3D Learning in anatomical and surgical education in relation to visual-spatial abilities

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General Introduction

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Anatomical knowledge

Anatomy has historically been a cornerstone in medical education. Appropriate knowledge of human anatomy is essential for medical specialties in general and surgery in particular. Mastering anatomical knowledge requires an accurate understanding of spatial relations of anatomical structures and the ability to translate this knowledge into practice. Unfortunately, changes in medical curricula have led to decreased teaching time for anatomy and limited exposure to traditional teaching methods such as dissections, prosections, and surface anatomy. As a result, students primarily learn from two-dimensional (2D) images in textbooks and anatomical atlases. Students experience difficulties in translating their 2D anatomical knowledge into practice. It is not surprising that the level of anatomical knowledge among medical students and junior doctors has been reported to be insufficient.[1-5] With reduced resident working hours, these challenges persist in surgical training as well. Surgical residents often feel unconfident performing surgeries characterized by spatial complexity.[6-8] This situation is imaginable because mastering spatially-complex procedures requires an accurate understanding of spatial relations of the relevant anatomical structures.

Visual-spatial abilities

Translating anatomical knowledge into practice depends mainly on the level of visual-spatial abilities (VSA). In anatomical and medical contexts, VSA is defined as the ability to construct visual-spatial, e.g., three-dimensional (3D), mental representations of 2D images and mentally manipulate them.[9-10] Two components of VSA can be distinguished (Figure 1):

- Mental visualization and transformation: the ability to mentally construct and transform complex 3D objects
- Mental visualization and rotation: the ability to mentally rotate 3D objects and recognize them in other positions

VSA accurately predict the assessment of anatomical knowledge among students and surgical performance among residents, especially in the early phases of surgical training.[11,12] Not surprisingly, VSA is often recommended as a selection tool in surgical training.

The available assessment tools for VSA include psychometric tests that measure both components (Figure 1). The *Paper Folding Test (PFT)* is a standard test of mental visualization and transformation skills.[13] The test consists of ten parts in which subjects are asked to imagine the folding and unfolding of pieces of paper. After a hole has been punched in the folded piece of paper, the subject needs to indicate where the hole(s) will be after the pieces have been unfolded and the appearance of the unfolded pieces.

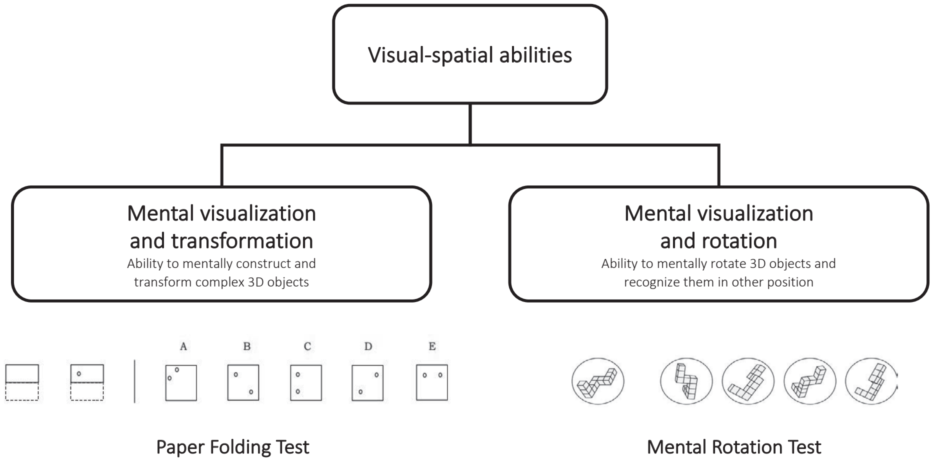

Figure 1. Components of visual-spatial abilities with examples of the most common used tests.

The *Mental Rotation Test (MRT)* is a validated test to assess mental rotation. This 24-item test has repeatedly showed significant positive associations with assessing anatomical knowledge and surgical skills.[14,15] Within each item, a 3D figure is presented as a 2D drawing with four possible rotated versions. Subjects must make a mental 3D representation of the figure and rotate it to identify the two correct options. One point is awarded for each correctly answered item, with a maximum score of 24 points.

Three-dimensional visualization technology

Three-dimensional visualization technology (3DVT) can fill the gap between learning anatomy and applying the acquired knowledge in practice. The great advantage of 3DVT lies in its ability to visualize anatomical structures and explore spatial relations among structures from numerous viewpoints and angles. The '3D effect', or visual depth perception, in 3DVT is shaped by a mental combination of *monocular* and *binocular* depth cues.

Monocular cues are visual cues that require only one eye to perceive visual-spatial depth. They include coloring, relative size, shading, and motion parallax.[16] Here, we refer to 3DVT, which provides only monocular depth cues as *monoscopic 3DVT*. Examples of monoscopic 3DVT include 3D anatomical models, animations, and videos viewed on 2D displays such as computer screens, tablets, or cellular phones.

Binocular cues are visual cues that require both eyes to perceive visual depth. They include binocular disparity and convergence.[16] Binocular disparity is an essential cue for depth perception in real life. It refers to a slight difference between left and right retinal images of a 3D object derived from the eyes' horizontal distance. The disparity is detected by the brain and is translated into stereoscopic vision or stereopsis. Here, we refer to 3DVT, which provides binocular cues in addition to monocular depth cues as *stereoscopic 3DVT*. Stereoscopic vision in 3DVT is obtained by supportive devices that project two slightly different images to the left and right eye. These include autostereoscopic displays, anaglyphic or polarized 3D glasses, and head-mounted displays. Depending on the type of supportive devices, various stereoscopic 3D environments can be created, as follows.

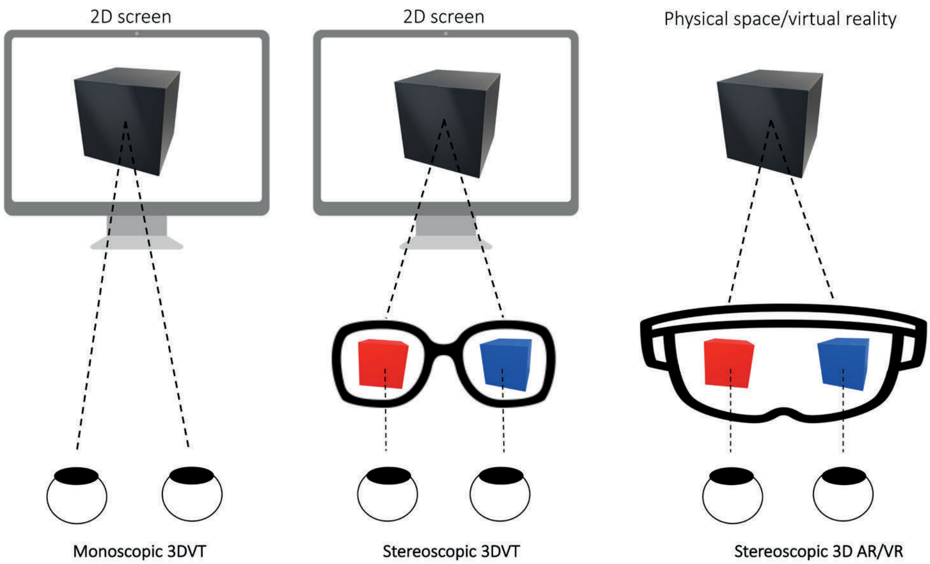

Figure 2. Monoscopic versus stereoscopic 3D environments. Stereoscopic vision is obtained by supportive devices that project two slightly different images to the left and right eye. 3DVT = three-dimensional visualization technology, AR = augmented reality, VR = virtual reality.

Stereoscopic 3DVT refers to the stereoscopic projection of 3D anatomical models, animations, or videos on 2D displays using anaglyphic, polarized, or shutter 3D glasses (Figure 2). Active interaction with the content is achieved by manual manipulation using a keyboard, computer mouse, or joystick. For 3D anatomical models, the user rotates the model, adjusts the size, and dissects anatomical structures layer-by-layer.

Stereoscopic 3D augmented reality (AR) refers to the stereoscopic projection of virtual 3D objects in natural environments using the HoloLens™, a pair of mixed reality smart glasses that run on the Windows operating system (Figure 2). The advantage of stereoscopic 3D AR is the ability to walk around the virtual object and explore it from all possible angles without losing the sense of one's physical environment. Active manipulation of the model includes rotation, size adjustment, relocation of the model in space, and dissection of structures layer-by-layer using hand gestures or voice commands. Multiple users wearing devices can share one model simultaneously. This type of technology is also referred to as interactive AR or mixed reality (MR).

Virtual reality (VR) refers to complete immersion into the virtual environment using VR head-sets such as Oculus Rift™ and HTC VIVE™ (Figure 2). VR allows the user to freely move in a virtual 3D space and explore 3D objects from all possible angles. Active manipulation of the model can include rotation, size adjustment, and dissection of structures layer-by-layer using motion-tracked handheld controllers.

3DVT in anatomical and surgical education

Although 3DVT may have distinct advantages for teaching and learning anatomy, its effectiveness remains a topic of continuing research and discussion. There are several reasons can be given to explain such a state of affairs.

First, most studies during the recent two decades focused on *whether* 3DVT works instead of *why* it works. In such cases, comparisons were made within levels of instructional design, meaning that the interventional method differed in numerous ways from the controlled method.[17] Therefore, the specific feature or mechanism of 3DVT that contributed to learning remained unknown. We must acknowledge that knowing whether a technology works is an essential step in the evaluation process of 3DVT. However, more importantly, research should focus on why a particular 3DVT works. The latter enables us to inform and advance medical education research and facilitate the implementation of 3DVT into daily educational practice.

Second, the learning effect of 3DVT appears not to be positive for all learners. Previous research has shown that monoscopic 3D desktop models have disadvantageous learning effects for students with low VSA.[17-21] Students with high VSA, however, do benefit from learning with monoscopic 3DVT. This situation brings two critical aspects into play. First, the disadvantageous learning effect of monoscopic 3DVT might be caused by the lack of accurate depth perception or stereoscopic vision. New technologies that provide good stereoscopic vision offer the potential to fill this gap. Second, VSA tends to cause a so-called aptitude-treatment interaction, or effect modification, in learning with various instructional methods.[18,20] This interaction occurs when the effect of an intervention appears to differ in groups of subjects with different characteristics (in our case, different levels of VSA). However, whether and how this VSA-induced interaction will occur in learning with stereoscopic 3DVT remains unknown.

In surgical education, 3DVT has the potential to be effectively used for learning and teaching surgical procedures. The need for additional teaching methods is increasing. According to the literature, surgical residents experience difficulties learning spatially-complex procedures and feel less confident performing such procedures despite proper preparation. Traditionally, surgical residents used surgical atlases and textbooks to prepare for surgeries; currently, they use online resources, including medical apps, books, and videos. Instructional videos are especially popular among residents.[22,23] This is not surprising because videos provide visual and auditory cues that facilitate mental visualization of procedural steps, including 3D aspects of anatomy. Nevertheless, the majority of research has focused on monoscopic visualization only. Whether a stereoscopic view of an instructional video would be more effective in preparing spatially-complex procedures remains unexplored.

Taking into consideration the above-mentioned aspects, the following questions arise:

1) How can we explain differences in learning with 3DVT between low- and high-VSA individuals?
2) Can we minimize these differences by providing stereoscopic vision in 3DVT?
3) Can VSA be taught to improve learning?

Theoretical framework

To answer these questions, the fundamental concepts of this thesis are defined and explained within the theoretical framework of Cognitive Load Theory (CLT).[24] CLT provides instructional design principles and strategies based on the model of cognitive architecture. In this thesis, CLT served as the guide on which assumptions and predictions were built across the studies.

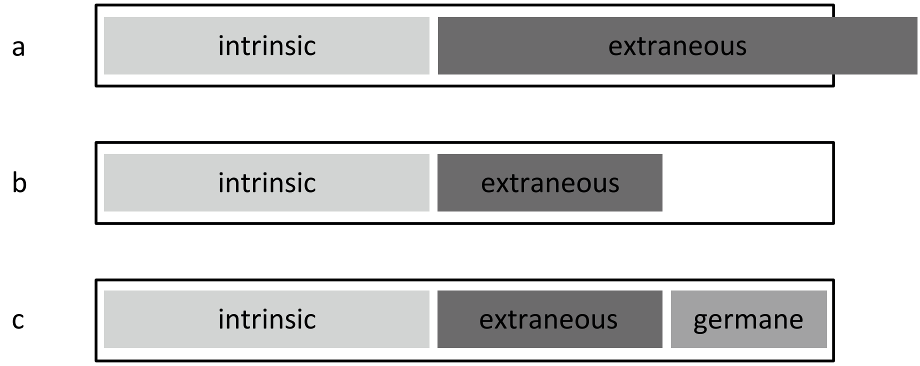

Figure 3. Human cognitive capacity: (a) cognitive overload, (b) preventing overload by decreasing extraneous load, (c) optimizing germane load (adapted from van Merrienboer & Sweller, 2010).[24]

The CLT model assumes that the human cognitive system has limited working memory capacity required to learn new information.[25] The task of working memory is to process novel information that is subsequently constructed into schemas in long-term memory. Three sources of working memory load can be distinguished: intrinsic cognitive load (caused by the nature of learning material content), extraneous cognitive load (caused by the way learning material is presented), and germane cognitive load (caused by actual learning process) (Figure 3).[25] When the sum of three sources exceeds the working memory capacity, cognitive overload occurs, consequently impairing the learning process. Based on this theory, individuals with low levels of VSA devote more cognitive resources to mental visualization and manipulation of 3D objects than individuals with high VSA levels. Therefore, when learning spatially-complex material (anatomy and surgical procedures), the intrinsic cognitive load in low-VSA individuals is elevated, leaving fewer available cognitive resources that they can spend on other learning tasks. To avoid cognitive overload, it is possible to decrease extraneous load by improving the instructional method, i.e., providing stereoscopic vision within 3DVT. The reduction in extraneous load will eventually provide more space for germane processing. With other words, teaching anatomy in 'real 3D' has the potential to improve actual learning by decreasing extraneous load.

General aim and outline of the thesis

The overarching aim of this thesis was the employment of evidence-based insights to improve anatomical and surgical education by determining how various levels of VSA interact with learning using stereoscopic 3DVT.

In **chapter 2**, a meta-analysis was performed to estimate the learning effect of stereoscopic 3DVT compared to monoscopic 3DVT for learning anatomy. **Chapters 3 and 4** consider the effectiveness of stereoscopic 3D AR technology and its working mechanisms in learning the anatomy of the lower leg among (bio)medical students in relation to their VSA. The effect of stereoscopic vision was further explored in surgical procedure learning. In **chapter 5,** a randomized controlled trial was performed to evaluate the effect of stereoscopic 3D instructional video on the performance of a spatially-complex procedure among low- and high-VSA residents. In **chapter 6**, we evaluated how particular levels of VSA affect surgical performance depending on the type of intraoperative feedback. In **chapter 7**, we evaluated whether VSA can be trained and improved by the repeated anatomy practice. Finally, in **chapter 8,** the results of this thesis are put into a broader perspective and suggestions for future directions are made.

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