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

Bogomolova, K.

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# General discussion and future perspectives

# GENERAL DISCUSSION AND FUTURE PERSPECTIVES

Currently, medical students mostly learn from two-dimensional (2D) images in textbooks and anatomical atlases, and they experience difficulties in translating acquired anatomical knowledge into practice. The latter is greatly affected by the level of visual-spatial abilities (VSA), i.e., the ability to construct visual-spatial, i.e., three-dimensional (3D) mental representations of 2D images and to mentally manipulate these representations.[1,2] VSA significantly predicts the level of anatomical knowledge among students and surgical performance among residents in the early phases of surgical training.[3,4]

Three-dimensional visualization technology (3DVT) has the potential to fill the gap between learning and applying anatomical knowledge in practice. The great advantage of 3DVT is its ability to visualize anatomical structures and explore spatial relations between various structures from numerous viewpoints and angles. One of the distinguishing features of new generations of 3DVT is their ability to provide accurate depth perception or stereoscopic vision. Stereoscopic vision results from the binocular disparity that various supportive devices can obtain by projecting a slightly different image to the left and right eyes. In this thesis, this type of technology is referred to as *stereoscopic 3DVT*. Examples of stereoscopic 3DVT include stereoscopic 3D desktop, stereoscopic 3D augmented reality (AR), and virtual reality (VR) environments (*see Figure 3, Introduction*). In the absence of stereoscopic vision, depth perception is created by so-called monocular depth cues that require only one eye for perception. They include cues such as coloring, shading, and motion parallax.[5] In this thesis, this type of technology is referred to as *monoscopic 3DVT.* Examples of traditional monoscopic 3DVT include 3D anatomical models viewed on a 2D computer screen (*see Figure 3, Introduction*).

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The overarching aim of this thesis was to evaluate the effectiveness of stereoscopic 3DVT and determine how various levels of VSA would interact with learning using this technology to improve anatomical and surgical education. The predictions in this thesis were made based on the model of Cognitive Load Theory (CLT).[6] This theory assumes that human working memory, which processes new information, has limited capacity. The working memory load consists of three sources: intrinsic cognitive load (nature of learning material content), extraneous cognitive load (the way learning material is presented), and germane cognitive load (the actual learning process).[7] When the sum of three sources exceeds the working memory capacity, cognitive overload occurs, impairing learning. Based on this theory, individuals with lower levels of VSA devote more available cognitive resources to mental visualization and manipulation of 3D objects than individuals with higher levels of VSA. Consequently, when learning spatially-complex material from 2D images, low-VSA individuals are left with fewer resources to spend on actual learning tasks. A potential way to facilitate learning is to decrease the input of other sources of cognitive load by improving the instructional design or changing the way learning material is presented such that learners will be able to re-allocate their resources to actual learning. Within this framework, providing stereoscopic vision in 3DVT can be interpreted as improving instructional methods to improve learning.

In this chapter, the main findings are discussed in light of CLT, and educational implications and suggestions for future directions are provided.

**The role of stereoscopic vision in learning with 3DVT**

As previously described, the '3D effect', or visual depth perception, in 3DVT is shaped by a mental combination of monocular and binocular depth cues. In this thesis, we evaluated the role of stereoscopic vision (binocular cue) as one of the most substantial providers of visual depth perception in 3DVT. By performing a meta-analysis, we demonstrated that providing stereoscopic vision has a significant positive effect on learning anatomy with 3D anatomical models. This finding emphasizes the importance of distinguishing between monoscopic and stereoscopic 3DVT **(chapter 2)**.

In the context of CLT, these differences are explained by two mental processes involved in learning with monoscopic and stereoscopic visualizations. A digital 3D object viewed monoscopically is memorized as a set of screenshots, or so-called key view-based 2D images.[8,9] These 2D images are then mentally combined to reconstruct a total mental representation of the 3D object. Consequently, this process consumes a relatively large amount of working memory capacity and leaves fewer cognitive resources for actual learning. In stereoscopic visualization, by contrast, mental representation of the 3D object is already built and provided by stereoscopic vision. The mental reconstruction required in monoscopic visualization can be skipped in stereoscopic visualization while leaving sufficient cognitive resources for other learning tasks. In other words, these findings strongly suggest that mental representations do not primarily consist of key view-based 2D images; instead, they might also include spatial information depending on the type of input. While monoscopic visualization stimulates mental key view-based 2D images, stereoscopic visualization stimulates structural 3D mental representations. This conclusion is further supported by neurocognitive research. Binocular cues appear to activate neurons in the brain that differ from those activated by monocular cues.[10-12] Researchers demonstrated using electroencephalography that learning with stereoscopic 3D models resulted in greater 3D object recognition than obtained using monoscopic 3D models.[13]

As was demonstrated in our follow-up studies **(chapters 4 and 5)**, the effect of stereoscopic vision was not comparable for all types of 3D environments. Our findings suggest that cues such as motion parallax provide sufficient visual depth perception, depending on the type of 3D technology used**.** The reasoning is based on the results of our study evaluating the effect of stereoscopic vision in a 3D AR environment **(chapter 4).** In that study, the stereoscopic vision did not provide better learning effects. However, in that study, students could walk around the model and explore it from several possible angles. According to research in neurocognitive sciences, motion parallax, in some cases, can provide even more effective depth cues than stereoscopic vision alone.[14-17] Furthermore, motion parallax compensates for the absence of stereoscopic vision and improves the recognition of 3D shapes.[18] It remains unknown to what extent stereoscopic vision and motion parallax (combined or separately) contribute to visual depth perception in a stereoscopic 3D AR environment. Recent research suggests that the effect of stereoscopic vision varies among types of technology. Wainman and colleagues performed a similar study to evaluate the effect of stereoscopic vision in a 3D AR environment.[19] They also found that stereoscopic vision in a 3D AR environment did not contribute to learning as expected. Additionally, authors compared the effect of stereoscopic vision in a 3D AR environment with its effect in VR. The effect of stereoscopic vision in VR appeared to be significantly greater than in AR. Unfortunately, due to stereoscopic 3D AR technology's novelty, no other studies are available to compare stereoscopic 3D AR technology's effectiveness with others. Future research will provide more clarity on this subject.



**Aptitude-treatment interaction caused by VSA**

Supported by the evidence of a positive effect of stereoscopic vision, we performed follow-up studies to evaluate the effects of VSA on learning with stereoscopic 3DVT. In the context of CLT, we hypothesized that providing stereoscopic vision would improve learning and that the most significant effect would be observed among individuals with low VSA. As demonstrated in **chapters 3, 5, and 6**, VSA greatly affected learning outcomes, although in different directions.

First, VSA caused an **aptitude-treatment interaction (ATI).** This interaction occurs when an individual with characteristic 1 learns better with instructional method A than with method B, while an individual with characteristic 2 learns better with method B.[20] In this thesis, ATI was observed in learning anatomy among students **(chapter 3)** and surgical procedures among residents **(chapter 5)** using stereoscopic 3DVT. Second, the observed ATI was not consistent across studies. VSA appeared to behave in two different directions, explained by two co-existing mechanisms, or hypotheses, in the context of CLT.[21]

*VSA as compensator*

The ability-as-compensator hypothesis predicts that individuals with high VSA can compensate for poor (monoscopic) instructional methods and, simultaneously, that improved (stereoscopic) instructional methods *compensate* for the lack of resources in individuals with low VSA. In other words, in the context of stereoscopic visualization, stereoscopic vision can act as a 'cognitive prosthetic' and improve learning in individuals with low VSA.[22] This mechanism was demonstrated in **chapter 3**. Learning with a stereoscopic 3D AR model was more effective than learning with a monoscopic 3D model only for students with low VSA. High VSA students performed equally well in all conditions.

*VSA as enhancer*

The ability-as-enhancer hypothesis predicts that high levels of VSA are required to derive benefit from the improved instructional method, while individuals with low levels of VSA are hindered due to increased demands imposed by processing new information.[23,] This mechanism was demonstrated in **chapter 5,** where surgical residents performed a spatially-complex procedure on a simulation model after watching an instructional video of the procedure either in 2D (monoscopically) or 3D (stereoscopically with active 3D glasses). Within this context, only residents with high VSA benefited from stereoscopic visualization and performed the procedure significantly better than with monoscopic visualizations. As novices with no prior knowledge, residents with low VSA were probably hindered by the high degree of visual interactivity in the instructional video and could not allocate sufficient resources to benefit from stereoscopic visualization.

In the context of monoscopic visualization, the enhancing mechanism explains why students with high VSA benefited from learning with monoscopic 3D models while low VSA students could not. This mechanism was recognized by Garg and colleagues more than two centuries ago.[25-27] Later, Huk tested and confirmed the hypothesis by evaluating the performance and the perceived cognitive load of medical students learning cell biology with monoscopic 3D desktop models.[28] Students with low VSA performed significantly worse on the test and reported their cognitive load to be high, whereas the opposite was observed for students with high VSA.

While *compensating* mechanisms in learning with stereoscopic 3DVT are recognized in anatomical education research[29-31], the *enhancing* mechanism has not been described previously. In other fields, including educational psychology and science, technology, engineering, and mathematics (STEM), the dichotomy between the two mechanisms has been widely recognized.[21,32] The majority of research in these disciplines has been performed in learning with multi-media. Similar to our findings, the observed mechanism depended on the type of instructional method and level of VSA. In addition to VSA, prior knowledge has also been recognized as a direct modifier.[22] Together with the existing body of evidence, our findings imply that learning with stereoscopic 3DVT can be effective for both low- and high-VSA individuals depending on their level of prior knowledge and expertise. This realization also means that for low-VSA individuals to benefit from stereoscopic visualization, learning material content should not be too complex or should build on prior knowledge.

### Personalized approach with VSA

The demonstrated ATI caused by VSA in learning with 3DVT (**chapters 3 and 5)** highlighted the importance of an individualized approach in medical training. In **chapter 6**, we demonstrated that an individualized approach based on VSA can make a difference. In a randomized controlled trial, we compared two types of intraoperative feedback on the performance of a spatially-complex procedure by medical undergraduates. Only after the results were stratified by VSA the fundamental differences were revealed. Students with low VSA performed significantly better after receiving task-specific, stepwise feedback than after receiving global rating scale feedback. Students with high VSA, however, benefited from both types of feedback. The findings can be relevant for both medical and higher education in general. They emphasize the importance of congruence between learning and assessment, as proposed by the constructive alignment theory[33], and between learning and feedback. This congruence provides opportunities for teachers who provide feedback or monitor peer feedback to evaluate the extent of this alignment on an ongoing basis and re-align them when needed. Feedback should be scaffolded with the learning activities, outcomes, and assessment.[34]



### The malleability of VSA

Another important finding of this thesis was that VSA, regardless of intervention type, was significantly associated with anatomical knowledge (**chapters 3 and 4)** and surgical performance **(chapter 5).** More importantly, this association was not comparable for all levels of VSA. As was shown in **chapter 5**, only low levels of VSA were positively associated with surgical performance. Among the studies reporting associations between VSA and surgical performance, only one study recognized a similar pattern by considering the possible ATI caused by VSA.[35] These findings suggest that VSA affects surgical performance when it is not well developed. They also suggest that when VSA is well developed, surgical performance is predicted by factors such as surgical experience. If VSA appears to be such an essential factor in learning anatomy and performing surgical procedures, the following questions arise: can VSA be trained or be improved by repeated practice, starting from the early stages of medical training?

In **chapter 7**, we demonstrated that repeated practice of cadaveric dissections improved VSA of medical undergraduates. The improvement of VSA occurred only among students with initially low levels of VSA, again reflecting the ATI caused by VSA. It is needed to say that cadaveric dissections are not the only effective way of training VSA. Methods that stimulate mental visualization and manipulation, such as evaluating cross-sections and mental rotation training, also effectively improve VSA.[36] As demonstrated in STEM domains, VSA training is practical, durable, and transferable across all categories of spatial skills.[37] The findings that VSA can be improved by training opens a new window of opportunity. It means that by improving VSA, one can improve its own level anatomical knowledge and surgical performance.

**Reflections on the methodology**

The merits of the results of this thesis are interconnected with its strengths and limitations. The overall methodological rigor is reflected in the use of experimental study designs that are essential to understand the working mechanisms of 3DVT. To avoid confounders - not uncommon in media-comparative research - most comparisons in this thesis were made within a single level of instructional design.[20] In this way, we examined the effect of stereoscopic vision as the only truly manipulated element in study designs. Additionally, to increase our findings' generalizability and share resources among collaborative institutes, we conducted multiple multicenter studies.

One of the limiting factors concerns using the Mental Rotation Test (MRT) as the assessment tool for VSA across studies. First, this test measures mental rotation as one of the two components of VSA. As the other component of VSA, mental visualization has been measured by the Paper Folding Test (PFT) but did not show any associations with our outcomes. Despite the demonstrated ability of PFT to measure mental visualization and transformation, other validated psychometric tests exist that could have impacted our findings if used. These tests include the Embedded Figure Test and the Mental Cutting Test, which are widely used in educational psychology and STEM.[37] Likewise, various other psychometric tests for measuring mental rotation are available. These include the Card Rotation Test, the Cube Comparison Test, and the Purdue Spatial Visualization Test.[37] Perhaps using the term 'mental rotation skill' would be a more appropriate term for VSA in this thesis.

Another interesting detail regarding the use of MRT is the difference in performance between sexes. Sex differences in MRT scores have been repeatedly reported in the literature and were observed in our studies as well.[37-41] However, evidence suggests that these differences are not primarily caused by actual differences in working memory capacity but can be altered by chosen strategy, confidence, and familiarity with the presented 3D objects. Research has shown that other strategies can be used to solve mental rotation tasks.[42] While men often use global-shape strategies, women often choose to analyze local aspects of the figure shapes.[43] The use of the global-shape strategy is associated with better test performance, suggesting that choice of strategy can give rise to sex differences. The differences in cerebral activation patterns further support the notion that women use different strategies to solve mental rotation tasks despite equal performance on the Mental Rotation Test.[44] In addition, females tend to rethink their choices, causing them to complete fewer items than men,[45,46] who rely on a 'leaping' strategy by moving on to the next item as soon as they have identified the answer.[47] Lastly, familiarity with manipulated 3D objects refers to the type of stimulus that can cause sex differences. The latter is supported by various studies in which human body parts were used instead of traditional cubes figures, minimizing the notable sex differences on performance.[48,49] Taken together, this could mean that the sex differences we found in our studies, and those in the literature, may have produced a distorted view of reality. In other words, the actual levels of VSA among females may have been underestimated by using an inappropriate instrument.

**Future implications**

The findings of this thesis lead to several important considerations for educational research and practice.

*An individualized approach in learning with 3DVT*

One fact emerges regarding the educational role of 3DVT in the medical curriculum: one size does not fit all. Individual learning needs of students should be paramount when determining whether and how 3D technology can be implemented. As demonstrated in this thesis, stereoscopic visualization can benefit both low- and high-VSA learners, depending on the complexity of the learning content and learners' prior knowledge. For example, monoscopic 3D models should be avoided for low VSA students because monoscopic visualization comprises learning by inducing cognitive overload. Instead, stereoscopic 3D models can be considered an additional teaching tool for low-VSA students. Small group sessions can be considered for using stereoscopic 3D AR technology because it enables collaboration and active learning simultaneously. In surgical procedure training, where the complexity of learning content increases, stereoscopic visualization of instructional videos is recommended for high-VSA residents only. For residents with low VSA, traditional 2D videos would be sufficient.

Future research should focus on the working mechanisms of 3DVT in anatomical and surgical education. This research will eventually aid the implementation of suitable types of technology in the correct educational settings. For example, future studies could focus on the effect of motion parallax in 3D AR environments on learning anatomy with or without stereoscopic vision. When essential features or elements of stereoscopic 3D AR technology are known, they can be effectively incorporated into instructional activities for learning with 3DVT. It would also be helpful to evaluate these effects concerning objectively measured cognitive loads. This evaluation can be performed by integrating eye-tracking functions within the 3D AR devices. Care should be taken to moderate factors such as prior knowledge, expertise, and complexity of the learning material.

*Accounting for ATI caused by VSA*

For research purposes, it is essential to emphasize the role of the aptitude-treatment interaction (ATI) caused by VSA on learning. In statistical terms, this phenomenon is called 'effect measure modification'.[50,51] As demonstrated in our studies **(chapters 2, 3, 5, and 6)**, this interaction can be revealed either by stratifying the overall results by VSA or by including VSA as an interaction term in the regression analysis. Adjusting for VSA only as a confounder will not reveal this interaction. Although ATI is widely recognized in educational psychology and STEM domains, it has been hardly mentioned in anatomical and surgical education research. Therefore, it is essential to account for the potential aptitude-treatment effect of VSA when planning new studies and analyzing the data.

*VSA as an identification tool*

Until now, VSA has been seen as a fixed individual characteristic that does not change over time. It is not surprising that VSA has been recommended as a selection tool in surgical training. However, the malleability of VSA demonstrated in our studies strongly suggests that VSA can be trained and improved. Therefore, one should consider using VSA as an identification tool rather than a selection tool. The goal is to identify individuals with low levels of VSA and provide them with practical tools for both VSA and anatomical and surgical training. This goal will be of great interest for students who pursue surgical careers but whose VSA skills need improvement.

Future research should focus on exploring the optimal ways of improving low levels of VSA and implementing VSA training in medical curricula. Using 3D technology could also be a training tool along with practical (dissection-based) and theoretical (mental rotation exercises) methods. The emphasis should be placed on the elements that are essential for the actual improvement of VSA. Simultaneously, the effect of VSA training on anatomical knowledge and surgical performance should be evaluated. By understanding the building blocks of practical VSA training and their effect on learning, various methods can be effectively designed and implemented. Next to improving low levels of VSA, it would be interesting to explore the effect of VSA training on high-performing individuals. Would it be possible for these individuals to improve their VSA further and achieve even higher performance levels? In other words, can we help excellent students excel even further? For this part of research, VSA assessment instruments other than the gold standard should be considered to avoid the possible ceiling effect among high-performance individuals.

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