Using a 3D Puzzle as a Metaphor for Learning Spatial Relations

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Abstract

We introduce a new metaphor for learning spatial relations—the 3D puzzle. With this metaphor users learn spatial relations by assembling a geometric model themselves. For this purpose, a 3D model of the subject at hand is enriched with docking positions which allow objects to be connected. Since complex 3D interactions are required to compose 3D objects, sophisticated 3D visualization and interaction techniques are included. Among these techniques are specialized shadow generation, snapping mechanisms, collision detection and the use of two-handed interaction.

The 3D puzzle, similar to a computer game, can be operated at different levels of difficulty. To simplify the task, a subset of the geometry, e.g., the skeleton of an anatomic model, can be given initially. Moreover, textual information concerning the parts of the model is provided to support the user. With this approach we motivate students to explore the spatial relations in complex geometric models and at the same time give them a goal to achieve while learning takes place. A prototype of a 3D puzzle, which is designed principally for use in anatomy education, is presented.

Keywords: Metaphors for spatial interaction, interactive system design, 3D interaction

1 Introduction

In many areas, learning involves the understanding of complex spatial phenomena. In engineering, the construction of machines has to be mastered as a prerequisite for maintenance purposes. To replace a part of a complex engine, a subset has to be decomposed in a well-defined sequence. The spatial composition of molecules is important in chemistry.

Probably the most complex system known to mankind is the human body. Therefore, medical students have considerable difficulties in imagining the spatial relations within the human body which they have to learn in anatomy. With interactive 3D computer graphics, based on high resolution geometric models, these spatial relations may be explored. To exploit this potential, dedicated 3D interaction and visualization techniques as well as convincing metaphors have to be developed.

The book metaphor as a general metaphor for the design of educational systems is well suited to structure the information contents, but is inadequate for learning spatial relations by itself. This is better performed by the atlas metaphor which offers more pictorial contents and is often based on 3D models which can be viewed from different directions [16]. In anatomy, for example, most of the systems available for learning spatial relations are based on this metaphor: Students explore geometric models and related textual information in a way inspired by a printed atlas. The leading example is the VOXELMAN [6] which additionally allows to remove parts of 3D models. Another more recent system is the ZOOM ILLUSTRATOR [14] which includes generated figure captions and sophisticated strategies to label 3D objects—both of which are inspired directly by anatomic atlases.

However, the atlas metaphor does not imply particular 3D interaction techniques. Though 3D interaction is provided to a certain extent, user studies have shown that students underutilize these possibilities or are even unaware of their existence [12]. Therefore, it is particularly useful to structure the user interface of such a learning system on the basis of a spatial metaphor and to provide specific tasks which necessarily include 3D interaction.

Based on the above observation, we introduce the metaphor of a 3D puzzle for learning spatial relations: Users compose specific geometric models from elementary objects. This idea was inspired by an empirical evaluation of the ZOOM ILLUSTRATOR with physicians and students of medicine [12]. Several students expressed the desire for more powerful 3D interaction like assembling parts of the model.

The paper is organized as follows: First we introduce the 3D puzzle metaphor and compare it with a related metaphor for spatial interaction. Then, the basic interaction tasks to be fulfilled by a learning system based on this metaphor are presented. In the next section, the requirements for the visualization and the 3D interaction techniques are discussed. We then focus on the realization of our 3D puzzle. An informal evaluation based on a scenario in medicine concludes the paper.

2 Metaphors for the Composition of 3D Models

Interactive systems, especially new and unfamiliar applications, should be based on metaphors [2]. Using metaphors helps interface designers to structure the design and supports users to handle the system. Metaphors should have their origin in daily life or in the work environment of the intended users. In the following we describe metaphors for the composition of 3D models. In particular we discuss the differences between the well-known construction-kit metaphor and our new 3D puzzle metaphor.

The Construction-Kit Metaphor: This wide-spread metaphor is used mainly in advanced CAD systems. Elementary objects are combined in varying ways to compose different models. The design of cars, for example, is based on various CAD models from different sources which are assembled into virtual prototypes using sophisticated 3D interaction techniques.

An interesting system based on this metaphor was developed in the VLEGO project [9]. Users take primitives, like LEGO bricks, and combine them at discrete, predefined positions and angles. Dedicated 3D widgets are provided for all 3D interaction tasks: composition, separation, picking, and copying. These 3D widgets can be handled with a 3D input device and for most of the 3D interaction tasks a two-handed interaction is suggested. Another example is Multigen's SmartScene product [11] which has been developed for construction and construction training in highly immersive environments.

In contrast to designing 3D-models using the construction-kit metaphor, learning of spatial relations requires the user to focus on unique parts which can be assembled in only one correct manner. Therefore, a new metaphor is required for the composition of complex models from unique elements.

The Metaphor of a 3D Puzzle: A 3D puzzle is a familiar concept for the composition of a *specific* 3D model. Consequently the puzzle metaphor is more appropriate for this task. Moreover, the clearly stated goal of the 3D puzzle—to assemble a given 3D model—motivates the user to focus on the spatial relations within this model.

This raises a question: Which aspects of a 3D puzzle can and should (from a user's point of view) be realized? In a puzzle, a set of elementary objects should be composed. The shape of these objects gives an indication as to which parts belong together. When working with dozens or even hundreds of objects, several deposits (e.g. tables) are used to sort and compose subsets. Obviously, when doing a puzzle one uses both hands and has all degrees of freedom of spatial interaction. In a puzzle, photos are provided to show how the final composed image (or 3D model) looks. These images motivate users and help them to perform the composition. These aspects should be included in a computer-supported 3D puzzle.

Our design has been guided by the metaphor of a 3D puzzle but differs in some major respects from real puzzles:

- Our system is intended to support learning rather than just providing entertainment.
- It is restricted as to what can be achieved in real time but offers additional possibilities in that the computer "knows" how the model should be assembled. This can be used to give guidance to the user.
- Textual cues can be integrated to provide additional information about the objects being composed.

In anatomy, for instance, objects have names, belong to regions and organ systems (e.g. an eye muscle), and have textual explanations as to their shape. This information may be exploited in order to place objects in the right position.

3 Interaction Tasks with a 3D Puzzle

In this section we describe the tasks which need to be accomplished in order to realize the metaphor of a 3D puzzle for learning spacial relations. Actually, there are two kinds of users:

- *authors* who prepare models

  The author segments the model or refines an existing structure, defines the position, shape, and color of docking points; and assigns related textual information. Furthermore, he or she decides on the level of difficulty (which objects are composed initially, which user support is made available, e.g. snapping).
- *students* who use the provided information space

  Students are able to adjust the level of difficulty in asking the system for assistance and additional information. They are, however, not allowed to change the structure of the prepared model itself.

In this paper we restrict ourselves to describing how students explore the information space and assume that it is carefully defined by an author. For students some typical interaction tasks include:

Recognition of objects: Two factors are crucial for the identification of objects: to be able to see an object from all viewing angles and to be able to inspect textual information as to spatial relations (e.g. name, description of shape). Therefore, direct manipulation of the camera is required to be able to inspect individual objects. From the experience Preim et al. described in [13] we hypothesize that visual and textual information mutually reinforce one another in their effect upon the viewer.

Selection of objects: The selection of 3D objects is the prerequisite for 3D interaction. Picking, typing the object name and choosing the name from a list are possible interaction techniques for this task.

Grouping of objects: The student must be able to create and manage subsets of the total set of objects. These subsets should be placed in separate views which

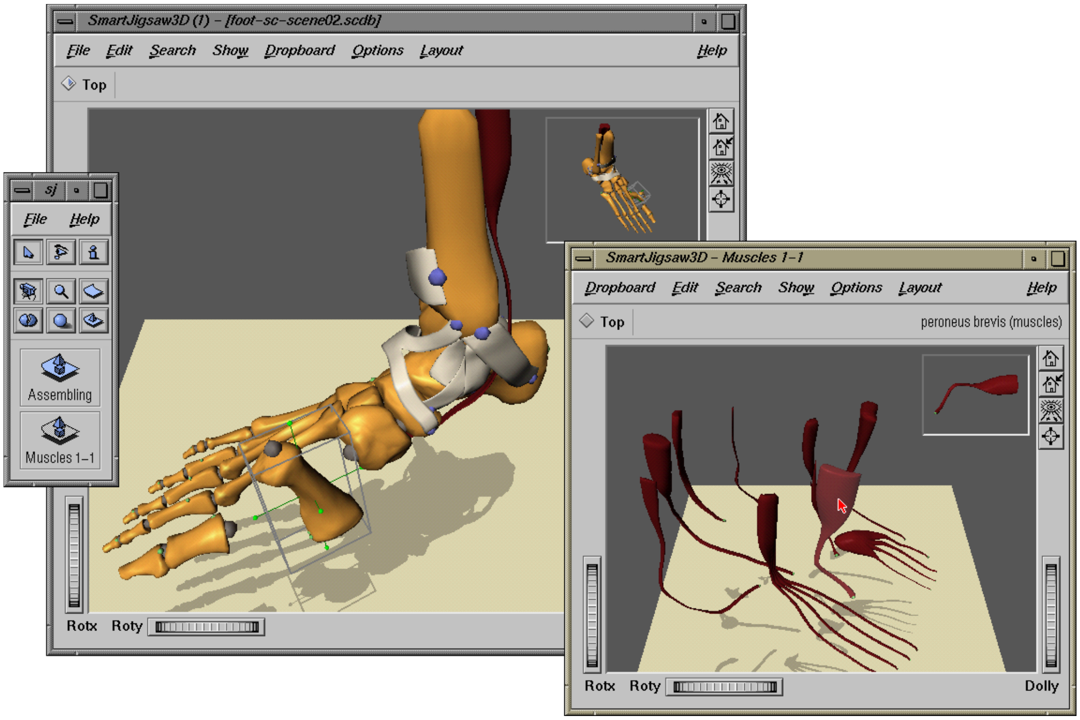

Figure 1: Overview of the interface: In the left view sinews and bones are composed, while in the right view muscles are randomly scattered. The small panel on the left provides an overview on all views.

can be named by the user. Within these views, 3D interaction is required to enable users to explore this subset. As not all views might be visible at the same time, an overview of existing views is crucial.

Transformation of objects: The transformation task includes translating and rotating 3D objects. Since this is the tasks the student is required to spend most of the time on, the success of learning the spatial relations highly depends on the selected interaction techniques.

Docking of objects: The final goal of exploring, selecting and transforming a set of 3D objects is to assemble objects at the "right" docking positions. Less obvious is that objects sometimes have to be separated. For instance, if objects in deeper layers must be assembled first but have been forgotten, objects in the outer areas may have to be decomposed to allow objects to be placed inside.

4 Visualization and Interaction Techniques

After describing the interaction tasks we now focus on what is necessary to support the user in perceiving the spatial relations.

4.1 Visualization of the 3D model

A 3D puzzle requires precise interaction in 3D and thus the simulation of depth cues and 3D interaction techniques similar to those in the real world. Humans perceive depth-relations particularly from the following depth cues [18]:

- shadows
- occlusion of objects
- partial occlusion of semi-transparent objects
- perspective foreshortening
- motion parallax
- stereoscopic viewing

Some of these depth cues, such as occlusion and perspective foreshortening, are part of standard renderers and are implemented in hardware. Shadow generation is usually not supported. In an evaluation, Wanger et al. [17] demonstrated that a shadow cast on the ground is the most important depth cue for distance estimation and shape recognition. Therefore, we developed a specialized view which provides shadow projection.

On graphics workstations with hardware-based alpha-blending, the display of semi-transparent objects and stereoscopic viewing is also feasible in real-time. As demonstrated in [7], motion parallax can be used most efficiently if the user has direct control over this effect. Thus we incorporated interaction techniques which allow the user the parallel manipulation of camera and objects. Even though user-controlled motion parallax is perceived, binocular disparity provides a strong additional depth cue [7].

4.2 Interaction with the 3D model

On the basis of a comprehensible rendition of objects, 3D interaction is possible. The design of 3D interaction techniques must take into account how humans interact in the real world. The following aspects are essential for interaction in the real world:

Collision detection: When one object touches another, it is moved away or will be deformed. Under no circumstances can one object be moved through another without deformation. We regard collision detection as one of the most important aspects of 3D interaction for the puzzle metaphor. However, this is a challenging task if complex non-convex objects are involved.

Two-handed interaction: People tend to use both hands if they manipulate 3D objects [3]. In medicine, two-handed interaction has been successfully applied, e.g., for pre-operative planning in neurosurgery. Hinckley et al. argue in [4] that for the interaction tasks involved (e.g. exploration of a brain with free orientation of head and cutting plane), the most intuitive handling can be achieved with two-handed 3D interaction where the dominant hand does fine-positioning relative to the non-dominant hand. In an empirical evaluation they demonstrated that physicians use these interaction techniques efficiently after only a short learning period.

Tactile feedback: When we grasp an object we receive tactile feedback which enables us to adapt the pressure to the material and weight of the object. Tactile feedback requires special hardware, such as data gloves with force feedback. To avoid the overhead with such an input device, we have not integrated this technique so far.

5 The Realization of the 3D Puzzle

The 3D puzzle incorporates the visualization and interaction techniques described in the section before. Our prototype is based on polygonal models (30,000 to 50,000 polygons segmented into 40 to 80 objects). The software is written in C++ using OPEN INVENTOR and OPENGL.

In addition to techniques required to enable users to compose models, some methods from technical and medical illustration have been added to further improve the understanding of spatial relations. In particular, students should be supported in the exploration of the final model before and during the composition. As mentioned above, the integration of names and short explanations is essential for the understanding.

For learning purposes it is also crucial that it is neither too easy nor too difficult to attach objects correctly. As the appropriate level of difficulty strongly depends on the task—the model to compose—and the user, enough flexibility must be provided to tailor the system.

The puzzle starts with two views: the *construction view* in which the user composes the model and a *deposit view* in which objects which do not belong to the construction view are randomly scattered. The initial position of the objects is adjusted such that they do not overlap (see Figure 1). In order to enhance the overview, an individual name can be assigned to each view, e.g. to circumscribe the subset of objects.

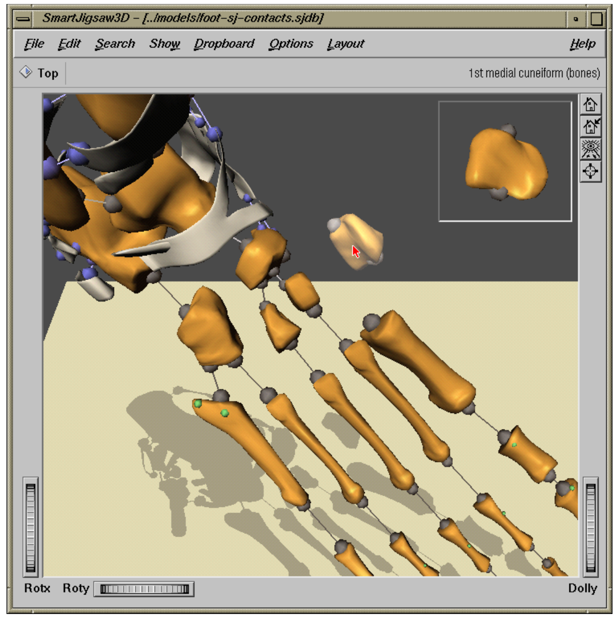

Figure 2: Exploded view of the partly composed model. Already connected docking points are interconnected by lines.

5.1 Recognition of objects

To improve the recognition of objects, we developed a shadow view with a light groundplane. This groundplane is scaled such that all objects cast a shadow on it whereby the orientation remains fixed with regard to the camera. Furthermore, we provide a detailed view like an inset in technical illustrations to allow the user to focus on the currently selected object. The object in this view is presented slightly enlarged without any occluding objects; it is rotated automatically to facilitate the perception of the shape (see the upper right of Figure 2).

To further support the recognition of objects, they are highlighted when touched by the pointing device. The object name and category (e.g. muscles) are displayed in the upper part of the viewer (see Figure 1). A double-click yields a short explanation as to the position and shape of this object. The structure of these explanations is inspired by anatomical atlases where this information is provided to support the understanding of the images.

In technical illustrations, exploded views are provided to improve the recognizability of objects and to enable users to become familiar with the spatial relations. In anatomy, exploded views reveal how bones are attached to each other—an important aspect (in manual drawings, as can be found in books, bones are deliberately separated). Exploded views are realized by scaling down all objects at their original positions, thus leaving empty space. The transition to this view is shown in a continuous change to be easily understood. As the connectivity and grouping of objects is known from the definition of contact points it can be considered in the generation of exploded views. We use this information to visually connect the docking points of the already composed objects by lines (Figure 2).

Motivated by the photos on the package of a real 3D puzzle which help the user to find the right place for a puzzle piece, we provide a *final view* where the model as such is displayed. The user may freely manipulate the camera and explode the model to explore insight objects.

We also integrated stereo-rendering which is realized as an extension of the Silicon Graphics X-Server and requires the use of shutter glasses to perceive the stereoscopic images.

5.2 Selection of objects

Selection by picking with a pointing device is the interaction inspired by the real 3D puzzle. Picking is useful but limited to objects which are visible and recognizable. Possible alternatives are selection by name or from a list. Since typing long anatomic names is tedious, an auto-complete mechanism is employed to expand names. When one of these textual interaction techniques is used, the selected object will be highlighted to provide feedback. If the object belongs to a view currently occluded it is sent to the front to make it visible. Moreover, the object might be occluded within its view. If this is the case, it is moved continuously towards the viewer until it is in front of other objects. In addition, semi-transparency can be used, so that all objects except the one selected by name are semi-transparent.

5.3 Grouping of objects

For the management of the objects, subsets can be created and attached to an unlimited number of 3D views. For this purpose, multiple selection of objects is possible. In addition, all objects in a region or category might be selected. The command “create view” opens a new view and moves all selected objects to this view while the relative position of the objects is preserved. An overview with icons for all views is presented to enable switching between them (recall Figure 1). In order to enhance the overview, an individual name may be assigned to each view. While the final view is read-only, objects can be exchanged between the other views by drag-and-drop (objects may be dropped either in the views or the corresponding icon in the overview).

5.4 Transformation of objects

The transformation of selected 3D objects is performed by direct manipulation of a surrounding 3D widget (Figure 3). This Transformer manipulator from OPEN INVENTOR makes it possible to translate and rotate the attached object with a 2D mouse. However, with a standard 2D mouse users often need to decompose 3D translations and rotations in sequential 2D transformations. It

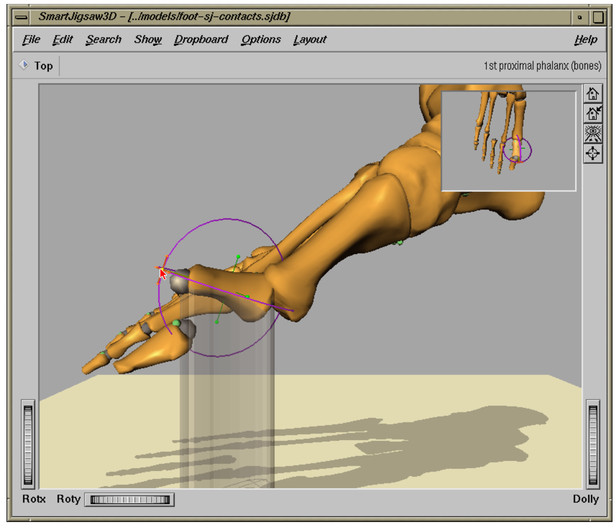

Figure 3: An object has been snapped at one docking point. The transformation is now restricted to the rotation to correctly orient this object.

is more effective to use several degrees of freedom (DOF) simultaneously like in reality. For this purpose a 3D mouse (Logitech Magellan) can be employed. To avoid unnecessarily complicated manipulations which may frustrate the user, the rotation of the objects is constrained to steps of 45 degrees. With this constraint users still have enough possibilities to rotate an object incorrectly. During transformation, the inset offers a different view on the manipulated object (see the upper right corner in Figure 3).

Collision detection

Collision detection prevents objects from being moved through others. When objects collide they are highlighted for a moment to provide visual feedback. If the user continues to attempt to move an object through another one, an acoustic signal is initiated and textual output is provided in the status line. We incorporated the software library V-COLLIDE [8] for collision detection, which accomplishes this test in a robust manner. The software also provides an interface which allows us to determine precisely on which objects the test is carried out. Thus, we restrict collision detection to the currently manipulated object, reducing the processing load considerably.

Since the objects in our puzzle cannot be deformed it is difficult to place an object immediately between two others. Normally, collisions cannot be avoided by the user in this case. Therefore, collision avoidance is disabled automatically if docking points are about to snap, but collisions are still detected and reported to the user.

Semi-transparent shadow volumes

A particularly useful technique for supporting the user during object translation is to connect the object and its casting shadow visually. The resultant shadow volume is

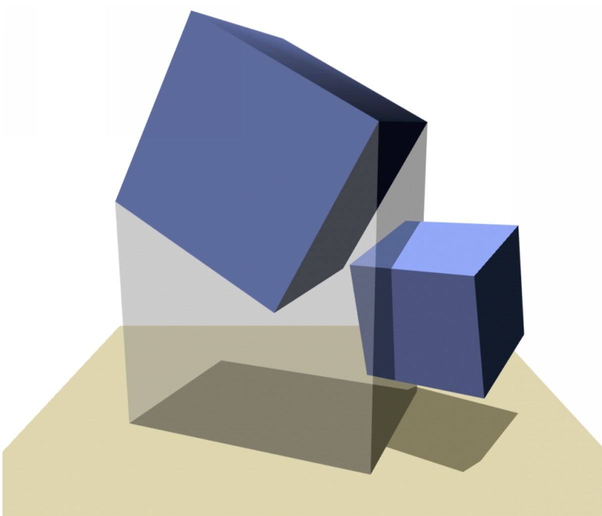

Figure 4: To ease the positioning task, a semi-transparent shadow volume is rendered for the manipulated object.

rendered by semi-transparent surfaces. As stated in Zhai et al. [18], semi-transparent volumes facilitate the perception of depth relations. Thus the correspondence of the object and the attached shadow volume helps to recognize the spatial relation between the object and its immediate neighborhood (see Figure 4 and Figure 3).

5.5 Composition and separation of objects

Objects are composed correctly if the docking points (e.g. spheres) touch each other. To ease this task, a snap mechanism is included (Figure 3). With snapping enabled, objects snap together if their distance is below a given threshold. If more than one docking point is in the immediate vicinity the behavior depends on the author's predetermination. If incorrect connections of objects have been permitted, the object snaps to the closest docking point regardless of correctness. Once an object is attached, the same algorithm prevents the user from detaching it inadvertently. With a quick movement, however, separation is possible. A technique we refer to as "reverse snapping" makes it difficult to attach an object to a wrong docking position. The opposite object acts repulsive by increasing the control-display-ratio for movements towards an inappropriate docking point. Currently, the author defines in the configuration whether or not these mechanisms are enabled.

Shape and color of the docking points give additional cues as to which objects can be connected. Unlike real puzzles where only two objects fit together, we found that providing the same docking points for well-defined groups and pairs of objects helps to transmit correspondences—and consequently spatial relations—in an easily understandable manner. Nevertheless, docking points should be simple to distinguish and simple in geometry, such as tetrahedrons, cubes or spheres.

5.6 Camera control

The virtual camera can be manipulated directly with the 3D mouse around a point of interest which is initially set to the center amid the objects. Additional control provide the OPEN INVENTOR widgets around the viewport. Wheel-widgets make it possible to change azimuth and declination angle and to zoom in and out. Camera control can be realized by intuitive two-handed interaction enabling the user to simultaneously rotate, zoom and pan.

5.7 Two-handed interaction

Our 3D puzzle supports the simultaneous use of two input devices—a 3D mouse and a 2D mouse. The use of these two input devices involves the user's bimanual motor skills enabling him or her to perform dependent subtasks in compound tasks [5].

In one configuration the 3D mouse is used exclusively to rotate the camera around a point of interest (POI) and to control the distance of the camera to this POI—a simultaneous manipulation of four degrees of freedom. The 2D mouse performs all other interactions like picking, selection from lists and the menu, and 3D transformations via the 3D widget. To provide intuitive interaction, people may use their non-dominant hand (NDH) for the camera manipulation task—an orientation task which is carried out with the NDH also in the real world—and the dominant hand (DH) to select certain objects from the scene. This separation of concerns is inspired by Leblanc et al. [10].

Another configuration enables the user also to control translation and rotation—including constraints—of a selected object with the 3D mouse. Here, the camera may be manipulated with the 3D mouse as long as there are no selected objects. Thus the user may explore the scene with the NDH, pick an object with the DH and rotate it with the NDH, finally placing it by translating the attached 3D widget with the DH.

6 Adapting the Level of Difficulty

Usually interactive systems should be as easy to operate as possible. However, with the 3D puzzle it should take some time to succeed because the time spent on solving this task is probably related to the learning success. On the other hand, users might become frustrated if it is too difficult to succeed [15]. There are two strategies by which the level of difficulty can be adapted: by "scaling" the task to be solved, and by providing support for solving the task.

To scale the task, the composition can be restricted to objects of certain categories (e.g. bones) and regions (e.g. eye muscles). Also, the composition can be performed at several levels. At the beginners' level, objects are rotated correctly when they are dropped to the construction view. The task is thus restricted to the correct translation of the object. To increase the level of diffi-

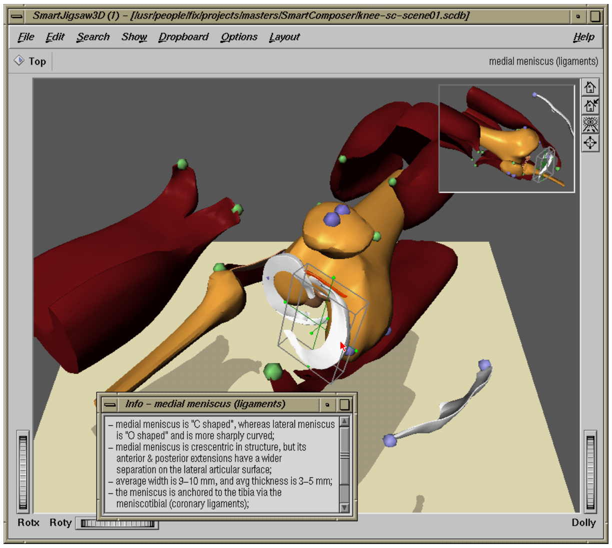

Figure 5: Assembling the right human knee. The system provides additional textual infomation to the selected item.

culty, rotation can be allowed but is constrained to steps of 45 degrees as mentioned before.

Additional support is provided by the display of textual information for a selected object (e.g. musculus procerus, eye muscle) and the mechanisms for snapping and reverse snapping.

7 Scenarios

Originally, the 3D puzzle was intended to enable students to explore and compose geometric models in their entirety, as it is required, for example, in anatomy. However, the 3D puzzle has some flexibility to restrict the task to subsets of the model. Moreover, the puzzle can also be used to decompose a model.

In anatomy, our system helps medical students in the preparation to the dissection of cadavers and can also be used to prepare for exams. As an example, Figure 1 showed the model of the right human foot where bones, sinews and muscles are to be connected. In Figure 5 a knee is assembled, which is a useful preparation to interventions in this area. The decomposition of models supports the rehearsal of surgical procedures and preparation tasks in which objects have to be removed to expose a particular part.

In car mechanic training the specific setup of complex engines has to be mastered. As an example we prepared the model of a six cylinder engine and discussed the scenario with mechanical engineers.

Another field where the 3D puzzle can help to ease the understanding of spatial relation might be chemistry. As stated in [1] the interactive work with complex molecules helps to gain new insights of molecular design. Puzzle pieces, such as proteins, might be composed in a specific way to form new drugs. In contrast to the other scenarios this has not been tested yet.

8 Informal Evaluation of a medical example

We have carefully discussed the 3D puzzle with two recently qualified physicians and four medical students who have some computer experience but had not used learning systems and 3D interaction before. Physicians are at first glance over-qualified as users of our system. However, as their anatomy courses date from former days the 3D puzzle can be used to refresh anatomic knowledge which is useful, for instance, to perform a certain intervention.

After a short introduction to the system's goal and functionality we asked all six candidates to explore a geometric model of a foot and finally to compose muscles and sinews onto the skeleton. For the composition snapping as well as collision avoidance was enabled and translation as well as rotation was required. After only a short time, the subjects were able to benefit from the 3D input device and used it in parallel with the 2D pointing device which seemed useful to them for zooming the camera and rotating the model at the same time.

Attaching the muscles and sinews—25 objects in total—to the skeleton took them approximately half an hour. This amount of time was deemed acceptable for this task.

For the composition it turned out that a frequent change between manipulating the viewpoint and transforming the selected object is necessary. The mode has to be changed which required the user to interrupt the manipulation. As a consequence, the mode may be switched with a button of the 3D input device and additionally in each view.

All subjects liked the management of the different deposits. Snapping was considered to be essential. Some of them also would like to have the system able to compose automatically a subset of the model in an animation and then do the same task themselves.

Furthermore, the evaluation turned out that the composite 3D widget used for translating and rotating objects (recall the left window of Figure 1) does not intuitively convey how to utilize it. Three subjects had difficulties to initialize rotation. For novice users, an explicit representation might be more appropriate. After a short explanation, however, all of them mastered all degrees of freedom to transform objects and succeeded in completing the puzzle having fun whenever they were informed that an object had been attached correctly.

9 Summary

We introduced the metaphor of a 3D puzzle for learning spatial relations and discussed its implication. The metaphor of a 3D puzzle guided our design and led us to incorporate advanced visualization and interaction techniques to enable students to compose 3D models. Furthermore, a prototype was developed and refined according to an informal evaluation to demonstrate the feasibility of this concept. With the metaphor of a 3D puzzle, users have a precise task involving spatial relations.

The puzzle task provides a level of motivation for learning which is hard to achieve with other metaphors. Different levels of difficulty are provided to accommodate users with different capabilities. The 3D puzzle of anatomic models is of interest for students of medicine, but also for students of physical education and physiotherapy who need an understanding of some structures inside the human body. The development of our system has been accompanied by informal usability tests which yielded promising results. We intend to perform a rigorous usability test. In particular, the use of two-handed interaction, the snapping mechanisms and the effects of the different levels of difficulty on the performance and satisfaction are being evaluated.

The 3D puzzle supports the perception of shapes, relative sizes, and other spatial relations at a glance. For educational or maintenance purposes a wealth of textual information, e.g., about objects and their meaning, about possible complications in repair tasks are required. Therefore, students benefit from the 3D puzzle *after* having a clear understanding of the object to be studied. Thus a 3D puzzle cannot replace traditional teaching materials and methods.

We will extend our system to adapt the level of difficulty automatically. For this purpose, it is recorded how many objects have been composed successfully, how often the user failed and how long it takes him or her. Techniques for the adaptation of the 3D puzzle might be derived from computer games where it is quite usual (and often attractive) that the level is adapted after successful completion of certain tasks.

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