Medical Illustration: Discovering and Comprehending Scientific Concepts Through Art

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Introduction

An image that initially looks as if it was abstract art is projected onto the screen at the forefront of the classroom. Different colored dots attached by multicolored lines and arrows connect to a simple graphic of a brain as the muddled words of the professor lose the competition for attention and the visual information is absorbed. Upon further examination, some of the different lines and dots are labeled delta and beta, along with how the brain is differentiated from the spinal cord. While the professor's voice takes back more attention, the dots and lines turn into receptors and neurons, with neural pathways projecting to and from the brain. As the articulated information emerges into the forefront of conscious attention, coupled with the visual input of the diagram, and the gate control theory of pain has been taught. However, has it been comprehended? In the classroom or through other media, for instance videos or textbooks, scientific information is portrayed through diagrams and illustrations in order to aid understanding.

However, the scientific diagrams projected through screen share on Zoom are different than those from a decade ago, and even more so from a century ago. Scientific diagrams have completely transformed over the last few centuries, largely due to advancements in technology, health practices, and scientific discoveries. Mass spectrometry, x-rays, proton accelerator, and artificial intelligence are just a few of the technological advancements that impacted the field of scientific illustration. Some of the major scientific discoveries that changed the field of scientific illustration include the advancements of mathematics, physics phenomena, deoxyribose nucleic acid, and the discovery of atoms along with different elements. Throughout history people have been using pictures to relay information, from the Egyptians depicting the process of embalming, to Leonardo da Vinci's anatomical drawings, to the modern father of medical illustration: Max

Brodel (Branigan, 1995). However, in the wake of the digital age, scientific diagrams and medical illustrations have taken on multiple dimensions (Hajar, 2011). With different emerging fields portraying scientific information, the way people learn is changing. However, are these effects aiding and enhancing learning? How are these diagrams utilizing different parts of the brain to elicit learning and memory?

In this paper, the use and effectiveness of different multimedia platforms for learning various scientific topics will be analyzed in conjunction with the different neural mechanisms and psychological theories that achieve this. Additionally, the processes involved in creating an effective medical illustration will be examined. The aim of this paper will be to address the following questions: Which is a more successful teaching aid: two dimensional diagrams or three-dimensional models? What is the balance point for the amount of detail to include within a diagram: how can an illustration be comprehensive, but not overwhelming? How does color affect the observer's ability to comprehensively process and learn from different diagrams? What new technologies have revolutionized medical diagrams, and have these developments made illustrations more effective? Where is the future of medical illustration going? These questions are important as the field of education works to further challenge and improve the way students learn and the quality of understanding students gain through the use of scientific diagrams.

History of Medical Illustration

Diagrams and illustrations have been an integral part of scientific literature since the 1800s; diagrams have had a parallel evolution to the scientific concepts they illustrate (Belknap, 2019). As diagrams adapted within the historical context of science, styles and techniques have changed; this in turn influenced the effectiveness of conveying scientific information. However,

using illustrations to demonstrate different topics predates the discovery of the hard sciences. People have been using illustrations to document nature for nearly 40,000 years (Wei-haas, n.d.). Medical illustration first appeared late into the fourth century B.C. in Hellenic Alexandria, modern day Greece (Branigan, 1995). These illustrations reported anatomical information, surgery, obstetrics and even plants of medicinal value.

The renaissance was a turning point in the world of scientific illustration as it revolutionized the field of human anatomy. One prominent change in the style of medical illustration made for the scientific discoveries that occurred in the renaissance was an increased level of detail. In this period, the discipline of anatomy was explored in many different artistic explorations: from extremely analytically drawn anatomical structures in the pursuit of artistic realism to life size statues of human figures with unprecedentedly accurate anatomy, including anatomical details (Righthand, n.d.). Leonardo de Vinci is considered the first medical illustrator due to his wide collection of anatomical renderings and sculptures (Pevsner, 2019). Within the renaissance period, Andres Vesalius took on his own anatomical exploration as Leonardo de Vinci ended his career; Vesalius eventually published the book De Corpus Fabrica Humani and to this day it is still the most well-known book of anatomy (Versalius, 1543). However, anatomy was not the only field being discovered and explored within the renaissance. Many other scientific discoveries were made during this time period and were explained and demonstrated through illustrations; these include Rene Descartes theory of vision and William Harvey's explanation of the circulatory system (Ford, 1993). Both of these scientific topics incorporated a significant amount of detail within their diagrams. Descartes theory illustrated the many different pathways, known today as neurons, that from the eye, converge at would soon to be known as the the corpus callosum, and ending up at the back at the head which is now known at the visual

cortex in the occipital lobe. This diagram included an abundance of labeling and detail. Harvey's diagram showed the circulation throughout the whole body and many different arteries and veins and the convergence of those, known today as capillaries. It depicted two scenarios in sequence, showing the effects of cutting off circulation at veins versus arteries. Despite both of these diagrams being two dimensional black and white sketches, they demonstrated complex topics using aspects and techniques still used in medical illustration today. New diagrams about this topic utilize other techniques, including color, three dimensional models, and dynamic computer simulations. Are these more or less effective at portraying these scientific concepts in comprehensible manners?

The field continued to grow and advance as different fields in science, particularly different medical fields, emerged, such as the study of obstetrics. However, Max Brödel revolutionized the field of medical illustration, forming it into a true profession and having his illustrations educate generations of students. His diagrams encompassed many different fields of medicine, including neurosurgery, an emerging field at the time of his career (Patel et al., 2011). His ability to render complex, and sometimes abstract concepts and scenarios into distilled, understandable diagrams has continued to impact medical illustrations. His legacy can not only be found in medical textbooks and journals but continues to influence the many medical illustrators that have come after him. Since then, research has been done within the field of medical illustration and scientific diagrams to assess their effectiveness. How did Max Brodel straddle this difficult line of too much and to little detail? How did he choose which details to focus on and which to exclude? How did he decide which colors to use and why? Why was he so successful while others weren't? Many scientific advancements containing an abundance of

detail have been made since his time, making the determination of how much and which details to include an increasingly difficult task.

The Devil Is In The Details

When designing a scientific diagram, there are many aspects to consider: finding the balance of how much detail to include, what colors to use, the level of realism to incorporate, how many words are on the page/what needs labeling, among many other aspects. On one hand, some of these decisions are dependent on the particular scientific concept such as learning goals and intended audience. For example, the illustrator must choose which particular details to include when portraying objects or organisms and whether or not to do so in their true color(s). While on the other hand, there are some universal aspects that should be included in almost all scientific illustrations.

One of the most difficult aspects to gauge is how much and which details to include. Medical illustrators attempt to balance the level of detail included in a diagram by providing enough cues to fully portray a concept without distracting and confusing the viewer. While Garry Henderson talks with great zeal about the delicate balance, he does not include any detail within his own literature review to support his claim (Henderson, 1999). While medical illustrations and scientific diagrams are not universal and depict different concepts with different illustrations that include and focus on differing details, the balance all illustrators of scientific diagrams aim to achieve is the same. It is to collect and include the right details to convey the information in an understandable manner. However, this optimal level is difficult to achieve because if it lacks detail or provides an overwhelming amount of detail, it can have detrimental effects to understanding. If too much detail is removed or not included, the entire context of the illustration may be lost, and the viewer may not be able to grasp the concept. On the other side of

the spectrum, if too many details are included, it may distract the reader from the key concept that is being addressed by the illustrator (Henderson, 1999). While the amount of detail and the determination of details are essential, they are dependent on the concept itself, and the intended viewer adds another dimension of detail consideration (Haragi et al., 2021). The intended audience changes the varying levels of specificity that should be included such as the details needed to explain the circulatory system to 5th graders versus 3rd year medical students. This added dimension of consideration for the intended audience was explored in a study conducted by researcher Haragi. The amount of detail to include on medical illustrations is dependent on a person's age and gender, and was studied for delivering cancer information to patients and laypersons. In this study, the researchers investigated the preferred amount of detail when delivering cervical cancer information. It found that women tend to prefer more comprehensive diagrams that demonstrated the entire concept rather than just one particular aspect, compared to men. It also found that older participants preferred greater levels of detail to their junior counterparts. This study supports the position that medical illustrators should take into account the intended audience when deciding the level of detail (Haragi et al., 2021). However, some experts within the field, for example researchers Brown and Loeb, tend to campaign for reductionist diagram designs, claiming that without the extraneous details' viewers can concentrate on target information without unwanted distractions (Brown & Loeb, 2000). The Australian National University conducted two qualitative focus group studies to explore the attitudinal responses of viewers to content in diagrams. This study concluded that there was a less overwhelmed, and thus less anxious emotional response to diagrams with less detail, supporting the reductionist diagram designs (Wood, 2018). What this study fails to explore are the learning outcomes in addition to the attitudinal responses. The debate is still ongoing on how

to best determine which details are extraneous and which aren't and whether the universality of it can be determined (Ollerenshaw, 1988).

Color Consideration in Designing Diagrams

While in daily life, colors may be preferred for esthetic reasons, colors may impact learning and attention and therefore have relevance to the extent to which messages may be conveyed through illustrations. One study conducted at New York University recruited graduate students to be exposed to different diagrams and educational images that had different colors and shapes. This study found that warm colors induced positive emotions in conjunction with other stimuli and did facilitate comprehension independent of other stimuli. However, what makes warm colors more apt to learning compared to cooler tones? One study investigated why certain colors facilitate learning by exposing different colored pictures to subjects and asking questions about how they felt. This study found colors considered to be cool tones, such as turquoise and violet, tend to have a relaxing and pleasurable effect. On the other hand they found warm tones such as yellow, orange, and brown are considered to be active, stimulating and even arousing. Meanwhile black, white and grey tones can take on a warm or cool color persona dependent on what color is close by (Kumi et al., 2013). Thus, different colors are associated with different emotions and feelings which may have subsequent impact on learning outcomes. One study found that while color preferences exist from culture to culture and even person to person, hue value and chroma tend to evoke more universal responses. For example, yellow hues tend to be disliked because the color demands attention forcibly while blue hues tend to evoke calmness and are well liked (Plass et al., 2020). Several studies have shown that color alone affects comprehension, most of which describe warm tones are best to use to aid learning.

However, the feelings and sentiments associated with certain colors are not necessarily always universal. One study found that the color red impairs cognitive performance during different academic tasks; the results were explained through the idea that the color red evokes avoidance motivation, thus hindering performance. The study measured heart rate variability while testing the participants in the study with or without the color red present in the environment and exam (Elliot et al., 2011). It is theorized this avoidance motivation may be a learned response; many studies have investigated the use of this color for grading and the subsequent emotional reactions of students. One study conducted by researchers Duke and Albanesi found that grading with red pen upset students and speculates inhibiting future learning (Dukes & Albanesi, 2013). Another study conducted by the University of Arkansas doesn't agree that the color red always evokes avoidance motivation, arguing that information encoding and retrieval are two distinct processes (Gnambs et al., 2015). The encoding that occurs is dependent on environmental context and the retrieval phase was more successful when it occurred in a similar environment. This study concluded that cultural environment and personal experience with a color affects how well one learns when that color is used in learning aids. For example, in Western societies red is associated with girls and is found in many toys for girls, thus it was not surprising that girls outperformed their male counterparts when the color red was used within learning and grading (Gnambs et al., 2015). These studies, among others like it, demonstrate that students are impacted by what color is used in diagrams, and can have an affect on their receptivity to learning. This impact is independent of what the response to a specific color is due to positive or negative association or an instinctually evoked response. The vast majority of this research did not take the next step past attitude and feeling, the impact to learning.

Exploring the Value of Three Dimensions Models in Learning

Since the sculptures of the renaissance, three dimensional scientific models have continued to advance, now taking on the form of digital printing, virtual reality, digital diagrams, and textured models. These models activate different regions within our central nervous system through spatial and tactile learning. This is in part due to spatial learning processes where visual sensory input is processed within the occipital lobe and then evokes the use of the hippocampus and the posterior parietal cortex within the brain; tactile learning processes the touch sensation and thus induces the use of the somatosensory cortex within the brain among other regions (Hsiao & Gomez-Ramirez, 2011). The spatial neural pathway also utilizes a region called the macaque inferotemporal cortex to specifically process three dimensional models, as shown through an experiment utilizing MRI imaging in monkeys shown both two dimensional and three dimensional stimuli (Verhoef et al., 2012). Both of these learning styles work in conjunction with visual stimulation that activates the primary visual cortex in the occipital lobe, the same and only sensory region activated when looking at two-dimensional illustrations.

There is plenty of evidence within educational literature to support the use of two-dimensional diagrams and illustrations to facilitate learning (Butcher, 2006; McTigue & Flowers, 2011). Whether it be across disciplines or fields, diagrams are a learning tool that have been effective for centuries (Duchastel, 1978; Dwyer, 1968); this point continues to be studied and supported through different scientific research inquiries (Butcher, 2006; Carney & Levin, 2002; Rogers & Scaife, 1998). However, there seems to be less published information about the effectiveness of learning with three-dimensional models and tactile learning. The literature also tends to be divided; one group of thought argues that learners with high spatial ability benefit greatly from three dimensional models because they have the cognitive capacity left for mental construction, while learners with low spatial abilities may be cognitively overloaded by them and

have difficulty constructing the model within their own head and don't benefit (Huk, 2006). Cognitive capacity or load refers to the amount of information that a person's working memory can hold at one time. This working memory model stems from Baddeley and Hitch who developed it in 1974. They theorized that sensory input is presented to the body, for example visual sensory input being presented to the eyes, and processed within sensory regions of the brain, like the visual cortex in the occipital lobe, which are either given attention or forgotten. If given attention, the sensory input moves onto being processed at a higher level by the 'central executive,' most likely at the frontal cortex and is at the forefront of one's mind. From this central executive, the processed information can then be further analyzed within the 'visio-spatial sketchpad' (Andrade, 2001). This is the region referred to that does not have sufficient capacity to be processed by certain students. The second body of thought within the literature is that everyone benefits from using three dimensional models and spatial learning is a developed skill. This theory is enhanced through the incorporation of tactile learning that comes with handling three dimensional models, activating kinesthetic and visual pathways simultaneously (Gadt-Johnson & Price, 2000). Tactile learning has been investigated as an effective mode of learning in several species. The cognitive functions involved in working memory were investigated in a research study completed in an Italian laboratory, having multiple species complete a maze, reinforced with a reward, and measured for repeated accuracy. This study laid the foundation that spatial memory of the environment is affected and even somewhat controlled by working memory abilities (Fassihi et al., 2014). Kong et al. (2016) explored tactile learning within medical education compared to the effectiveness of a three-dimensional visualization (3DV) with that of a three-dimensional printing (3DP) with the experimental group having a textured model to assess if it aids in learning hepatic segment anatomy. This study found the

group of students who had the textured three dimensional model performed better on the exam and thus had a deeper understanding of the topic taught. This study differentiated the importance of tactile learning as a separate aspect from three dimensional models alone (Kong et al., 2016).

Learning in the Digital Age

Within this modern era, technology has revolutionized scientific diagrams; medical illustrations can now be developed utilizing digital media. Several studies have shown that the use of different digital visual diagrams and programs are associated with student achievement measured by higher grades. In one study, the researchers investigated the use of digital diagrams and digital programs in university classes and found that students who were exposed to either or both digital and traditional resources outperformed their counterparts who did not have access to the digital resources (Boozer & Simon, 2020). Another emerging digital illustration sub-field that is being developed to help educate healthcare professionals are volume illustration overlays with different medical imaging techniques. It is used to provide insight into CT/MRI scans to aid in understanding/reading of the scans, leading to more accurate assessment of medical ailments (Svakhine et al., 2009). This technique is hypothesized to improve spatial learning as it relates to neurological imaging, illustrating specific regions of the brain within the context of specific imaging.

Using a digital interface to show different visual diagrams gives interesting possibilities for simple animation, spatial learning through object manipulation among other things, and even visual virtual games. One study investigated color theory and psychology to examine the effects of expression, color, shape, and dimensionality for emotional game learning in children. This study demonstrates that while these additional digital components are interesting, they build on the same factors discussed in the inspecting aspects portion of this article and have the same

trends for effectiveness based on those components (Plass et al., 2020). However, most interestingly, three dimensional virtual representations of diagrams were associated with increased levels of arousal, resulting in improved learning outcomes. This is specifically shown in a study conducted that looked at the dynamics of communication in the classroom through computer animations and visuals, finding that students were more aroused with dynamic animations than stagnant figures (Shreesha. & Tyagi, 2018). Arousal is a very important aspect of learning, as it allows students to hold their attention on the subject at hand so that the sensory input can move into their 'central executive' within the working memory theory (Andrade, 2001). These results were also seen with interactive applications and animations when they were simplistic and minimal. With too much detail working memory overload occurs and it is viewed as distracting, having an inhibitory effect on learning. This has the implication that despite the use of different media and mediums to create drawing, the delicate balance of how much detail to use is universal across platforms.

Virtual Reality

Another advancement in the form of virtual reality has also made its way into the learning sector. Virtual reality (VR) is a computer-generated simulation of the environment or three-dimensional image, allowing the user to interact with in a seemingly real or physical way. Most VR systems include a pair of goggles with built-in speakers and a handheld controller, similar to that used for recreational video games. With applications that allow one to completely immerse oneself within the body and explore different phenomena in ways not previously fathomable. One medical school studied the effectiveness of using these VR modules to learn forearm anterior compartment musculoskeletal anatomy by comparing it to a control group and a group taught with traditional methods. The results demonstrated that virtual reality anatomy

learning was equivalent to traditional learning, however the authors call for VR to be used to complement traditional teaching methods rather than to replace them (Codd & Choudhury, 2011). Another medical school implemented an extremely similar study by creating and using a VR environment of the human heart to teach the heart anatomy system. However, they only reported that VR enhanced their experience learning anatomy along with traditional teaching methods (Alfalah et al., 2019). Neither of these studies recommended replacing traditional teaching methods, such as use of a cadaver, with VR representations despite it having the same success in learning outcomes.

Conclusion

The components that make up a scientific diagram can influence learning outcomes. The colors illustrators use have the ability to facilitate learning: warm colors facilitate learning (Plass et al., 2020). The level of detail to include within a diagram is a delicate balance that is dependent on many factors: subject material, intended audience, necessary versus extraneous (Haragi et al., 2021). Certain artistic styles better facilitate learning over others (Krasnoryadtseva et al., 2020). Various media, traditional and modern, are effective learning tools. However, the question of why and how these components make a difference weren't answered.

To evaluate the effectiveness of any learning aid, it may be helpful to understand the neural pathways involved in processing and comprehending sensory information, in particular visual, auditory, and kinesthetic information (Censor et al., 2012). Each of these sensory inputs project afferently through the peripheral nervous system and to the central nervous system where they are routed through the thalamus to their perspective specialized cortical regions to be processed by the brain to promote understanding. After, the sensory information translated in the form of action potentials traveling through and between neurons are potentially projected to the

frontal cortex to be used in higher level thinking or potentially the hippocampus to be stored in long term memory (Bird & Burgess, 2008). Through the understanding of the neural mechanisms behind visual processing, the how and why behind the comprehension of diagrams and illustrations can be assessed. By examining the learning mechanisms involved in processing auditory sensory information, the efficiency of lectures can begin to be discerned. The pathways activated in kinesthetic and tactile learning, may offer clues to why three-dimensional models and virtual reality applications may be effective learning tools. Understanding how the neural circuitry involved with different sensory input is processed to allow learning may help us discern which features of a scientific diagram make it an effective learning tool.

By understanding the neural pathways and psychological foundations to sensory information processing and learning, more effective learning aids can be made. The use, or lack thereof, of these components in scientific diagrams have real world implications to instruction. Within the medical field, knowing and understanding different concepts can be the difference between life and death. Thus, it is essential to educate the healthcare providers of tomorrow with any and all tools to ensure the best healthcare treatment to all people. In a time where online education was the only form of education for months and continues to be the only mode of education for some students, evaluating the effectiveness of online illustrations and interactive digital diagrams is even more essential. While some studies have begun to examine these neurological foundations that create an effective scientific diagram, not enough have been conducted to explicitly determine these relationships. Most importantly, none of these findings are facilitating best practice for how scientific diagrams or illustrations should be made. The lessons and guides of how to create a medical illustration do not include information guiding the artist to make informed decisions about certain aspects of their piece that will enhance learning,

rather instructional guides on the physical or operational aspects of how to make one (Culley, 2016; *Expert Techniques*, n.d.). The process is dependent on the personal choices or preferences of either the illustrator and/or the commissioner of the piece.

Experiments should be designed and completed to determine the effectiveness of diagram components as it directly relates to how they are neurologically processed. For example, further studies should be conducted on levels of detail to include by presenting subjects diagrams of various details while attached to a fMRI and have them take exams about the demonstrated material to determine how much and where the brain is activated by an illustration. By doing this across disciplines a firm line can begin to explore how much detail should be included within a diagram that is optimal for retention. Other studies should also be conducted directly comparing the use of digital and printed two dimensional diagrams to determine the differences in effectiveness as well as have the subjects neurologically imaged to determine if different brain regions are being utilized dependent on the type of media being utilized.

The field of medical illustration and scientific diagramming must grow and adapt with the emerging technology and current global circumstances; however, it should not neglect or ignore the neurological and psychological foundations that determine what makes an effective diagram. The field should also continue to study the effectiveness of new and emerging multidimensional learning aids. While the proposed studies include great methodological rigor, they need to be done in order to accurately assess the effectiveness of different components that make up a diagram and prevent illustrators and professors alike from creating diagrams based off of personal preference and assumptions. This research is difficult to complete because it also calls for the collaboration between artists and scientists and calls into question the protocols already established within the field of medical illustration and scientific diagramming.

Not enough research has been published in regard to the widespread use of VR for educational purposes. It would be helpful to be able to identify how these new emerging technologies might draw on different neural pathways and circuitry compared to traditional models to improve learning outcomes. The use of direct comparison through testing and neurological imaging across different ages could be helpful in determining the effectiveness of this media. An emerging and exciting technology emerging within medical training are simulations through VR. A student can not only view different parts of the body through the VR system, but interact with simulated patients, conduct physical examinations, run tests and labs, etc. (Mariani & Pêgo-Fernandes, 2011). Unfortunately, it is possible that VR technology may be marketed as learning tools without the sufficient research data to support it as being effective. As visual learning aids, such as this, develop and continue to emerge, developers might strive to take into account the different aspects of what defines an effective learning tool, thus making more informed decisions during development and for its implementation.

References

Alfalah, S. F. M., Falah, J. F. M., Alfalah, T., Elfalah, M., Muhaidat, N., & Falah, O. (2019). A comparative study between a virtual reality heart anatomy system and traditional medical teaching modalities. *Virtual Reality*, *23*(3), 229–234. https://doi.org/10.1007/s10055-018-0359-y

Andrade, J. (2001). *Working Memory in Perspective*. Psychology Press.

Belknap, G. (2019). 150 years of scientific illustration. *Nature*, *575*(7781), 25–28. https://doi.org/10.1038/d41586-019-03306-9

Bird, C. M., & Burgess, N. (2008). The hippocampus and memory: Insights from spatial processing. *Nature Reviews Neuroscience*, *9*(3), 182–194. https://doi.org/10.1038/nrn2335

Boozer, B. B., & Simon, A. A. (2020). Teaching Effectiveness and Digital Learning Platforms: A Focus on Mediated Outcomes. *Journal of Instructional Pedagogies*, *24*. https://eric.ed.gov/?id=EJ1263918

Branigan, A. (1995). *History of Medical Illustration*. AMI. https://ami.org/professional-resources/advocacy/legal-news/27-main/medical-illustration/49-history-of-medical-illustration

Brown, I. E., & Loeb, G. E. (2000). A Reductionist Approach to Creating and Using Neuromusculoskeletal Models. In J. M. Winters & P. E. Crago (Eds.), *Biomechanics and Neural Control of Posture and Movement* (pp. 148–163). Springer. https://doi.org/10.1007/978-1-4612-2104-3_10

Butcher, K. R. (2006). Learning from text with diagrams: Promoting mental model development and inference generation. *Journal of Educational Psychology*, *98*(1), 182–197. https://doi.org/10.1037/0022-0663.98.1.182

Carney, R. N., & Levin, J. R. (2002). Pictorial Illustrations Still Improve Students' Learning from

Text. *Educational Psychology Review*, *14*(1), 5–26. https://doi.org/10.1023/A:1013176309260

Censor, N., Sagi, D., & Cohen, L. G. (2012). Common mechanisms of human perceptual and motor learning. *Nature Reviews Neuroscience*, *13*(9), 658–664. https://doi.org/10.1038/nrn3315

Codd, A. M., & Choudhury, B. (2011). Virtual reality anatomy: Is it comparable with traditional methods in the teaching of human forearm musculoskeletal anatomy? *Anatomical Sciences Education*, *4*(3), 119–125. https://doi.org/10.1002/ase.214

Culley, J. (2016). Creating a digital medical illustration. *Journal of Visual Communication in Medicine*, *39*(1–2), 77–84. https://doi.org/10.1080/17453054.2016.1182424

Duchastel, P. C. (1978). Illustrating Instructional Texts. *Educational Technology*, *18*(11), 36–39.

Dukes, R. L., & Albanesi, H. (2013). Seeing red: Quality of an essay, color of the grading pen, and student reactions to the grading process. *The Social Science Journal*, *50*(1), 96–100. https://doi.org/10.1016/j.soscij.2012.07.005

Dwyer, F. M. (1968). The Effectiveness of Selected Visual Illustrations in Teaching Science Concepts to College Freshmen. *The Journal of Educational Research*, *61*(8), 343–347.

Elliot, A. J., Payen, V., Brisswalter, J., Cury, F., & Thayer, J. F. (2011). A subtle threat cue, heart rate variability, and cognitive performance. *Psychophysiology*, *48*(10), 1340–1345. https://doi.org/10.1111/j.1469-8986.2011.01216.x

Expert Techniques. (n.d.). AMI. Retrieved March 15, 2021, from https://www.ami.org/professional-resources/expert-techniques

Fassihi, A., Akrami, A., Esmaeili, V., & Diamond, M. E. (2014). Tactile perception and working memory in rats and humans. *Proceedings of the National Academy of Sciences*, *111*(6), 2331–2336. https://doi.org/10.1073/pnas.1315171111

Ford, B. J. (1993). *Images of Science: A History of Scientific Illustration*. Oxford University Press.

Gadt-Johnson, C. D., & Price, G. E. (2000). Comparing Students With High and Low Preferences For Tactile Learning. *Education*, *120*(3), 581.

Gnambs, T., Appel, M., & Kaspar, K. (2015). The effect of the color red on encoding and retrieval of declarative knowledge. *Learning and Individual Differences*, *42*, 90–96. https://doi.org/10.1016/j.lindif.2015.07.017

Hajar, R. (2011). Medical Illustration: Art in Medical Education. *Heart Views : The Official Journal of the Gulf Heart Association*, *12*(2), 83–91. https://doi.org/10.4103/1995-705X.86023

Haragi, M., Hayakawa, M., Watanabe, O., & Takayama, T. (2021). An exploratory study of the efficacy of medical illustration detail for delivering cancer information. *Journal of Visual Communication in Medicine*, *44*(1), 2–11. https://doi.org/10.1080/17453054.2020.1834838

Henderson, G. (1999). Learning with diagrams. *Australian Science Teachers Journal*, *45*(2), 179.

Hsiao, S., & Gomez-Ramirez, M. (2011). Touch. In J. A. Gottfried (Ed.), *Neurobiology of Sensation and Reward*. CRC Press/Taylor & Francis. http://www.ncbi.nlm.nih.gov/books/NBK92803/

Huk, T. (2006). Who benefits from learning with 3D models? The case of spatial ability. *Journal of Computer Assisted Learning*, *22*(6), 392–404. https://doi.org/10.1111/j.1365-2729.2006.00180.x

Kong, X., Nie, L., Zhang, H., Wang, Z., Ye, Q., Tang, L., Li, J., & Huang, W. (2016). Do Three-dimensional Visualization and Three-dimensional Printing Improve Hepatic Segment Anatomy Teaching? A Randomized Controlled Study. *Journal of Surgical Education*, *73*(2), 264–269. https://doi.org/10.1016/j.jsurg.2015.10.002

Krasnoryadtseva, A., Dalbeth, N., & Petrie, K. J. (2020). The effect of different styles of medical illustration on information comprehension, the perception of educational material and illness beliefs. *Patient Education and Counseling*, *103*(3), 556–562.

https://doi.org/10.1016/j.pec.2019.09.026

Kumi, R., Conway, C. M., Limayem, M., & Goyal, S. (2013). Research Article Learning in Color: How Color and Affect Influence Learning Outcomes. *IEEE Transactions on Professional Communication*, *56*(1), 2–15. https://doi.org/10.1109/TPC.2012.2208390

M., S., & Tyagi, S. K. (2018). Effectiveness of animation as a tool for communication in primary education: An experimental study in India. *International Journal of Educational Management*, *32*(7), 1202–1214. https://doi.org/10.1108/IJEM-04-2016-0077

Mariani, A. W., & Pêgo-Fernandes, P. M. (2011). Medical education: Simulation and virtual reality. *Sao Paulo Medical Journal*, *129*(6), 369–370. https://doi.org/10.1590/S1516-31802011000600001

McTigue, E. M., & Flowers, A. C. (2011). Science Visual Literacy: Learners' Perceptions and Knowledge of Diagrams. *The Reading Teacher*, *64*(8), 578–589. https://doi.org/10.1598/RT.64.8.3

Ollerenshaw, D. K. (1988). The challenge of medical illustration today. *Journal of Audiovisual Media in Medicine*, *11*(1), 5–7. https://doi.org/10.3109/17453058809063646

Patel, S. K., Couldwell, W. T., & Liu, J. K. (2011). Max Brödel: His art, legacy, and contributions to neurosurgery through medical illustration. *Journal of Neurosurgery*, *115*(1), 182–190. https://doi.org/10.3171/2011.1.JNS101094

Pevsner, J. (2019). Leonardo da Vinci's studies of the brain. *The Lancet*, *393*(10179), 1465–1472. https://doi.org/10.1016/S0140-6736(19)30302-2

Plass, J. L., Homer, B. D., MacNamara, A., Ober, T., Rose, M. C., Pawar, S., Hovey, C. M., & Olsen, A. (2020). Emotional design for digital games for learning: The effect of expression, color, shape, and dimensionality on the affective quality of game characters. *Learning and Instruction*, *70*, 101194. https://doi.org/10.1016/j.learninstruc.2019.01.005

Righthand, J. (n.d.). *The Anatomy of Renaissance Art*. Smithsonian Magazine. Retrieved February 1, 2021, from

https://www.smithsonianmag.com/science-nature/the-anatomy-of-renaissance-art-36887285/

Rogers, Y., & Scaife, M. (1998). *How Can Interactive Multimedia Facilitate Learning?* 25.

Svakhine, N. A., Ebert, D. S., & Andrews, W. M. (2009). Illustration-Inspired Depth Enhanced Volumetric Medical Visualization. *IEEE Transactions on Visualization and Computer Graphics*, *15*(1), 77–86. https://doi.org/10.1109/TVCG.2008.56

Verhoef, B.-E., Vogels, R., & Janssen, P. (2012). Inferotemporal Cortex Subserves Three-Dimensional Structure Categorization. *Neuron*, *73*(1), 171–182. https://doi.org/10.1016/j.neuron.2011.10.031

Versalius, A. (1543). *De Corpus Fabrica Humani*. School of medicine, Padua.

Wei-haas, M. (n.d.). *World's oldest animal drawing found in Borneo cave*. Retrieved February 1, 2021, from https://www.nationalgeographic.com/science/2018/11/news-oldest-animal-drawing-borneo-cave-art-human-origins/

Wood, M. C. (2018). *Visual context and affect in diagram interpretation*. https://doi.org/10.25911/5d51406ed39fc