. The lecturers also informally tested our prototype and considered the basic concept as a feasible and innovative teaching aid. In the following, we discuss requirements in detail.

For VR applications a frame rate of 50 frames per second is needed to ensure a real time experience and prevent potential nausea to a certain degree [17]. It is further required that the system regularly provides feedback about its activity. Feedback is essential to enable the reception of the real-time functionality and to ensure that the system is responding to input. As the scenario takes place in a room scale setup, it is essential that the environment gives the user a feeling of assurance. Users should not be concerned with accidentally walking into real world walls or obstacles while wearing the VR headset. The interaction with the virtual world should be as natural and intuitive as possible [3, 4]. Applications that are easy to learn and not demanding are generally adopted more positively by students and teachers alike [21]. A higher degree of immersion and involvement leads to a more pleasant user experience and often

to an improvement of the user’s performance. The virtual world should be presented without unnecessary distractions to allow the user to fully focus on the task, instead of being diverted by outside influences.

As primarily medical students are using the system, the application needs to consider their terminology and meet their visualization expectations. Teachers need to be able to add their own 3D models to the application in an uncomplicated manner. When talking about the target audience, it is also necessary to discuss a certain degree of accessibility.

Furthermore, students with color vision deficiency need to be taken into consideration. Even though the room scale setup allows the user to walk around, it must be possible to operate the application in a seated position to minimize potential exhaustion effects.

We consider design principles for performance-oriented interaction techniques [3]. Virtual objects need to be globally selectable, i.e. the user must be able to select virtual objects within her reach as well as objects that are far away. The selection, the manipulation and connecting of their virtual 3D puzzle pieces needs to be especially precise. It is also necessary to ensure that the 3D puzzle always has a correct solution that is attainable by the user. To support the user in experiencing the scenario, it is relevant to support the most essential task of the application: solving the 3D puzzle. As students will initially not know how to perfectly put all the pieces together, the application must provide supportive feedback mechanisms. A number of solutions are presented and evaluated to determine which approach is most suitable to support the student. Ultimately, it is required that the conceived educational scenario covers all of Dave Meier’s phases of learning (recall Section 2). The application must arouse interest in anatomical structures and then present all the necessary information. It shall further be possible to repeat and rehearse the acquired knowledge and even apply it to a new context.

3.2 Concept for an Educational Environment

The main task of the scenario is to fit 3D puzzle pieces of anatomy models together, hereby learning the names of anatomical structures and their spatial relations. The educational scenario is proposed as a single application that contains different modes that all cover the relevant phases of learning. Furthermore, a virtual world is designed that is appropriate for medical education. In addition, it is necessary to create features that improve the user’s experience of the scenario. The proposed application uses a room scale VR setup. This means that the user can navigate the environment by walking around. The system is operated via two fully tracked motion controllers that provide buttons for certain interactions. After selecting a model, the application automatically prepares it to be usable as a puzzle. It further ensures that the puzzle is neither too small nor too large for the user’s VR space. This means that the model is scaled to fit into a 2 m × 2 m cube that is positioned so that it does not collide with the user on the start of the application.

3.2.1 Selection. Within the virtual world the user can select puzzle pieces by either touching them with a controller or by pointing at them with a virtual laser that originates from the front of the controllers. By rendering a semi-transparent outline around it, the

selected object is clearly highlighted to give a significant feedback about the selection. Additionally, the object's base color is slightly tinted. As soon as the laser or the controller no longer touches the selected object, the highlighting is disabled. If an object is selected with the laser, a label appears on the laser that shows the according anatomical name as defined in the loaded 3D model file. (see Figure 2) Thus, a student can easily learn and associate the names of different anatomical structures.

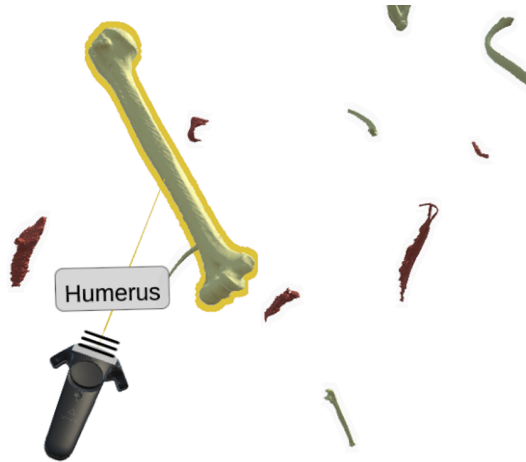


Figure 2: Selecting pieces with the laser highlights the piece and displays its name.

3.2.2 Manipulation. While being selected, pieces can be grabbed by holding down the grab button on the controller. As soon as a piece is grabbed, the highlighting is removed. To maintain the association between a piece's shape and its name, the label with the name is also displayed when the piece is grabbed. The piece follows the respective controller's movements as long as it is grabbed. This supports the close examination of each individual piece. To avoid conflicts, a piece can only be grabbed by one controller at a time and each controller can only grab one piece at once.

If the user cannot reach a piece that is far away, it can be drawn near, either by double clicking the grab button while the piece is selected or by using the touch pad while the piece is already grabbed. Grabbing two pieces at the same time indicates an assembly attempt, i.e., the user wants to put these pieces together. This decision is made to detect that the user wants to assemble the pieces and prevents the system from accidentally putting pieces together when moving an object through other objects. The two pieces need to be aligned within a certain threshold regarding their distance and orientation to each other. This threshold is further referred to as *snapping range*. When two pieces are within this *snapping range* they will be connected as soon as one controller lets go of its piece (see Figure 3). This process is further referred to as *snapping*.

After the *snapping* the concerned group of pieces is treated like a single piece. It is possible to detach individual pieces from an assembled group by grabbing the whole group with one controller and then grabbing one of the connected pieces with the other controller.

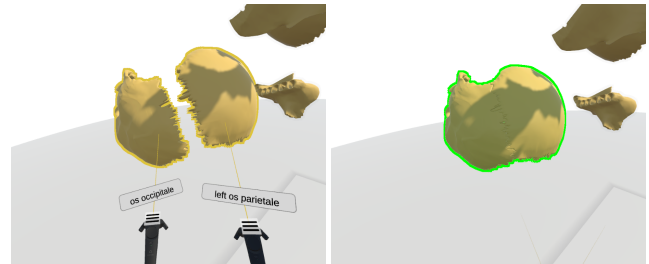


Figure 3: The assembling of two pieces resulting in a connected group.

To give the user the possibility to more thoroughly examine the model, the model can be scaled and rotated by holding down the grip buttons on both controllers. Moving the controllers closer to each other or further away from each other results in an increase and decrease of the size of the whole model. It is not possible to scale pieces individually, as this would cause problems with the assembling. Additionally, the whole model can be freely rotated by rotating the controllers around each other. The arising transformation can easily be reverted by clicking a button in the user menu. In contrast, in a real world scenario it is not easily possible to freely rotate, e.g., a cadaver during a dissection and it is impossible to enlarge it to get a better view at tiny structures.

3.2.3 Virtual Environment. To achieve a better user performance, the environment should be based on real world rooms [32]. This does not only improve the immersion but also prevents a certain degree of discomfort. The user is surrounded by a sky dome of a very light whitish color. Such bright colors are commonly found in healthcare environments. Another positive aspect is the resulting contrast that the bright color provides to the anatomy models (see Figure 1). If the surroundings had textures, shading or animations applied, this might not always be the case.

The ground floor serves as a crucial landmark for orientation [5]. It is designed as a circular shape that is significantly bigger than the actual area the user can navigate in, which is defined by the setup of the VR system. This should prevent that the user feels cramped in the virtual world.

By moving pieces around in the environment it can happen that a piece is moved below ground level. To avoid that such a piece can no longer be found, the respective piece is presented semi-opaque instead of completely hidden. Obviously the ground floor object does not interfere with the selection of pieces. The environment is deliberately left empty to reduce cognitive load. Decoration might not only distract the user from the virtual anatomy model, but might also cause confusion as functionality of the decoration might be assumed.

As the application provides a room scale experience, it is necessary to communicate the boundaries of the real world surroundings. This is realized with a subtle rectangle on the ground showing the approximate boundaries.

The environment does not simulate gravitational effects on the puzzle pieces. Even though it might improve the sense of immersion, it will most likely be annoying for the user if the pieces fall to the

ground as soon as they are released. Not only would this mean that the user needs to reach down, every time to pick up a piece, it would also heavily limit the possibility to arrange and assort pieces. Accordingly, the anatomical structures behave without any sense of inertia and gravitation. If the user releases a piece, it stays in the exact same place. For the same reason the pieces do not collide with each other.

However, this could lead to two or more pieces overlapping each other, which can make it harder to identify individual pieces or even let some pieces be mistaken for others.

3.2.4 3D Models. Actual 3D scan data of a foot, a human skull and a shoulder section were used as test data (see Figure 4). The models were prepared so that each structure that is interesting for a student is presented as a single piece which can then be used for the puzzle. It is ensured that each structure is named correctly with their English term. The textures are attempted to be looking lifelike by using high-resolution (1024×1024 px) textures provided by *DOSCH DESIGN*². Some structures are colored in an abstract way that is more familiar to medical students. Arteries are tinted red, veins are blue and nerves are yellow. To test the basic interaction strategies with students not familiar with anatomy, more plain models were used. Two models that only consist of four pieces each, a house and a circle were especially useful for the training in the evaluation, as it is very easy to spot two pieces that correctly fit together (see Figure 4). Additionally, the model of a *Rubik's Cube* was used, as this is widely known by many people and provides an interesting subject for puzzling. However, it is necessary to point out that the application did not replicate the actual functionality of this toy, as this was not in the scope of our research.

The model database can easily be extended by anatomists by putting the required 3D data into a dedicated folder of the application. In the current state, the application supports the 3D file formats .obj and .fbx. It is required that the data represents the object in an assembled way. Further, it is essential to make sure that each structure is named correctly, as the application will only show the names according to the 3D model file. This data preparation process is not possible in the current version of our application.

3.2.5 Feedback Mechanisms. It is necessary that the proposed feedback mechanisms (recall Section 3.1) need to approach two basic tasks. If the user knows how two pieces need to be aligned, but struggles to put them together due to inexperience with the application, the system must assist. Secondly, the system must provide mechanisms to learn the spatial relations of two specific objects that should be associated with each other, e.g. a muscle attached to a bone. Some feedback mechanisms are more appropriate for the first task, while other approaches are useful for the second task.

Each feedback mechanism can be freely enabled or disabled by the teacher to adjust the difficulty to the student's level of knowledge. Additionally, all feedback mechanisms can be combined as desired. To avoid distraction from the virtual world, a feedback is only visible when the user is holding two pieces at the same time to indicate an assembly attempt. Some feedback mechanisms require the use of colors to illustrate information. To indicate that

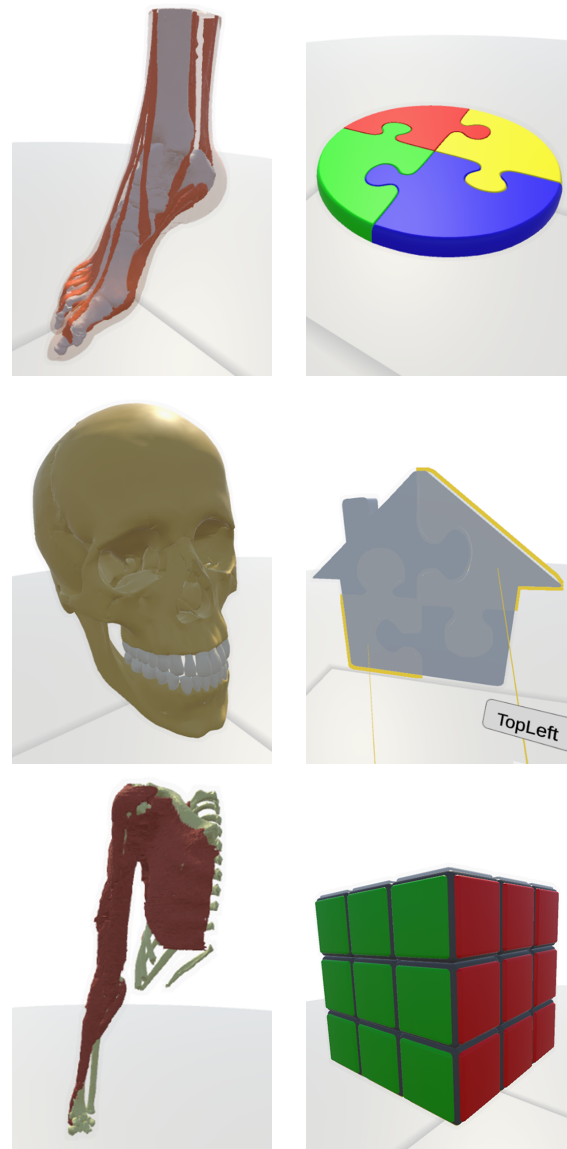


Figure 4: Realistic anatomical and abstract models used for the prototype.

objects are correctly composed, the concept applies a light green color. A dark red color is applied to indicate an error. The light and dark contrast makes it possible to distinguish these colors even for people with color vision deficiency [16]. Some mechanisms make use of a transition between those complementary hues.

This specific color association is kept consistent for the whole concept.

In the following, five types of implemented feedback mechanisms are discussed, mainly comprising visual stimuli and additionally one type of tactile stimuli.

Display Values. A straightforward approach for a visual feedback that conveys information about the difference of the orientation

²https://www.doschdesign.com/produkte/textures/Medical_Visualization_V3.html (Last accessed: 05.04.2019)

of two objects is to directly present this difference as quantitative values (see Figure 5). For the user, it is important to know the distance between the two pieces that are grabbed as well as the difference between their orientations. As long as the pieces are not in *snapping range*, the values are tinted dark red. This choice additionally highlights that the orientation of the pieces is not yet correct. For an optimal snapping it is necessary to bring both values close to zero. Since the application provides a certain threshold, it is not necessary to be perfectly precise. As soon as the two pieces are in *snapping range*, the color of the values turns light green. This color highlights that both pieces are oriented correctly. An obvious disadvantage of this solution is the interference with the user's view, which might be obstructed by the displayed values.

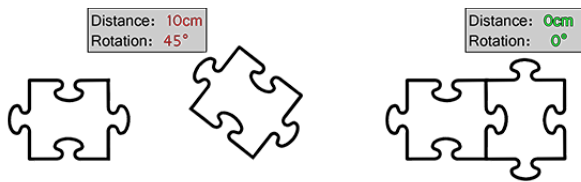


Figure 5: The *Display* mechanism showing values.

Tinting. This approach conveys the correctness of the current distance and rotation of the two pieces that the user wants to merge. Instead of directly presenting these values, they are coded into a color. As soon as the user holds two pieces, the last selected piece is tinted with a color that signals correctness. The tinting color changes from a dark red to a light green (see Figure 6). As long as the tinting color is not light green, the pieces are not in *snapping range*. The light green color is assigned to an average value of zero, while the dark red color is assigned to an average of 100. This transition value is calculated by the average of the correctness of distance and rotation. Average values in between are accordingly interpolated with respect to the red-green gradient. If the distance between both pieces is equal or less than the snapping threshold, the distance value is zero. If it is larger than 500 mm, the value is 100. Equally, if the orientation difference between both pieces is less equal or less than the rotational snapping threshold of 10°, the rotation value is zero.

Accordingly, it is 100 when the difference between both rotations is 180°. Compared to the *Display Values* approach, this approach has the clear advantage of not blocking the user's view with additional visual elements.



Figure 6: The *Tinting* mechanism.

Elastic Strings. This approach separates the presentation of distance and rotation differences. The rotation is represented through a rubber string metaphor. This is realized by assigning four anchors to each puzzle piece. These anchors are not actual objects, but rather values that are stored inside the piece. Two anchors are assigned along the piece's local x-axis and two more along its y-axis. One of each follows the positive direction of the axis, the other follows the negative direction. Each pair of anchors has the same distance from the piece's visual center. This distance is determined by the model's most extreme point on the respective axis. When the user is holding two pieces, a cuboid is drawn between each anchor and its respective counterpart. Altogether, this creates four cuboids that resemble elastic strings attached to the pieces (see Figure 7). These strings continuously adapt to the orientation of the pieces. The difference between the rotation of the pieces is now represented through these strings. If two or more strings are crossing each other, the rotation is not correct. Using real-world experience and imaginative power, the user can then rotate the pieces to "untangle" the strings. The distance difference is represented similarly to the *Tinting* approach, but in this case the strings are tinted. This tinting is identical to the *Tinting* only without regards to the rotation values.

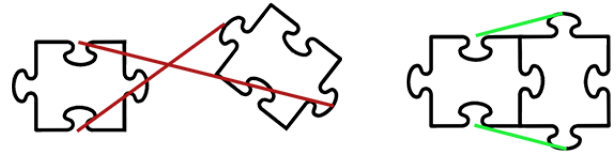


Figure 7: The *Elastic Strings* mechanism.

Ghost Copy. In real-world jigsaw puzzles, the user has a picture of the solved puzzle at hand. When figuring out the orientation of a single piece, this picture can easily be referred to. Such a 2D depiction is less helpful in a 3D environment. Instead, a 3D model of the solved puzzle may be provided for interactive exploration [27]. However, pieces may occlude each other in the 3D model with some internal anatomical structures not visible from any viewing direction. Thus, this 3D model does not provide supportive information for merging internal structures. To provide support, we only present the solution to the user, i.e. we show a copy of one of the pieces aligned correctly with the other piece. The user can then just match the piece he is holding with the copy he is seeing. To make the copy more distinguishable from the actual pieces, it is rendered with a semitransparent dark grey material, which resembles a ghost, hence the name *Ghost Copy* (see Figure 8). Please note that the term ghost copy is also used differently, e.g. in the original desktop 3D puzzle it relates to the display of a single anatomical structure that can be freely rotated out of the overall 3D model [28]. Ghost copies for exploring 3D models were introduced by Tan et al. [36].

Vibrotactile Feedback. Sensory feedback is a key element of VR interaction [31]. Haptic experience is not only useful to enhance the user's immersion and involvement into the virtual world, but also a possibility to convey information [6]. It has been shown

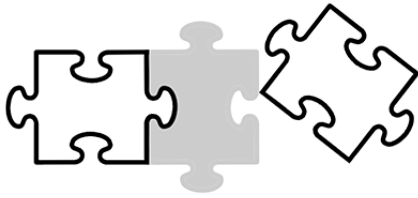


Figure 8: Ghost Copy mechanism.

that users are able to comprehend very fine vibrotactile stimuli [37]. Using the vibration feature of the *HTC Vive* controller, the prototype provides two kinds of feedback to the user. If the user's attempt to assemble two pieces is successful and the pieces snap together, the user experiences a distinctive, steady vibration for 0.5 s from both controllers. This helps the user to understand that this attempt was successful. Beforehand, while trying to align the pieces, the controllers vibrate lightly as soon as the pieces are in *snapping range*. The actual feedback is a loop of increasing vibrations, with each loop lasting for 0.3 s, starting with an intensity of zero going to an intensity that is determined by the correctness of the solution. All values of the vibrotactile feedback have been empirical determined to be distinguishable and comfortable for the user.

3.2.6 Puzzle Modes. To cover the different *Phases of Learning* (recall Section 2), three modes are available that consider the needs of anatomical education:

- *Exploration Mode*
- *Training Mode* and
- *Testing Mode*.

These modes are described in the following. The first phase of learning (Preparation), should be covered to an extent by the fact that medical students are interested in learning about human anatomy. Additionally, it can be argued that the use of an exciting technology such as VR arouses interest in this application and the assigned educational scenario.

Exploration Mode. Within this mode, all information that can be gained in the proposed educational scenario is presented. This mode supports the *Presentation* learning phase. When starting this mode, the application loads and prepares the selected model and presents it in an assembled state. The user can then examine and explore the anatomical models and various structures. By grabbing individual pieces, the structures can be disassembled and reassembled. Inspired by exploded views often applied in engineering environments [35], we provide a similar *scattering* feature. By clicking the according button in the user menu, the user will see an animation of the model “exploding” (see Figure 9). All pieces will simultaneously move away from the center of the object. This is evidently helpful to identify spatial relations. A similar mechanism was part of the original 3D puzzle [27]. However, it was realized in a different manner, namely by scaling each object down—thus enlarging the inter-object distances.

The scattering can be affected by two factors that are adjustable in the user menu. One factor is “Random Position” and the other is “Random Rotation”. The first factor determines if the pieces are

scattered randomly or follow the exact path that goes from the models' center through each individual piece. The second factor determines if a random rotation is applied to the piece as it is scattered. If both factors are deactivated, the scattering is identical to an explosion animation that is commonly found in computer-aided design applications that are used in engineering environments. As opposed to this, if both factors are activated, the scattering will be fully random, which is identical to the starting situation in the *Training* and *Testing* mode.

This setting is useful to practice the assembling of individual structures or the whole model. The scattering feature is only available if the model is in a solved state. In case the model is scattered, the user is provided with the possibility to automatically reassemble the puzzle. The reassembling takes place in form of an animation which can be observed by the user.

The *Exploration* mode is not only relevant for gaining knowledge, it is also valuable to refine the user's skills in operating the features of the application. Moreover, it is plausible that a teacher applies this mode as part of a lecture to present anatomical information in a novel and interesting way.

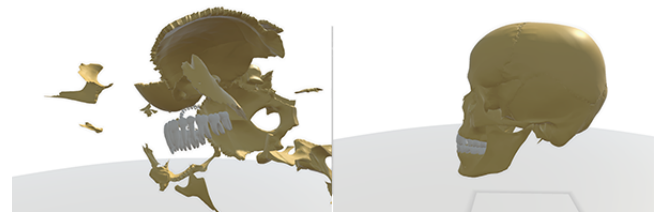


Figure 9: The random explosion of the skull model and the complete skull model.

Training Mode. The learning phase *Performance* is covered by this mode. The user can review gained knowledge by applying it in a situation that is familiar, without getting extensive help. In this mode, the actual puzzling takes place. When starting, the application loads and prepares the model. Afterwards, it randomly scatters the individual pieces around the user. Only then the user can see the virtual environment. Now, the task is to assemble the model, based on the knowledge gained in the *Exploration* mode, analogous to Ritter's 3D puzzle metaphor [28].

The user can activate various feedback mechanisms that support the solution. As soon as the user has completely assembled the model, a floating screen appears that shows the time and number of grabs it took to solve the task. Additionally, the minimum number of grabs required to solve the puzzle is displayed.

Such results can be used to keep track of the individual learning progress. It also adds a competitive element, as students can compare their individual scores, which might lead to an increased motivation for using the software.

Testing Mode. This mode can be considered as the final stage of the application. It is almost identical to the *Training* mode, with one important difference. The user has a specified order in which the pieces need to be handled.

Either students or teachers can easily create sequences for this mode by simply putting a csv-file that contains the name of the

model, the desired variation and the desired order into a designated folder of the application. Students can then easily review their knowledge by providing test sequences for each other. Furthermore, the nature of this mode makes it an interesting possibility for actually testing students' anatomy knowledge as part of an exam.

This mode satisfies the learning phase *Performance* as the students need to apply knowledge in an unfamiliar situation. The mode has two variations: *Assembly* and *Disassembly*. A floating text describes the order the user needs to follow. With this mode not only the knowledge about the structure's names can be tested, but additionally a more profound knowledge about the spatial alignment of each piece. The *Assembly* variation follows the same idea as the *Training* mode. The user finds the puzzle in an unsolved state with each piece being scattered randomly around. It is then required to put the pieces together as described by the displayed text. Only the pieces that are indicated can be put together.

The other variation, the *Disassembly* mode, is less familiar to the students. As in the *Exploration* mode the model gets presented in a solved state. The task is to remove the correct piece in the order indicated by the floating text. Only the indicated piece can be grabbed by the user. The task is considered as finished as soon as all pieces are removed from the model. This variation is similar to a real world dissection, where external structures need to be removed before internal structures can be reached. After finishing the *Assembly* or *Disassembly* the user is presented with a floating screen that shows the time it took to solve the task (see Figure 10). This feature helps to keep track of the individual learning progress and serves as meaningful measurement to compare different user results.

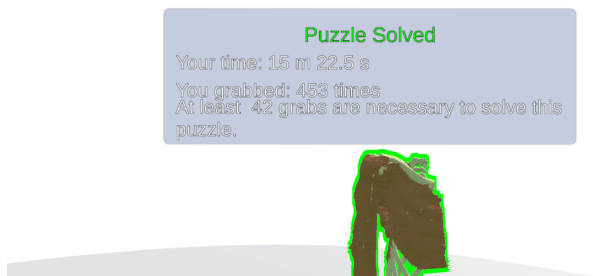


Figure 10: The result screen signaling the finished puzzle state.

4 PILOT STUDY

For the pilot evaluation, we used a *Mixed-Method* design [10]. Qualitative insights are gained through the *Thinking Aloud* method [22]. Subjective ratings are acquired by using a questionnaire. The questionnaire contains questions regarding the usability and the usefulness of the application's features. Additionally, the prototype was presented to anatomy educators in the development phase in an informal setting. This resulted in first feedback and suggestions for improvement.

4.1 Procedure & Tasks

First, the purpose of the prototype was briefly explained. It was also declared that the task of the study would be to learn the names and spatial relations of structures from a human shoulder and that the examiner would be present and could be talked to during the whole process. After putting the *HTC Vive* headset on, the participants had to start the *Exploration* Mode. To convey the idea of this mode, the participants first started it using the simple model of a *Rubik's Cube*. It did not pose a problem to the participants that the real-world functionality of this toy had not been recreated in our application (recall Section 3.2.4). They could freely explore the model using the different features of this mode. Every feature was explicitly introduced by the examiner. Afterwards, they had to restart the mode, but this time use the shoulder model.

The next step was to actually solve a puzzle by using the *Training* Mode. This mode was first introduced with the *Rubik's Cube* model. Using the jigsaw puzzle metaphor, the task was thoroughly described by the examiner. Afterwards, the participants restarted the mode using the shoulder model. This evaluation segment was further divided. At first, all feedback mechanisms had to be disabled by the participants. Now, they had to try to solve the task without any feedback. Following this, the five feedback mechanisms were iterated so that the participants could only use one mechanism at a time. The order the feedback mechanisms had to be used was randomly decided for each participant. After having used each feedback mechanism once, the participants were given some time to freely solve the puzzle.

Finally, the participants had to start the *Testing* Mode. For this segment, the *Assembly* variation of the mode was used. As with the previous segments, this mode was first introduced with the *Rubik's Cube* model followed by the shoulder model. Each step of this evaluation was strictly timed so that each participant had exactly the same time available for each step.

The participants had to answer questionnaires before and after each step of the evaluation. Beside demographic questions, the familiarity with VR software was determined. The questionnaire focused on the usability of the modes and feedback mechanisms. The participants had to rate these on a scale from 1 to 5, with 1 being the worst and 5 being the best, in terms of comprehensibility and usefulness. The participants were also asked to give an assessment of the relevance of the application in general.

4.2 Results

The group of participants mainly consisted of people that were eager to experience a VR application. For this reason, the presentation of results from the pilot run will focus on qualitative information. Results from the informal evaluation process are individually presented for the different puzzle modes and the feedback mechanisms.

Participants. Ten persons (two females, all persons aged between 24 and 32 years) participated in the study. Three participants were left-handed. One participant suffers from a mild red-green color vision deficiency. Half of the participants were majoring in computer science. Two participants were engineering students. Of the remaining participants, two were psychologists and one was a paramedic.

The two psychologists had to learn the anatomy of the human skull and the human brain during their curriculum. The paramedic

had to gain comprehensive basic knowledge about human anatomy during his apprenticeship and even took part in an actual dissection as preparation for his future career. Thus, these three participants and their impressions are further referenced as *participants of interest* (POIs). Due to their educational background, all participants were familiar with computer systems and 3D applications.

Exploration. All participants enjoyed exploring the *Rubik's Cube* model, as they were familiar with it. Everyone commented that it would be interesting if the pieces could actually be rotated like in the real world counterpart. Even though this remark seemed not to be relevant at first, similar comments were related to the shoulder model. Here, the *POIs* noted that anatomical structures are not always attached to their adjacent neighbors, as implied by the nature of the 3D puzzle. As an example the jawbone was mentioned, which is only attached to the skull at specific fixation points. Understanding such functional relations can be very helpful for understanding spatial relations.

In general, all participants understood the purpose of this mode and liked the general concept of the 3D puzzle. After randomly scattering the pieces using the *Explosion* feature, the participants tried to assemble different structures and would then watch where this assembled structure is located in the completed model. Furthermore, the *POIs* noted that the possibility to freely scale, rotate and move the whole model and individual pieces in this VR environment was a great feature which gave the application a huge advantage over the learning methods they used when they gained their anatomical knowledge.

Four participants explicitly wished for additional “entertaining” features. As the main purpose of this application is educational and not entertaining, this remark needs to be evaluated accordingly.

Training. The task and purpose of this mode was easily understood by all participants. While being confronted with the *Rubik's Cube* model, most of the participants already underestimated the difficulty of the puzzle task. This mindset changed immediately when the participants encountered the scattered shoulder model. For the first minute, where no feedback mechanism was active, none of the participants managed to assemble any pieces. The same occurred during the following five minutes where the participants had to try out each feedback mechanism individually.

Afterwards, when the participants were allowed to freely use any feedback mechanism combination they preferred, the situation improved. Every participant immediately activated the vibrotactile feedback and the *Ghost Copy*. Four participants also activated the *Tinting* while two chose the *Elastic Strings*. The *Display* was used by no participant at all. With the help of this feedback mechanisms all participants were able to assemble some parts of the structure. Most of them focused on parts that were somehow familiar, such as the rib cage or the arm bones.

While no participant was able to finish the puzzle in time, the most progress was gained by the paramedic. This participant attributed his performance to the limited amount of time and the fact that the smaller pieces are very hard to select with the laser, especially if one is not used to the controllers.

All other participants explained their performance with the absence of relevant anatomical knowledge. For an average user without prior anatomical knowledge, this task was rated as too difficult.

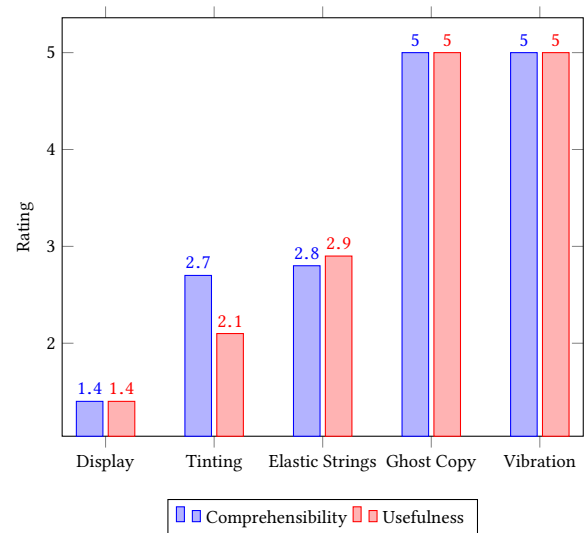


Figure 11: The ratings of the feedback mechanisms with 1 being the worst and 5 being the best.

However, all participants remarked that they would most likely be able to solve the puzzle of a model they are familiar with. All participants agreed that the basic idea behind this mode is enjoyable and remarked that an actual medical student would most likely perform better.

Testing. Similar to the *Training* mode, no participant was able to solve the task of this mode. Apart from the paramedic, all participants first relied on a trial-and-error search for the stated pieces and then used the vibrotactile feedback and the *Ghost Copy* to assemble them. Due to his experience from the prior mode, the paramedic was able to easily identify most of the pieces and assemble them using the same feedback mechanisms as before. Again, due to the small pieces being too difficult to select, he was not able to finish the task. This mode was well received by all participants. Despite their performance, all participants claimed that this mode was really “fun” and could see the relevance in an educational scenario.

Feedback mechanisms. As all feedback mechanisms were initially presented to the participants, it was up to them to later choose which mechanism they prefer. The presence of the feedback mechanisms was very much appreciated, even though some were clearly more useful than others (see summarized results in Figure 11).

According to the questionnaire, the *Display* mechanism was rated as useless and incomprehensible. All participants agreed that they were not able to translate the shown values into the movements they had to make to assemble pieces.

Contrary to the *Display* mechanism, the participants agreed that the *Ghost Copy* was very useful. According to all participants it was the only mechanism that supported to adjust the correct orientation of the pieces. Seven participants put this further into perspective by saying that even if the *Ghost Copy* suggests the correct orientation, it is still not easy to fit the piece into the shown shape. This is not attributed to inaccurate interaction with the virtual world, but to the fact that many structures do not have very significant features

that are required to compare a piece to its *Ghost Copy*. Especially for muscular structures it is hard to tell which orientation is the correct one.

The vibrotactile feedback was appreciated as well. While the vibrotactile feedback was not immensely helpful with orienting the pieces, it was the most significant indicator for a successful snapping attempt. Without it, participants performed significantly worse and felt more “helpless”, according to their statements.

The *Elastic Strings* and the *Tinting* were met with mixed feelings (see Figure 11). Half of the participants did not even use either of these mechanisms after initially trying them out. According to the participants, the idea behind the *Elastic Strings* was clear, but it was not always easy to comprehend which movements are necessary to align the pieces correctly. The people that kept using the *Tinting* said that this mechanism was a great addition to the vibrotactile feedback and the *Ghost Copy*.

The results of the questionnaire clearly show that the participants preferred the combination of vibrotactile feedback and *Ghost Copy*. Some participants additionally named the *Tinting* as a preferred addition. No participant included the *Display* feedback or the *Elastic Strings* feedback in their list of favorites.

General Remarks and Suggestions for Improvement. According to the participants’ statements, neither of them experienced any effects of nausea while using the application. Some remarked that they indeed experienced light exhaustion after using the application for more than an hour. They attributed this to the fact that they had to hold up their arms for a long time. In this context, they agreed that sitting on a chair might help to reduce such effects.

The choice of the dark red - light green hue for some of the feedback mechanisms was considered acceptable and the participant with color vision deficiency said he was clearly able to discriminate the hues.

All participants agreed that it was intuitive and to a certain degree natural to select and grab the pieces. However, the selection of small objects that were far away required too much accuracy with the laser from the participants. This was mellowed by the possibility to easily get objects to come closer once they were successfully grabbed. Nevertheless, a feature should be provided that makes it easier to select small far away objects. A possibility would be an adjustment of the size of the laser to increase the potential selection area.

Some participants remarked that the names of the different feedback mechanisms were not always intuitive and that they sometimes confused the mechanisms.

Both engineering students agreed that working with an application like this would be very welcome in their curriculum as well. This suggests that the concept of a 3D VR puzzle is potentially interesting for students that are looking for non-traditional ways of gaining knowledge. The *POIs* noted that it would be an interesting addition to not only connect the pieces like a puzzle, but to consider how they are actually attached to each other. Adjacent parts in a real human body are not always conjoined, as suggested in the current state of our application. This would require a whole new approach for the functionality of a 3D puzzle.

They further noted that it would be interesting to provide models that are as lifelike as possible. Not only the shape and the texture

of the anatomic structures should be photorealistic, but even their consistency could be conveyed. Real life muscle tissue is, for example, not as rigid as the application presents it. For many students it could be interesting to get an impression of how soft or even fragile some anatomical structures actually are.

The only participant that has actually attended a real life dissection, the paramedic, really enjoyed the prototype. He agreed that it is imaginable to supplement anatomy education with an application like this. Even though he is well aware of the problems that come with real life dissections, he declared that these procedures would be irreplaceable in the context of anatomy education.

5 CONCLUSION

The presented immersive approach for interactive learning challenges the user with the task of assembling virtual 3D models of anatomical structures. This task is inspired by real world jigsaw puzzles. To create a comprehensive educational experience, the application features three modes that either provide knowledge to the user, let the user review their knowledge or let them apply their knowledge to an unknown scenario. The application provides feedback mechanisms that support the assembly of the anatomical structures. Even though some of the presented feedback mechanisms were positively received by the users, it needs to be discussed which mechanisms are actually beneficial for which scenario of the use case. Our results might suggest that some solutions might oversimplify the process of *Training* or *Testing*.

The pilot indicates that the overall concept is feasible and generally led to positive comments. The interaction with the virtual objects is precise and intuitive and operating the user menu poses almost no challenge for inexperienced users. The selection of small, far away objects is still a subject for improvement. As the prototype has not been tested with the target audience, another more thorough user study is required that specifically includes medical students that do not yet have extensive anatomical knowledge. It is also required to further evaluate the feasibility of the application for users that are not able to unrestrictedly use contemporary virtual reality technologies; for example users with problems of stereoscopic perception. The study must also run on a long-term basis to determine if potential educational benefits regarding retention can be attributed to the proposed system.

The educational scenario contains a basic set of features required to teach anatomical knowledge with a 3D VR puzzle. Instead of providing multiple 3D models, the system could provide a complete model of the human body, where the user can choose an area of interest from. This could create the possibility to get a more comprehensive understanding of the spatial relations of certain parts and lets the user additionally decide which information is relevant for the current learning session. Likewise, it is necessary to look into potentials to improve the user’s experience and performance; e.g. by adding widgets that make it easier to judge the orientation of single parts. The learner’s performance could also benefit from supplementary *gamification* features that reinforce the entertainment aspect of the application. Further, it is inevitable to evaluate the potential of collaborative work in virtual reality in the context of medical education.

REFERENCES

- [1] MJ Ackerman, VM Spitzer, AL Scherzinger, and DG Whitlock. 1995. The Visible Human data set: an image resource for anatomical visualization. *Medinfo. MEDINFO* 8 (1995), 1195–1198.
- [2] Steven Birr, Jeanette Mönch, Dirk Sommerfeld, Uta Preim, and Bernhard Preim. 2013. The LiverAnatomyExplorer: a WebGL-based surgical teaching tool. *IEEE computer graphics and applications* 33, 5 (2013), 48–58.
- [3] Doug A Bowman. 2002. *Principles for the design of performance-oriented interaction techniques*. Lawrence Erlbaum Associates, Hillsdale, NJ, USA, 277 pages.
- [4] Doug A Bowman, Jian Chen, Chadwick A Wingrave, John F Lucas, Andrew Ray, Nicholas F Polys, Qing Li, Yonca Hacıahmetoglu, Ji-Sun Kim, Seonho Kim, et al. 2006. New directions in 3D user interfaces. *IJVR* 5, 2 (2006), 3–14.
- [5] Henrik Buchholz, Johannes Bohnet, and Jurgen Dollner. 2005. Smart and physically-based navigation in 3D geovirtual environments. In *Ninth International Conference on Information Visualisation (IV'05)*. IEEE, IEEE, London, UK, 629–635.
- [6] Angela Chang, Sile O'Modhrain, Rob Jacob, Eric Gunther, and Hiroshi Ishii. 2002. ComTouch: design of a vibrotactile communication device. In *Proceedings of the 4th conference on Designing interactive systems: processes, practices, methods, and techniques*. ACM, ACM, ACM, NY, USA, 312–320.
- [7] L. Chittaro and R. Ranon. 2007. Web3D technologies in learning, education and training: motivations, issues, opportunities. *Computers & Education* 49, 1 (2007), 3–18.
- [8] Luca Chittaro and Roberto Ranon. 2007. Web3D Technologies in Learning, Education and Training: Motivations, Issues, Opportunities. *Comput. Educ.* 49, 1 (2007), 3–18.
- [9] Chris Fowler. 2015. Virtual reality and learning: Where is the pedagogy? *British Journal of Educational Technology* 46, 2 (2015), 412–422.
- [10] Jennifer C Greene, Valerie J Caracelli, and Wendy F Graham. 1989. Toward a conceptual framework for mixed-method evaluation designs. *Educational evaluation and policy analysis* 11, 3 (1989), 255–274.
- [11] Michael Halle, Valentin Demeusy, and Ron Kikinis. 2017. The open anatomy browser: a collaborative web-based viewer for interoperable anatomy atlases. *Frontiers in neuroinformatics* 11 (2017), 22.
- [12] Karl-Heinz Hohne, Bernhard Pflesser, Andreas Pommert, Martin Riemer, Thomas Schiemann, Rainer Schubert, and Ulf Tiede. 1996. A virtual body model for surgical education and rehearsal. *Computer* 29, 1 (1996), 25–31.
- [13] Susan Jang, Jonathan M. Vitale, Robert W. Jyung, and John B. Black. 2017. Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment. *Computers & Education* 106 (2017), 150–65.
- [14] Sankar Jayaram, Hugh I Connacher, and Kevin W Lyons. 1997. Virtual assembly using virtual reality techniques. *Computer-aided design* 29, 8 (1997), 575–584.
- [15] Nigel W John. 2007. The impact of Web3D technologies on medical education and training. *Computers & Education* 49, 1 (2007), 19–31.
- [16] Lindsay W MacDonald. 1999. Using color effectively in computer graphics. *IEEE Computer Graphics and Applications* 19, 4 (1999), 20–35.
- [17] Stefan Marks, Javier E Estevez, and Andy M Connor. 2014. Towards the Holodeck: fully immersive virtual reality visualisation of scientific and engineering data. In *Proc. of the International Conference on Image and Vision Computing New Zealand*. ACM, ACM, ACM, NY, USA, 42–47.
- [18] Dave Meier. 2000. *The accelerated learning handbook: A creative guide to designing and delivering faster, more effective training programs*. McGraw Hill New York, New York, USA.
- [19] E. Messier, J. Wilcox, A. Dawson-Elli, G. Diaz, and Linte C. A. 2016. An Interactive 3D Virtual Anatomy Puzzle for Learning and Simulation - Initial Demonstration and Evaluation. *Stud Health Technol Inform.* 20 (2016), 233–40.
- [20] Mariana Flavia Mota, Fabiana Ribeiro da Mata, and Tales Alexandre Avers-Ferreira. 2010. Constructivist Pedagogic Method Used in the Teaching of Human Anatomy. *International Journal of Morphology* 28, 2 (2010), 369 – 374.
- [21] Daren T Nicholson, Colin Chalk, W Robert J Funnell, and Sam J Daniel. 2006. Can virtual reality improve anatomy education? A randomised controlled study of a computer-generated three-dimensional anatomical ear model. *Medical education* 40, 11 (2006), 1081–1087.
- [22] Jakob Nielsen. 2012. Thinking aloud: The# 1 usability tool.
- [23] Ian Pitt, Bernhard Preim, and Stefan Schlechtweg. 1999. An evaluation of interaction techniques for the exploration of 3d-illustrations. In *Proc. of Software-Ergonomie*. Vieweg+ Teubner Verlag, Wiesbaden, Germany, 275–286.
- [24] Bernhard Preim, Andreas Raab, and Thomas Strothotte. 1997. Coherent zooming of illustrations with 3D-graphics and text. In *Graphics Interface*, Vol. 97. Canadian Information Processing Society, Toronto, Ont., Canada, 105–113.
- [25] Bernhard Preim and Patrick Saalfeld. 2018. A Survey of Virtual Human Anatomy Education Systems. *Computers & Graphics* 71 (2018), 132–153.
- [26] Felix Ritter, Bettina Berendt, Berit Fischer, Robert Richter, and Bernhard Preim. 2002. Virtual 3d jigsaw puzzles: Studying the effect of exploring spatial relations with implicit guidance. In *Mensch & Computer 2002*. B. G. Teubner, Stuttgart, Germany, 363–372.
- [27] Felix Ritter, Bernhard Preim, Oliver Deussen, and Thomas Strothotte. 2000. Using a 3d puzzle as a metaphor for learning spatial relations. In *Graphics Interface*. Morgan und Kaufman, (Montréal, Qc, Canada, 171–178.
- [28] Felix Ritter, Thomas Strothotte, Oliver Deussen, and Bernhard Preim. 2001. Virtual 3d puzzles: A new method for exploring geometric models in vr. *IEEE Computer Graphics and Applications* 21, 5 (2001), 11–13.
- [29] GS Ruthenbeck, CJ Carati, IL Gibbins, and KJ Reynolds. 2008. A virtual reality 3D jigsaw for teaching anatomy. *interfaces* 6 (2008), 7.
- [30] Jinsil Hwaryoung Seo, Brian Michael Smith, Margaret Cook, Erica Malone, Michelle Pine, Steven Leal, Zhikun Bai, and Jinkyoo Suh. 2018. Anatomy Builder VR: Applying a Constructive Learning Method in the Virtual Reality Canine Skeletal System. In *Advances in Human Factors in Training, Education, and Learning Sciences*, Terence Andre (Ed.). Springer International Publishing, Cham, 245–252.
- [31] R Sherman William and B Craig Alan. 2002. Understanding virtual reality: Interface, application, and design.
- [32] Mel Slater, Vasilis Linakis, Martin Usoh, and Rob Kooper. 1996. Immersion, presence and performance in virtual environments: An experiment with tridimensional chess. In *Proc. of the ACM Symposium on Virtual Reality Software and Technology*. ACM, ACM, NY, USA, 163–172.
- [33] Noeska Smit, Cees-Willem Hofstede, Annelot Kraima, Daniel Jansma, Marco deRuiter, Elmar Eisemann, and Anna Vilanova. 2016. The online anatomical human: web-based anatomy education. In *Proceedings of the 37th Annual Conference of the European Association for Computer Graphics: Education Papers*. Eurographics Association, Lisbon, Portugal, 37–40.
- [34] Victor M Spitzer and David G Whitlock. 1998. The visible human dataset: the anatomical platform for human simulation. *The Anatomical Record: An Official Publication of the American Association of Anatomists* 253, 2 (1998), 49–57.
- [35] John Strobel and Guy W Zimmerman. 2011. Effectiveness of paper, VR and stereo-VR in the delivery of instructions for assembly tasks. *Journal of Computer Information Systems and Industrial Management Applications* 3, 11 (2011), 578–585.
- [36] Desney S. Tan, George G. Robertson, and Mary Czerwinski. 2001. Exploring 3D navigation: combining speed-coupled flying with orbiting. In *Proc. of ACM SIGCHI Conference on Human Factors in Computing*. ACM, ACM, NY, USA, 418–425.
- [37] Hong Z Tan, Nathaniel I Durlach, William M Rabinowitz, Charlotte M Reed, and Jonathan R Santos. 1997. Reception of Morse code through motional, vibrotactile, and auditory stimulation. *Perception & psychophysics* 59, 7 (1997), 1004–1017.
- [38] Ulf Tiede, Michael Bomans, Karl Heinz Höhne, Andreas Pommert, Martin Riemer, Thomas Schiemann, Rainer Schubert, and Werner Lierse. 1993. A computerized three-dimensional atlas of the human skull and brain. *American Journal of Neuroradiology* 14, 3 (1993), 551–559.