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RESEARCH REPORT

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How students discern anatomical structures using digital three-dimensional visualizations in anatomy education

Anna F. Pettersson[1] | Klas Karlgren[2,3,4] | Jonathan Al-Saadi[5] | Hans Hjelmqvist[2,6] | Björn Meister[7] | Hugo Zeberg[7] | Charlotte Silén[2]

[1]Division of Physiotherapy, Department of Neurobiology, Care Sciences and Society, Karolinska Institutet, Stockholm, Sweden

[2]Department of Learning, Informatics, Management and Ethics, Karolinska Institutet, Stockholm, Sweden

[3]Department of Research, Education, Development, and Innovation, Södersjukhuset, Stockholm, Sweden

[4]Faculty of Health and Social Sciences, Western Norway University of Applied Sciences, Bergen, Norway

[5]Department of Clinical Neuroscience, Karolinska Institutet, Stockholm, Sweden

[6]School of Medical Sciences, Örebro University, Örebro, Sweden

[7]Department of Neuroscience, Karolinska Institutet, Stockholm, Sweden

Correspondence
Dr. Anna F. Pettersson, Division of Physiotherapy, Department of Neurobiology, Care Sciences and, Society, Karolinska Institutet, Huddinge 141 83, Sweden.
Email: anna.pettersson@ki.se

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Abstract

Learning anatomy holds specific challenges, like the appreciation of three-dimensional relationships between anatomical structures. So far, there is limited knowledge about how students construct their understanding of topographic anatomy. By understanding the processes by which students learn anatomical structures in 3D, educators will be better equipped to offer support and create successful learning situations. Using video analysis, this study investigates how students discern anatomical structures. Sixteen students at different levels of education and from different study programs were recorded audiovisually while exploring 3D digital images using a computerized visualization table. Eleven hours of recorded material were analyzed using interaction analysis and phenomenography. Seven categories were identified during data analysis, describing the qualitatively different patterns of actions that students use to make sense of anatomy: *decoding the image*; *positioning the body in space*; *purposeful seeking*, *using knowledge and experience*; *making use of and creating variation*; *aimless exploration*, and *arriving at moments of understanding*. The results suggest that anatomy instruction should be organized to let the students decide how and at what pace they examine visualized images. Particularly, the discovery process of decoding and positioning the body in space supports a deep learning approach for learning anatomy using visualizations. The students' activities should be facilitated and not directed.

KEYWORDS
3D technology, gross anatomy education, learning anatomy, medical education, undergraduate education, visualization table

INTRODUCTION

Learning anatomy is a complex endeavor and carries the specific challenge of appreciating three-dimensional (3D) relationships between anatomical structures.[1–3] The use of dissections and light microscopy to learn gross- and microscopic anatomy has, in the past, been motivated by their graphic demonstration of the wide variation in human structures that are difficult to capture in a textbook or atlas.[4] As pointed out by Schaffer, most students are astonished by the extent to which a specimen differs from the images in their atlas and Schaffer argues that "any substitute for these methods would have to address this variability in a substantial way".

Three-dimensional visualization technologies now offer new approaches to teaching and learning anatomy.[2,5,6] Traditional approaches such as cadaver dissections are complemented with technologies like two-dimensional (2D) and three-dimensional (3D) digital imaging to investigate and learn the anatomy of the human body.[7,8] In the literature, the term 3D technology has various meanings. In this article, the term "3D images" is used to denote computed tomography scans (CT) and magnetic resonance imaging (MRI) which are presented as three-dimensional (3D) images. In this study, visualization is defined as the ability to perceive an object (anatomical structures), envision relationships among objects, and recognize the relationship between structure and function.[3,9]

Interactive tabletops visualizing human bodies have been developed for use in health care education. Visualization tables provide interactive, natural-sized views of the anatomy of real patients that are rendered from x-ray computed tomography (CT) and magnetic resonance (MR) images. Such tables have a multi-touch screen that allows users to interact with the virtual body.[10–12] There are currently seven universities in Sweden using the Sectra Table (Sectra AB), mainly in medical education and, to a lesser extent, in other health care professions education. (personal communication with Sectra AB, Linköping Sweden). Visualization tables provide the ability to not only experience the natural variation that exists between different human individuals but also the variation between healthy and sick bodies, and differences related to age and aging. It is also possible to create variation by contrasting the whole body to parts of the body.[3] Such variation is difficult to achieve using more traditional methods: anatomical models typically display a single prototypical body, whereas the number of bodies available for dissection by students will, for practical reasons, be limited. It is also possible to virtually slice, segment, or peel off layers of tissue. The table format itself can be beneficial: enabling students to interact with visualizations of bones, muscles, and organs; and offering opportunities for collaborative learning.

Research indicate that 3D visualization technologies are effective and result in higher levels of student satisfaction than other teaching methods.[13–15] The use of virtual dissection tables in anatomy and pathology teaching has been found beneficial for learning, and well perceived as a learning tool by students.[11,16] McLachlan et al.[17] argue that learning anatomy by using images may be better suited than dissection for integrating basic science with clinical science. Beerman et al.[18] showed that students' understanding of complex anatomy improved when presented with computer-generated 3D images, and that male students benefitted more from 3D displays. Paech et al.[19] compared different approaches in anatomy education and demonstrated that medical students who were introduced to the use of cadaver computed tomography (CT) scans and life-size virtual dissection tables obtained significantly higher test scores than those who were not.

Comprehensive literature reviews of research evaluating technology-enhanced learning in anatomy education studies have mainly focused on students' perceptions and learning outcomes.[15,20] Little is known about the process of learning, or how students construct their understanding of topographic anatomy; especially when using novel technologies.[2,20,21] In addition, Tam et al.[14] demonstrated that research on computer-assisted learning was limited to short course lengths and specific areas of anatomy, and they called for further research to guide decisions about teaching and learning strategies in anatomy education.

While digital imaging has created possibilities for students to study and conceptualize otherwise hidden structures and functions, there are several educational challenges related to learning anatomical structures. Examples of these include spatial relationships and complex physiological processes.[22–25] Health care students have difficulties developing a conceptual understanding of the three-dimensionality of anatomy.[5,26–28] Pandey and Zimitat[9] studied medical students' approaches to learning anatomy and compared those to learning outcomes. They found that successfully learning anatomy required a balance between memorization, understanding, and visualization. Deeper approaches to learning, meaning attempts to understand instead of memorizing, correlated with higher quality learning in the course. A scoping review on research about the impact of using digital and plastic 3D models on anatomy learning concluded that there is progressive interest in the topic but emphasized the need to better understand the interactions between learners and 3D technologies to identify potential advantages, limitations, and ideal methods.[21]

Interview-based studies of medical students illuminated students' experiences of their studies in anatomy and physiology and showed that students approach their studies in different ways and that they have differing capacities when it comes to elaborating on their knowledge.[22,24,25,29]

Hence, there are many aspects that influence learning, such as the topic under study, the instructional design, what students do, and what they bring to the situation.[30] A constructivist view of learning means that learning processes are regarded as active constructive processes in the learner.[31] To construct understanding, skills, and attitudes, information is processed cognitively, emotionally, and through practical actions.[30,32,33] A basic motivational force for the individual is to attempt to understand and handle situations that are perceived as relevant and meaningful.[9,30,34,35] Learning is also dependent on the learner's previous knowledge, interaction with others, the learning situation, and the learning environment.[30,36] In addition, learning theories increasingly emphasize not only individual learning or interaction with others but also how learners collaboratively create knowledge, and how they make use of technology to do so.[13,37,38] One example is Bereiter's knowledge-building theory[39] which highlights how people develop conceptual artifacts. Another is Paavola and Hakkarainen's knowledge-creation (or "trialogical") approach to learning which brings attention to how learners create conceptual artifacts, practices, and products.[38] Essential to learning is discernment; and a prerequisite for discernment is the experience of variation.[35,40] A learner of anatomy, for instance, needs to discern an anatomical structure in its environment to be able to 'see' it and 'experience' it. For learning to occur, repetition per se is not enough. There needs to be a certain pattern of variation present in the experience. To learn means seeing the object of learning in a qualitatively different way than before. To see or experience an object of learning, the student must be aware of and discern critical aspects connected to the object of learning. Following this reasoning, a necessary starting point for learning is the discernment of an object. Yet, as learning is a complex process, there is no simple cause-and-effect relationship between what teachers do and what students learn. As discussed, above factors such as context, interaction, attitude, and pre-understanding will influence what is discerned.[30,32,35,41] Teachers need knowledge about how to guide and support students for meaningful learning and how to design appropriate learning activities using 3D technology. Without such knowledge, there is a risk that students may engage in ineffective learning strategies and that the potential of the new technologies is lost.

This study aims to contribute to the understanding of how students discern the human body using 3D digital imaging.

The objective of this study was to carry out observations focusing on students' actions and interactions with visualization tables, and to address the following research questions:

- How do students discern and make sense of anatomical structures when exposed to different kinds of images visualizing the human body on a visualization table?
- What characterizes students' discernment and strategies to make sense of what they see?

An interpretative qualitative approach was used in the study[42] to examine students' interactions using a visualization table displaying images of the human body.

One assumption underlying this work is that thoughts, feelings, and intentions are reflected through individual actions as well as in verbal and nonverbal interactions with the visualization table and its context.

MATERIAL AND METHODS

The study was conducted at an anatomy teaching facility in Neuroscience Department, Karolinska Institutet, Stockholm, Sweden, a department responsible for the anatomy education for different health care professional training programs. The study was performed entirely outside the regular curriculum.

Data were collected between October 2019 and May 2020. On March 11, 2020, the World Health Organization declared a global pandemic. On March 15, 2020, the Swedish Higher Education Authority introduced teaching restrictions. All data but three were collected before the pandemic was declared and before the introduction of these restrictions. Data from the last three students were collected between March 11 and May 13, 2020. These students were all in the later part of their education, in semesters 6 and 10. This meant that not one student in the study experienced anatomy education during the pandemic.

A visualization table (Sectra AB, Linköping, Sweden), described in more detail below, was used in this study to observe how students go about learning while exposed to a variety of images visualizing the human body.

Pilot study

A pilot study with a sample of student participants with varying experiences of anatomy education ($n = 8$) was conducted. In the pilot study, the following observations were noted: an introduction to the functions of the table and an overview of what kind of images were shown was helpful; connection to a clinical case helped the students to orientate themselves in relation to the images; students from different study programs and different study levels approached the images differently; students needed to be reminded and prompted to think aloud about their thoughts and actions. Results from the pilot study were used to design the main study.

Main study

Participants

To obtain variation in the data[42] students from different professions and with different experiences in anatomy education and clinical experience were sought. Students were informed about the study during an ordinary lecture in their study program and asked to contact the researchers if they were interested in participating. Sixteen students between 20 and 30 years of age agreed to participate in the study (12 women, 4 men, mean age = 24.8 ± 3.0 [SD]).

The students represented three different study programs: 6 physiotherapy students; 2 nursing students; and 10 medical students. Twelve students were in semesters 1 (the early part of their education), and 6 students came from semesters 5–6 and 8–10 (the later part of their education).

The students worked in pairs using a Sectra table, model F18, with a 65″ monitor and 4K resolution (Sectra, AB. Linköping, Sweden), displaying 3D images of the anatomy of the human body rendered through x-ray computed tomography (CT) and magnetic resonance (MR) from real patients. The images were connected to a fictive clinical case. Students were observed during the sessions and immediately following the sessions they were interviewed about their experiences and thoughts using the table and the displayed images.[43]

Prior experience of anatomy education

As previously mentioned, the study was performed outside the regular curriculum. To give an idea of the students' experience of anatomy education prior to participating in the study, a short description of the course length, and educational activities and resources used is provided below.

The study program in medicine

The study program in medicine at Karolinska Institutet is five and a half years (11 semesters) long. Systematic and topographic anatomy is studied during the first three semesters, for a total of 11 weeks. Anatomy is then integrated and applied in different clinical courses. Educational activities include lectures, human dissections, prosections, and laboratory sessions. Teaching resources include cadavers, plastic models, and a visualization tables.

The study program in physiotherapy

The physiotherapy program at Karolinska Institutet is three years long (6 semesters) and includes a five-week gross anatomy course during the first semester. Anatomy is subsequently integrated and applied in practice-based, clinical courses. Educational activities include lectures, human dissections, prosections, laboratory sessions, and articulation of anatomy through dance. Teaching resources include cadavers, plastic models, and a visualization tables.

The study program in nursing

The nursing program at Karolinska Institutet is three years long (6 semesters) and includes an 8-week long anatomy and physiology course related to nursing in semester 1. Anatomy is then integrated with care sciences and pathology. Educational activities include lectures, group work, and laboratory sessions. Teaching resources include plastic models and, to some extent visualization tables.

The Visible Body Courseware (Visible Body, Newton, MA), a web-based teaching and learning platform for 3D anatomy, which is available to all students at KI and can be downloaded via the library's website to mobile devices such as smartphones and tablets.

Data collection

A high-definition (HD) camcorder (Samsung VP-HMX10 PAL) mounted on a tripod and an external, omnidirectional lavalier microphone (JJC SGM-38II) hanging from the ceiling above the participants was used for video and audio recording. After each session, recordings were transferred from the camera to a portable hard disk (Lacie Rugged) and stored as MP4 files. The audiovisual recording captured the participants' communication and interaction as well as the screen. To complement the recordings, field notes were taken of verbal and non-verbal actions and interactions while students were exploring images using the visualization table.

One to two students participated in each session. The allocated time for each session was about two hours. They were presented with two cases describing a medical condition, one related to the brain and one related to the abdomen. Before the session started, students were introduced to each other and to the research team. They were informed about the procedure and were interviewed regarding background information and their previous experience studying X-ray images. Students were also introduced to the functionalities of the visualization table by an experienced anatomy tutor (J.S.). The tutor was on hand to support students in case they had questions about the table but otherwise played a passive role. Students were instructed to read about the case and then explore the images using the visualization table. Furthermore, students were told that they could look at the images in whatever order they liked and were asked to think aloud while looking at and browsing through the images. The images constituted of CT and MR scans from real patients and dissected specimens showing anatomical structures of relevance to the cases. If needed, students were asked prompting questions by one of the research team members to facilitate thinking aloud; for example, "What are you looking at?," "What do you see in this image?," and "What do you find interesting about this image?" When students were finished, the tutor explained the images related to the case.

Data analysis

The phenomenon under study was how students go about discerning anatomy using a visualization table. The unit of analysis was the instances and courses of events that reflected attempts at discernment. These courses of events encompass interactions between participants, technologies, and different kinds of visualizations. Data analysis was informed by interaction analysis,[44] and phenomenography.[45–47] Interaction analysis has its roots in ethnography, which focuses on observations of what human beings say, what they do, and how they interact with objects in their environment.[48] The purpose is to identify and describe patterns of actions within a group and to understand their meaning. Interaction analysis makes use of the power of video to perform detailed analyses of human activities, such as talk, non-verbal interaction and the use of artifacts and technologies, to identify routine practices and problems, as well as resources for solutions. The analysis method places a strong emphasis on grounding all assertions on verifiable observations. The video recordings, therefore, play a key role in overcoming gaps between what people say they do and what they, in fact, do and also in avoiding the bias of the researcher. Interaction analysis does not use predetermined coding schemes, but particular attention was on the participants' talk, pauses, turn-taking, gestures, movement, postures, facial expressions, gaze, focus of attention, and how they used the visualization table and its images.

Phenomenography deals with the qualitatively different ways in which people understand or experience a phenomenon. In this study, action patterns that occurred while students used the visualization table to explore images of anatomy were investigated. The purpose was to identify qualitatively different ways of how students discern and make sense of anatomical structures.[45–47] The analysis was founded on a total of 11 h of recorded material. The audiovisual recordings were played back and analyzed by members of the research team (A.P., C.S., K.K).

An interpretive, abductive approach guided the data analysis process.[49] This analysis assumed a dialectic relationship between data and theory and was characterized by iterative rounds of playing back the recorded material, documenting instances that reflected tentative categories, and discussions among the research team. To get an overall understanding of the data, recordings and field notes were first examined separately by research team members, after which, notes were taken, and reflections were later discussed in the entire research team. The purpose of the discussions was to identify qualitatively different categories in the recorded material that reflected students' different ways of discerning the images presented to them and achieve consensus regarding these themes among the research team. After tentative categories had been identified the material was examined separately again; this time to find and document specific instances of interactions or sequences of interactions of a certain category. The identified instances were compared, discussed and revised by the research team until consensus was reached.[45–47] Representative examples of instances were then singled out for each category and are explained and presented as excerpts and still photographs from the recording in the results section.

RESULTS

Seven categories emerged from data analysis describing qualitatively different patterns of actions that students used to discern and make sense of anatomy (Figure 1). All categories are concerned with discernment and there is no hierarchy or order between them. The categories are explained below and supported by quotes. The same patterns of actions were present and recurrent among the students at different instances during the sessions. Interpretation was based on a model connected to variation theory as described by Marton and Booth.[50] Marton and Booth distinguish between a 'what' and a 'how' aspect in learning. This study has its focuses on the "how aspect" and describes students' actions and intentions while trying to understand 3D images of anatomical structures of the body. The "what aspect" is the direct object of learning; the outcome. It has critical features that must be brought to the fore and be discerned for it to be learned. The "how aspect" has two dimensions: it is concerned with actions; what the students do to learn as well as the intentions of their actions. The 'what' and 'how' aspects are intertwined and interdependent and will thus influence outcomes and variation in learning.

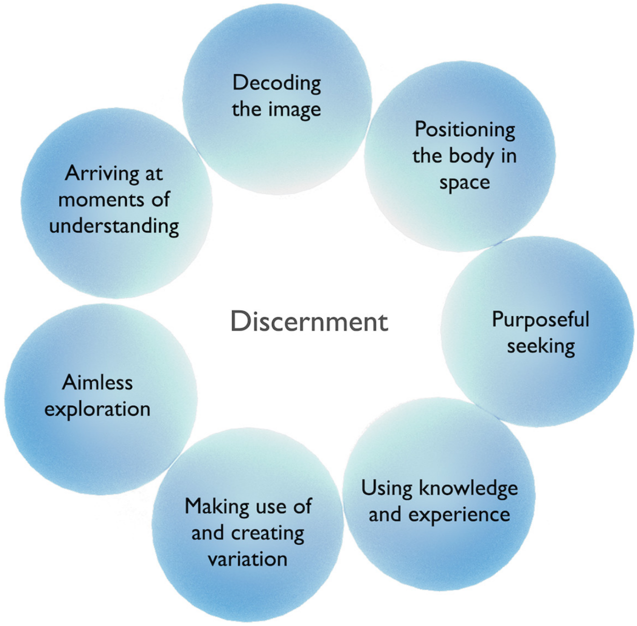

FIGURE 1 Seven qualitatively different patterns of actions that students used to discern and make sense of anatomy.

Decoding the image

This category describes students' intentions of understanding an image. This seemed to be crucial to be able to move on in their learning process. The students' intention here was to discern critical features of the images like colors, shades, or shapes by asking themselves questions like the following: what is this shape? What is the black, the white, and the gray, and how do they correlate to relevant anatomical structures like bones, gas, or fluid? (See Figure 2). To achieve this, they would zoom in and out of the image or draw across the image to change the contrast or switch between different kinds of images, comparing the way a certain feature stood out or asking questions about the technique behind capturing the image. To achieve this, they would repeatedly scroll up and down, searching for familiar anatomical structures to help them understand the image itself and the critical features of a particular structure.

The following citations reflect situations where students are trying to decode the image.

- "*I don't understand this line! It's horizontal. There is some kind of content there. It's blood, liquid, in some kind of hollow space*" (Nurse student, semester 1, looking at an image of a stomach that is dilated and filled with fluid).
- "*Here, it is light, but not very light. Some quantity can still pass through*" (Medical student, semester 9, looking at an image showing a kidney stone blocking the ureter).
- "*This must be … [thinking] Air is black right? How about fluid is that*

black as well? … It's grey … then this must be air then!" (Physiotherapy student, semester 5, looking at an image of the lungs).

Positioning the body in space

This category describes a pattern of actions that are connected to the students' intentions to orient themselves concerning the displayed image and to the whole body. Managing to orient oneself appeared to be fundamental for being able to move on in the learning process. The intention was to interpret the perspective and its relation to the visualized body: what is front and what is back; which side is right or left; where is the head in relation to the feet; or where in the body is the specific structure/organ that was mentioned in the case description located? To orient themselves they would repeatedly scroll up and down, searching for familiar anatomical structures to use as a reference, looking at the image while palpating their own body or placing themselves in a similar position as the displayed image, or rotating the image while looking at the presented structure from different angles (See Figure 3).

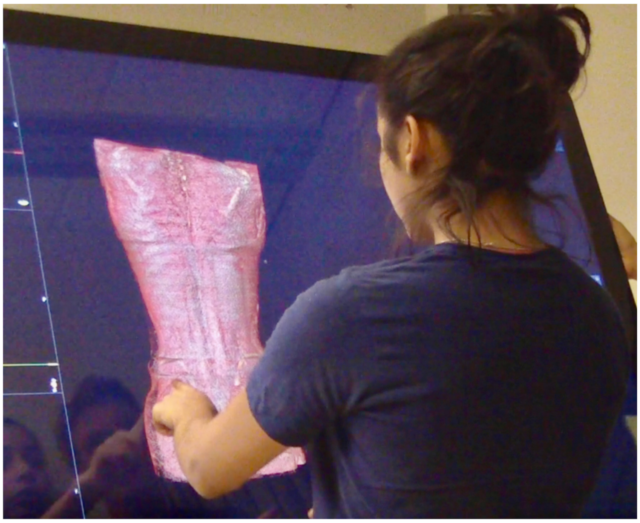

FIGURE 2 "What a weird line here! Could the patient have had trousers on during the X-ray?" Physiotherapy student, semester 1, trying to understand the image.

Purposeful seeking

In this category students' actions were more deliberate and target-oriented and they would often express a hypothesis or an expectation of what to find or look for. They did not always immediately know what the image was showing or its exact location in the body, but they acted upon preunderstanding, assured that they should be able to orient themselves if they only found a familiar structure that they could use as a reference. In attempts to find and understand a structure and its location, students would either systematically scroll top-down or start from a position where they had a known reference. If the displayed image did not show what the students wanted, they would ask for help orienting the image from a particular perspective.

The following quotes come from situations where students are purposefully exploring the images using a known reference to them.

- *"I'm looking for the lungs so that … they are probably here. They should be these two, that's air, right?"* (Physiotherapy student, semester 1).
- *"I'm thinking, I would like to look at the level of the kidneys and then go down to follow the urinary tract to see if I can see a stone"* (Medical student, semester 1).

Using knowledge and experience

This category reflects how students use what they know or their experiences in a way that helped them discern the images presented. While looking at the images they would make connections to clinical practice, lectures, or the information in the written patient case and previous experiences from their personal lives. Interactions between the students seemed to promote these connections. Students asked each other questions, confirmed suggested hypotheses, directed attention to specific aspects from lectures, or recalled a case from clinical practice. In this way they were collaborating in front of the table, using its different functions, and reasoning with each other. They would suggest anatomical terminology that they recalled and map it against the images, and then search for confirmation from their fellow students. These actions helped them

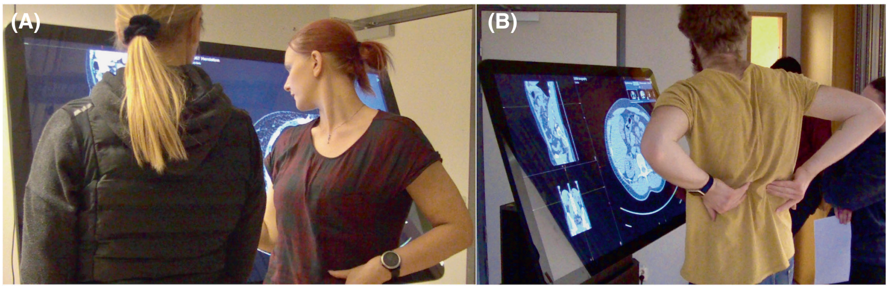

FIGURE 3 (A) "So, this must be the left side" Physiotherapy student, semester 1, positioning her hand to orient herself in relation to the imageb) (B) "No, those are not the kidneys. They are higher up. So, those must be muscles that go between the kidney and the spine." "We are somewhere here, right?" Medical student, semester 1, palpating his back to orient himself in relation to the image.

become aware of their knowledge gaps and their need to repeat exercises or study more.

The following quotes came from situations where students used knowledge and experience to reason about the meaning of what they saw in the images.

- "*I don't know what it looks like in a healthy abdomen. I'm thinking, there is gas there naturally, but not that much. If the black, if the black really is gas? You know, those hollow spaces we were talking about* [during lectures]." (Nurse student, semester 1).
- Student a: "*I am thinking of those gas bubbles*."
- Student b: "*Yes, but it's because nothing can pass through! Like, imagine that you clamp a garden hose*."
- Student a: "*Yes, that's right, it gets blocked there*."
- Student b: "*It lies completely still*" (Physiotherapy student, semester 1).

In the following citation, the student identifies the urinary bladder and sees that it looks shrunken

- "*It* [the bladder] *is not very big when it is empty*" (Medical student, semester 8).

Making use of and creating variation

In this category, the way in which students discerned anatomy was characterized by taking an active role in seeking variation, systematically manipulating the image using the functionalities of the table, rotating the image, and looking at it from different angles to understand its shape, size, and place. They would zoom in and out of the image to detect details, scrolling up and down or peeling off layers to get a sense of depth and of relationships. Students would deliberately and systematically go back and forth between images, compare them, or state a wish to compare images if they lacked the know-how to do so (See Figure 4). Students would typically express wishes about what they needed or wanted to do, to be able to advance toward discernment. A recurring wish was to compare images side by side. For instance, they would assume that the presented image showed a deviation or abnormality and would want to compare this image with an equivalent image of 'normal' anatomy. They would also ask for help displaying images from different planes simultaneously, or help displaying different kinds of images. If they could not view the images side by side, they would browse back and forth through the series of images to compare. In instances where they did have the ability to compare left and right sides, they expressed satisfaction. They would also compare the symptoms presented in the patient case with what they saw in the images.

The following quotes come from situations where the student has taken an active role in seeking variations to discern anatomy.

- Facilitator: "*Ok, so you want to see all planes simultaneously?*"
- Student: "*Yes, exactly, because then you can see how the slices are taken*" (Medical student, semester 1).
- "*Here, I would really like to have an anatomical image of the intestines and switch to that, then one could look at this one and compare it to the other one*" (Physiotherapy student, semester 5).
- "*I want to go back to the first image and then I want to know what it should look like so that I know what it looks like when it's wrong—what the abdominal wall looks like, what the intestines are supposed to be like*" (Physiotherapy student, semester 1).

Aimless exploration

The pattern of actions in this category is characterized by repeatedly scrolling up and down, in an aimless way, quickly switching images, or haphazardly zooming in and out. This was done either in a carefree or in a detached manner and students would often remain quiet while doing this.

The following quote illustrates situations where students were scrolling up and down aimlessly for a while silent and need prompting to think aloud.

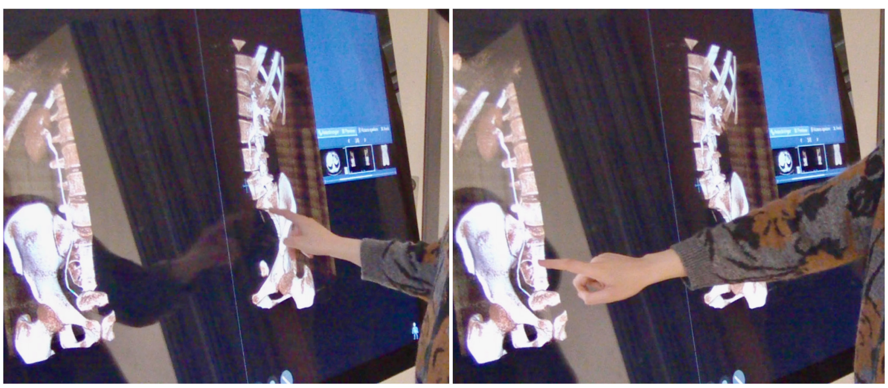

FIGURE 4 "You see a little contrast here and some there. That is why you see this part [pointing to one side], but not this one because this is where the stone is". Medical student, semester 9, comparing two images.

- Student: "*I just quite don't know where I am. I don't know what I see.*"
- Facilitator: "*Are you looking for something in particular?*"
- Student: "*Now I'm just looking at the image*" (Nurse student, semester 1).

The student is repeatedly scrolling up and down.

- "*I hardly know where the organs are*" (Physiotherapy student, semester 1).

An unexpected discovery by the learner or the peer could change the scenery, helping them to move on and orient themselves. Also, discovering a function in the visualization table or making connections between symptoms described in the written patient case and the image could help students move on and become aware of structures that helped them orient themselves.

The quote below comes from a situation where the students are looking at an image of the torso and discovered the ability to remove layers from the image.

- *Student b*: "*Wow, look!*"
- *Student a*: "*Now we can see some of the organs!*" (Physiotherapy student, semester 1).

Arriving at moments of understanding

This category denotes the moments where students came to a meaningful understanding of anatomy as it was presented by the images, the direct object of learning. A meaningful understanding meant recognizing certain features as critical, discerning them from their surroundings, and making sense of their relationship or function. This process of discernment looked different and took different paths. Sometimes students made a sudden discovery, and at other times they struggled with what they saw in the image. In the latter case, students would typically first be stymied, become silent, and back away from the visualization table, looking at the image from a distance. However, when they found and discerned a structure or an organ that they had been looking for or trying to understand, common reactions were exclamations of satisfaction, joy, fascination, or awe. The following quotes come from situations where students made that kind of discovery.

- "*Here you can actually see the urinary tract, there it is suddenly [the stone], like floating in the air!*" (Medical student, semester 8).
- "*I'm trying to get a cohesive picture from all the angles of what we think is wrong here*. [then later] *There! We have the hernia, it's the colostomy bag that is the culprit!*" (Physiotherapy student, semester 1).

DISCUSSION

Much of the research on technology-enhanced learning has addressed the issue of the educational effectiveness of new technologies on learning, that is, focused on 'whether it works'. Clunie et al.[20] concluded in their systematic review of studies assessing the range of approaches used to evaluate technology-enhanced learning across anatomy education that there is a need to explore meaningful causative relationships between such resources and improvements in learning. This study applied a clarification research approach[51] focusing on *why* or *how* questions to provide knowledge about students' learning processes. The findings of this study provide insights into the processes by which students construct their understanding of anatomy. It reveals qualitatively different categories of actions and strategies used by students interacting with a visualization table trying to discern and make sense of images displayed in 3D.[40] To further deepen the meaning of the findings they will be discussed in relation to relevant theories about learning as well as to previous research on students learning anatomy.

Decoding the image and positioning the body in space

According to variation theory, discernment is a prerequisite to understanding something.[40] The ways in which students went about discerning and reaching an understanding had similar features, but different actions were also displayed. A critical feature of understanding visualizations of anatomical structures and organs is the attempt to interpret the qualitative dimensions of the image. This critical feature was observed in the present study, in which all students were exploring the images, trying to find out and decode what color or shape certain anatomical structures had. Another vital approach coming to the fore is students' intention to grasp the 'wholeness' of the body under display. They identified parts and structures in relation to the whole, trying to locate the body in space. These two approaches are related to spatial understanding, and they emerged as fundamental for students to proceed in their learning process. Spatial ability is a complex phenomenon and there is agreement that it encompasses various related skills. However, the naming of the skills may differ. Fernandez et al.[52] distinguishes between visual mental rotation, scanning, categorical spatial relation, and metric spatial relation. Sweeney et al.[53] recognize the terms for different aspects like spatial perception, spatial reasoning, spatial sections, spatial orientation, and mental rotation. The approaches observed in the current study seem most similar to the term" visual mental rotation" as students oriented anatomical structures in the images, and to "categorial spatial relations," where students judged the relationship between one object to another. Spatial ability, which encompasses different skills, has been recognized as important in learning anatomy in several studies and literature reviews.[1,3,5,52,54,55] Although different aspects of spatial ability are likely to vary over time and depend on the context, Fernandez et al.,[52] Foo et al.,[1] and

Roach et al.[55] claim that spatial ability can be improved by training; by examining 3D images. The findings of students' actions in decoding the image and placing the body in space are in line with these suggestions. Students improved in their management of these processes over time during the sessions. However, for each new image, these actions were still necessary for students to interpret what they were seeing. Regarding research about self-directed learning,[56] these processes appear to be important in learning to learn how to discern anatomical structures and understanding 3D visualizations of the human body. Students' discovery of how to go about interpreting images appears to be crucial. This is in line with Esteves et al.[54] who had students construct 3D models using a foam-like material and concluded that "hands-on" and interactive interventions seem to help improve learning about complex 3-D relationships. If the teacher decodes the images and places the body in space, there is a risk that students only memorize what is pointed out and they will not acquire the necessary experiences and ability to apply this knowledge the next time they are looking at an image.[33,57]

Exploration strategies and use of knowledge and experiences

Although all students tried to decode the images and place the body in space, their actions displayed variations. The categories "purposeful seeking" and "aimless exploration" described such qualitative differences. The actions connected to these different strategies were related to individuals, the clinical cases, and different phases of the sessions. Students who were able to use previous knowledge about the body and connections to bodily functions and clinical experiences more often displayed deliberate search strategies. However, the seemingly less-useful aimless exploration also appeared to play a part in the learning process. Students stopped, contemplated, and eventually figured out how to proceed. There seemed to be differences between students in the early versus late stages of their education, as aimless exploration seemed less frequent among late-stage students. To some extent, late-stage students also showed a more purposeful and systematic approach when examining the images. The extent of clinical experience may influence this difference in approaches. Differences in the use of strategies were also dependent on peer cooperation and attitudes, and the ability to make use of the information they received about the circumstances of the actual patient. The strategies they used were also influenced by how well they knew or could master the functions of the table. The students in this study all applied a so-called 'deep' approach; they used strategies to reach an understanding of what the images showed.[50] Pandey and Zimitat[9] focused on students' study approaches when learning anatomy and found that students' approaches correlated with the learning outcomes. A deep approach led to higher quality learning. Fyrenius et al.[29] studied medical students' approaches to learning physiology and found that there are qualitative differences even within a deep approach.

Making use of and creating variation

This study shows that if students are allowed to examine 3D images on a visualization table and decide among themselves how to proceed, they will choose strategies correlated with a deep approach. However, their approaches varied concerning effectiveness in reaching an understanding. The students' actions in this study were characterized by actively making use of and creating variations in visualizations on the table. These actions strengthened the impression that students are stimulated to adapt to a deep approach to their learning. This means fully understanding the object of learning; not only one specific feature, but all critical features of organs, vessels, spaces, soft tissue, and bones in the body, and their interrelationships. This was a continuing process involving repeatedly decoding the image, locating the body in space, and relying on previous experience. During this process students created variations by manipulating the image, using the functions of the table, and looking at the images from different angles to gain a meaningful understanding of the size, shape, relationships, and depth of the anatomical structures. The purpose is to compare images to detect, understand, and distinguish between critical features. While Ling and Marton[41] emphasize the role of the teacher in bringing about optimal conditions for learning, interestingly, in this study, students themselves actively created these variations without the involvement of teachers.

Understanding anatomy

In this study, a meaningful understanding of the displayed images meant that the students could recognize anatomical structures and discern them from their surroundings. This is in line with the learning processes described by variation theory.[35,40] Understanding also included discovery of how variations of structures related to the whole body, the patient's disease, and to some extent, function. The process of constructing understanding was sometimes fast and sudden, in other cases characterized by struggle, hesitations, and lack of confidence to spell out what they believed the images showed. To some extent, these differences can be related to the student's clinical knowledge and experiences and to the earlier practice of looking at such images.[30,33] However, even students in their early parts of education managed to apply successful strategies to reach understanding. Students commented the fact that the images were authentic and reflected real patients, which seemed to add to their motivation to engage in the learning situation. Since motivation is well known to play an important part in learning, this is worth noticing.[35,58] Other observations concerning motivation were the students' satisfaction, joy, fascination, and even awe when they discovered that they could decode and understand what they saw in the displayed images. The students' experiences using the visualization table to learn anatomy, were followed up with interviews after the sessions.[43] The analysis of these interviews confirms that exploration of authentic images creates interest and meaningfulness in studying anatomy but points out that tutor guidance is important.[43]

Further research

Common features, and differences in learning anatomy, using 3D digital imaging, were revealed in this study. To broaden the understanding of students' learning processes, confirmation of these findings, and further exploration is needed. We need to know more about how students' preunderstanding, stage of education, different expectations of professional use of anatomical knowledge, and contextual factors affect decoding, ability to place the body spatially, and construct understanding. Another issue important to explore, is how well the understanding of 3D visualizations learned in this way transfers to clinical situations. The rapid development of technology-enhanced learning and the consequences of the Covid-19 pandemic has also raised interesting questions about how this knowledge may be applied to self-directed online learning.

Limitations of the study

Although the participants reflected diversity in terms of profession, their experience of anatomy education, and sex, there is a possibility that additional dimensions, as well as an increased number of students, should have been included to ensure richer and more adequate data about the phenomenon under study. The categories represent patterns of actions about learning across the student group. At an individual level, however, there might be different ways of learning. Another limitation might be the process of analysis and interpretation, which might reflect researcher bias. To achieve trustworthiness, co-analysis and peer discussions were employed, and the researchers' assumptions about learning have been described.

Methodological considerations

Several factors must be considered when interpreting the results. Being observed and recorded might have altered students' normal behavior, compared to their behavior during an ordinary learning situation. The role of the facilitators was not in focus in this study, and they were instructed to assist only when necessary. What a facilitator says and does may, however, be decisive in students' learning and what they 'see'.[59] The teacher role—focusing on how and when to offer support—is yet to be studied in this context. Qualitative data from a study by Fruhstorfer[60] found that the learning environment mattered to the students' perceived value of anatomy education. The reactions observed in this study when students came to insights indicated joy and satisfaction. To ensure diversity and rich information concerning the studied phenomenon,[61] the students represented different professions and different parts of their education. Additionally, two different cases were used, one relating to the abdomen and another relating to the brain. The cases were chosen to capture aspects that were expected to be challenging to discern, such as air-filled spaces or fluids. The choices of cases probably affected the way students went about discerning the images. The study result is based on 11 h of audiovisual recordings and rendered a large amount of data capturing what students said, and how they interacted with each other and with the table. The recordings allowed the research team to replay sequences for discussion and analysis, which adds value to the findings. All the chosen excerpts were based on the recorded material.[44]

CONCLUSION

This study contributes to a better understanding of the student's learning processes. It reveals insights into how students can construct an understanding of anatomy by using images of the human body displayed by visualization table. The findings point to the importance of letting students decide how and at what pace they should examine the images. The student's actions were characterized by creativity and deep learning approaches. The processes of decoding the image and striving to grasp anatomical structures concerning the wholeness of the body, emerged as fundamental in their approaches. It appears to be crucial that the discovery process of how to decode and place the body in space is made by the students themselves. Students' own discoveries became a way of learning how to best learn anatomy using visualizations. Different approaches used were not only related to students' level of knowledge and clinical experiences but also to peer cooperation and ability to handle the functions of the table. Students appreciated the authentic variations of the human body, which students found motivating in their learning. Notable was that students deliberately sought variations to improve their discernment and understanding. Integrating this knowledge into regular education requires careful consideration. Considerations should include when and how it is appropriate to give students time for discovery sessions supporting a deep approach to learning, the choice of case or task, instructions, interactions among students, time, and place in the curriculum, as well as what the teacher can do to facilitate learning.

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ETHICS STATEMENT

The study was conducted following the Declaration of Helsinki. Ethical approval was sought from the Swedish Ethical Review Authority (reference 2019/05095) and the study was exempted. The study adhered to the principles of the ethical framework for research on learning.[62] All participants provided informed consent.

ORCID

Anna F. Pettersson https://orcid.org/0000-0001-6610-4353
Klas Karlgren https://orcid.org/0000-0003-1255-7650
Jonathan Al-Saadi https://orcid.org/0000-0002-8832-7176
Hans Hjelmqvist https://orcid.org/0000-0001-5294-8387
Björn Meister https://orcid.org/0000-0003-3169-8707
Hugo Zeberg https://orcid.org/0000-0001-7118-1249
Charlotte Silén https://orcid.org/0000-0001-7952-4808

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AUTHOR BIOGRAPHIES

Anna F. Pettersson, R.P.T., Ph.D., is a physiotherapist and Director of the Physiotherapy Program in the Division of Physiotherapy, Department of Neurobiology, Care Sciences and Society, at Karolinska Institutet in Stockholm, Sweden. She teaches professional issues to physiotherapy students and has a special focus on reflective practice in her free-standing courses. Her research interest is in educational research, learning, and professional development.

Klas Karlgren, Ph.D., is an associate professor in medical education at the Department of Learning, Informatics, Management, and Ethics at Karolinska Institutet, the Department of Research, Education, Development and Innovation at the Södersjukhuset in Stockholm, Sweden, and the Faculty of Health and Social Sciences, Western Norway University of Applied Sciences in Bergen, Norway. He supervises Ph.D. students in the areas of medical education and health informatics, and his research interests include learning processes, technology-enhanced learning, and simulation.

Jonathan Al-Saadi, is an MD and Ph.D. student in the Department of Clinical Neuroscience, at Karolinska Institutet in Stockholm, Sweden. He is a senior instructor in anatomy and teaches anatomy to medical students at Karolinska Institutet. His research is focused on experimental radiology, regenerative medicine, and novel treatments for cardiovascular and kidney diseases.

Hans Hjelmqvist, M.D., Ph.D., is a professor and senior consultant in anesthesiology and intensive care at the School of Medical Sciences, Örebro University in Örebro Sweden. He is affiliated with the Department of Learning, Informatics, Management and Ethics at Karolinska Institutet in Stockholm, Sweden. He teaches pedagogy and science to medical students and other health care professionals at the undergraduate and graduate levels, and his research interests are in education research, interprofessional learning, and professional development.

Björn Meister, M.D., Ph.D., is a professor of microscopic anatomy and Head of Education in the Department of Neuroscience at Karolinska Institutet in Stockholm, Sweden. He teaches histology to medical and dental students and his research interest is focused on brain control of food intake and body weight.

Hugo Zeberg, M.D., Ph.D., is an assistant professor of anatomy in the Department of Neuroscience at Karolinska Institutet at Stockholm, Sweden. He teaches anatomy to medical students and clinical anatomy to residents and clinicians. His research interests are evolutionary biology and genetics. He has been a consulting editor for several anatomy textbooks and atlases, and is the current president of the Swedish Society for Anatomy.

Charlotte Silén, R.N., Ph.D., is an associate professor in medical education and senior lecturer in the Department of Learning, Informatics, Management and Ethics at Karolinska Institutet in Stockholm, Sweden. She teaches about learning and education to faculty in health care professions, and supervises Ph.D. students in medical education. Her research has a qualitative approach and focuses on understanding learning processes and development related to students and professionals in higher medical and clinical education.

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