Master of Science in Biomedical Communications | Master's Research Project Proposal

Scaffolding Learning in a 3D Twin-Twin Transfusion Syndrome Surgical Simulator for Novice Learners

MSC2020H Research Methods

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Abstract

Twin-twin transfusion syndrome (TTTS) is a rare, but major complication during monochorionic twin pregnancies. The treatment of choice for TTTS is fetoscopic laser ablation, a complex procedure only performed at specialized centers. Currently, a gap exists in the training of surgeons learning TTTS procedures as cases are infrequent, the surgery has a steep learning curve, and patient safety must take priority. Digital simulators can help fill this gap using elements of serious gaming and immersive technology to create accessible, adaptive, 3D surgical simulations that teach requisite anatomical, procedural, and skill-based knowledge. While there is significant evidence supporting the use of digital simulators in medical training, there is little evidence examining the impact of visual complexity within these simulators. Instead there is a widespread assumption that simulators featuring high-fidelity models and immersive environments—or high-complexity simulators—lead to better learning outcomes. This one-size-fits-all approach is not ideal, and learning science suggests that low-complexity simulators can play a role in helping build, or scaffold, knowledge. By using this low- to high-complexity scaffolded approach, it is hypothesized that difficulty can be scaled to increase content retention and learning gains. This proposal outlines a summative evaluation to test the impact of scaling visual complexity within a simplified surgical simulator covering aspects of the procedural knowledge necessary to perform fetoscopic laser ablation therapy for TTTS.

1 Introduction

Twin-twin transfusion syndrome (TTTS) is the most common major complication seen during identical twin pregnancies where a single placenta is shared by two fetuses (monochorionic twins). Under normal circumstances each fetus is connected to the placental surface via blood vessel anastomoses, continuously exchanging blood. In TTTS there is an imbalance in this blood exchange, with one fetus receiving more blood than it gives away (the recipient, colloquially called "Poly") and the other fetus giving more blood away than it receives (the donor, colloquially called "Oli"; "Laser for Twin-Twin Transfusion Syndrome (TTTS)," 2018; Peeters et al., 2014). This blood imbalance causes the recipient fetus to become volume overloaded, and in turn results in a compensatory increase in urinary output that produces too much amniotic fluid (polyhydramnios). Conversely, the blood imbalance causes the donor fetus to conserve fluid by stopping urination, resulting in too little amniotic fluid (oligohydramnios; "Laser for Twin-Twin Transfusion Syndrome (TTTS)," 2018).

When untreated, TTTS and polyhydramnios can cause the recipient fetus to die in-utero from heart failure, and fetal survivors have a heightened risk of being born with a long-term disability. To avoid these adverse consequences, swift action must be taken to correct the imbalance in blood exchange. Currently, the most successful treatment for TTTS is using fetoscopic laser ablation therapy. This treatment targets the placental blood vessels supplying each fetus, cauterizing some to normalize blood flow ("Laser for Twin-Twin Transfusion Syndrome (TTTS)," 2018; Peeters et al., 2014).

While fetoscopic laser ablation is the treatment of choice for TTTS, the surgical outcomes depend largely on the experience of the operator. There is a growing concern that over the coming years complications from the procedure will become more common—at least temporarily. This concern stems from an anticipated rise in the number of TTTS surgeries required as the procedure becomes more well known and developing countries gain access to the technology and knowledge necessary to perform the surgery; coupled with the fact that a generational shift is occurring as new surgeons begin to take over the practice of those who established the fetoscopic procedure (Peeters et al., 2014, 2015).

New surgeons wishing to learn fetoscopic laser ablation can only be taught at specialized fetal centres such as the Maternal Fetal Medicine (MFM) unit at Mount Sinai in Toronto, Canada; however, even at these centers TTTS cases are seen infrequently. Additionally, many patients who undergo the surgery are uncomfortable with a surgeon-in-training performing the operation. As a result, those surgeons hoping to learn the fetoscopic procedure may not see and perform enough cases to surpass the associated learning curve; especially given that research indicates as many as 25 fetoscopic laser procedures must be completed to achieve a level of sufficient competence (Peeters et al., 2014, 2015). The best way to overcome the learning curve of fetoscopic TTTS procedures and prioritize patient safety is to use alternative teaching methods; namely through the use of surgical simulators (Peeters et al., 2015).

2 Background

2.1 Modern Surgical Education: Surgical simulators and Immersive Technology

Traditional surgical education relies on observation, practice on cadavers, and ultimately learning on the job with patients. This traditional model is flawed, as it often provides surgical trainees with the minimum practical experience necessary, endangering patients as surgeons enter the operating room (OR) with a gap in their knowledge (Peeters et al., 2014; Pittini et al., 2002). Traditional methods can also be cost-intensive and infrequent because of the limited availability of suitable cadavers, restricting training to intensive courses that span only a few days (Podolsky et al., 2010). These fast-paced courses offer learners little opportunity to practice and develop skills, and instead they must often rely on knowledge and technique recollection months or even years after being trained in a procedure, increasing the likelihood of patient injury. These limitations in traditional teaching methods indicate a clear need for a different education tool that allows learners to practice surgical skills in an environment that doesn’t impact patient safety, lowers costs, and allows more freedom to practice and develop skills throughout their careers (Peeters et al., 2015; Pittini et al., 2002; Podolsky et al., 2010).

More recently, there has been a shift from traditional teaching methods to surgical simulators, which have been broadly adapted and validated as successful teaching tools. Initial simulators relied on physical models, indirectly mimicking the surgical environment (e.g. a “box trainer” in which learners grasp objects hidden in a box with laparoscopic controls) or more directly representing the surgical environment (e.g. a mannequin placed in an OR with multiple learners forming a practice surgical team; Windrim et al., 2014). These simulators work best when paired with a comprehensive training curriculum, rather than simply making the simulations available for use at the convenience of learners (Ferrero et al., 2014; Peeters et al., 2015; Pittini et al., 2002).

While physical simulators improve the delivery, cost-effectiveness, and quality of surgical training, these models are not without their limitations. Physical models are often limited in scope, only serving to educate learners about the specifics of a single procedure. This means that while more cost-effective than traditional, cadaver-based teaching methods, physical simulators are still an expensive method of training surgeons on a procedure-by-procedure basis. Furthermore, the storage and access of physical models pose additional problems, as space in many teaching hospitals is at a premium and in-person training is often needed—a difficult barrier for remote and underdeveloped health care centers (Dargar et al., 2015; Podolsky et al., 2010; Sappenfield et al., 2017).

Current technological advancements and increased access to technology have led to a shift away from physical models. Medical educators are now interested in digital technologies that create more accessible surgical simulators and are simultaneously more immersive, interactive, and realistic. These digital simulators often employ 3D models, serious gaming elements, and immersive technology including virtual, augmented, and mixed reality (VR, AR, and MR respectively), and can offer many advantages over physical simulators (McGrath et al., 2018):

I. They can be more physically and temporally accessible, allowing for participation and practice at the convenience and pace of the learner(s)
II. They offer the opportunity to practice individually ("single-player" simulators) or in teams ("multi-player" simulators)
III. They are adaptive and feature reusable assets, enabling them to be used for a wide range of procedures that can be updated and expanded upon
IV. They allow for better integration of realistic problem-solving through serious gaming elements
V. They allow learning and practice in a safe environment that does not risk patient safety
VI. They can be used with or without facilitators
VII. They are less expensive to maintain

Surgical simulators relying on immersive technology present an exciting option for medical education; however, they are not without their limitations. Some shortcomings, such as lack of haptic feedback, can be addressed by combining digital and physical models in a MR simulator (Dargar et al., 2015; Graafland, Bemelman, & Schijven, 2017; Huber et al., 2017, 2018; McGrath et al., 2018). Other limitations, while not inherent to the technology itself, stem from the way the technology is implemented. It is important that the use of digital simulators avoid the pitfalls of traditional teaching methods and physical models. If digital simulators are not accessible, or are used to teach surgical trainees in a manner similar to traditional methods (e.g. in an intensive class over a short time period), their success at knowledge-building is no different, and the possible benefits they possess are wasted (McGrath et al., 2018; Podolsky et al., 2010).

Regardless of their limitations, given the evidence that digital simulators and other novel approaches to medical education—such as serious gaming—are effective teaching tools, there has been a profound shift toward immersive technology in medical education. Alongside this shift there has been general agreement amongst medical educators that high-complexity (high-fidelity and/or high-immersion) simulators present the best option for training (Dankbaar et al., 2016; Dargar et al., 2015; Graafland et al., 2017). However, despite evidence validating the success of digital teaching models and their widespread adoption, there is surprisingly little research validating the exclusive use of high-complexity in simulators.

2.2 Media Audit

In addition to the external validation of digital simulators for medical education in the literature, their broad utility for training healthcare professionals can be highlighted through prominent examples in use and development across the United States, Canada, and the United Kingdom.

Osso VR is a simulator created by a team of surgeons in the United States and was initially designed to train orthopedic surgeons. Currently the platform is marketed towards "surgeons, sales teams, and hospital staff of all skill levels" with the hope that the simulator will expand to include additional surgeries and procedures. The model used by Osso is a high-complexity, high-fidelity VR simulation using handheld controllers and a head mounted display (HMD; Fig.1; Fig. 2). Osso VR mimics the steps involved in orthopedic procedures to familiarize learners with the OR. Rather than focusing on teaching surgical precision, the simulator works to help build a knowledge of the overall timeline, steps, devices, and general anatomy needed to perform a surgery. As a result, Osso VR purports that the tool enables learners to better focus on precision when they eventually enter the OR ("Osso VR," 2018). The design and educational success of this commercial tool has not been investigated or validated experimentally; however, it is an excellent representation of the current trends in medical education.

Figure 1: A video demo for Osso VR, a modern surgical simulator. The video can also be found at: https://youtu.be/aBQTtp_NbgI

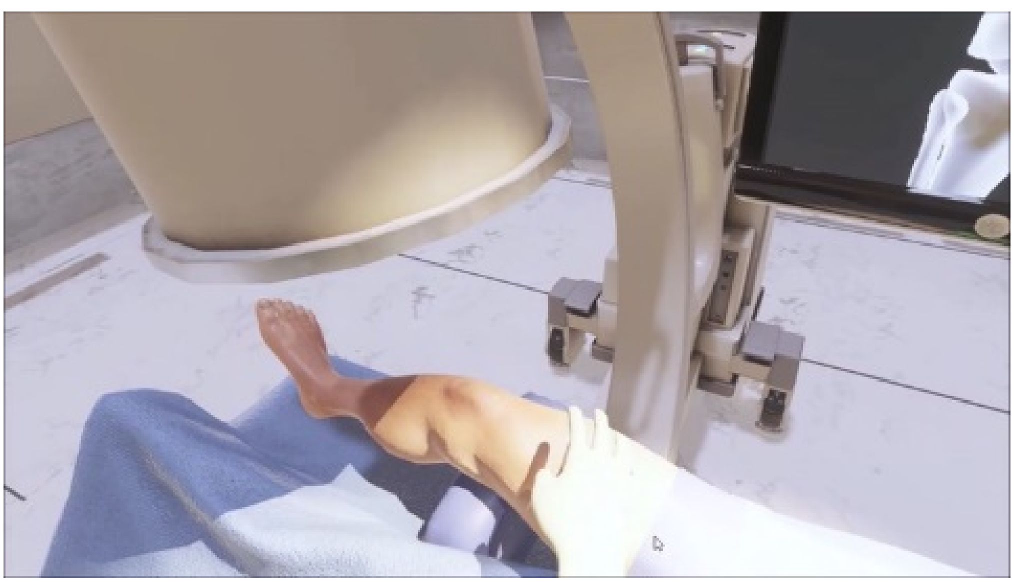

Figure 2: A still image of the Osso VR surgical simulator. Note the high-fidelity of the 3D models and environment, all of which play a role in the high-complexity of the overall simulator. According to Osso VR, the simulator is realistic, but stylized to avoid an "uncanny valley" feeling for those using the tool.

Another commercial tool currently employed in surgical education is PeriopSim, which uses two different digital simulators to train perioperative nurses and surgical staff. The first simulator is an iPad app that employs a mix of filmed surgical footage and 3D models that can be dragged or "handed" to a virtual surgeon. The second simulator is high-complexity, using VR to place learners in an OR and then tasking them with placing specific tools into a bin (Fig.3). The 3D assets in both models are realistic and high-fidelity. Within the VR simulation, the tools can be directly interacted with and the environment is also presented in an immersive 360^{o} view. PeriopSim has more substantial research and validation behind its educational methods as they have conduced a series of pilot studies with Canadian Hospitals; however, the evidence supporting its VR simulator is still sparse as these studies were limited to the iPad application (Hayden, Smiley, Alexander, Kardong-Edgren, & Jeffries, 2014; "PeriopSim: Home," 2018). Additionally, while the VR simulator is indeed immersive, the skills it teaches are basic as it currently requires learners to drop surgical tools into a bucket. Evidence from other simulators indicate that these skills could be taught with a simpler, less resource-intensive application that minimizes cognitive load for the learner (Dankbaar et al., 2016).

Figure 3: A video highlighting the PeriopSim VR application. The video can also be found at: https://youtu.be/Y6sXnx0H7js

Digital simulators also show great potential in other areas of medical education. This is particularly true in emergency situations where critical decision-making skills must become second nature. The LIFE (Life-saving Instructions for Emergencies) Project from Oxford University is designed to teach these skills to rural physicians in developing countries, filling a gap in regions where the use of mobile devices has grown exponentially over the past decade (Edgcombe, Paton, & English, 2016). LIFE consists of serious game models available on two platforms: a scenario-based mobile game and a VR simulator. The fidelity and complexity of both simulators is high as they seem to rely on the same assets; however, the mobile game requires learners to answer a series of questions and complete matching exercises, while the VR simulator adds a layer of realistic action and immersion. Currently, no academic research has been published to validate the design of the LIFE Project; however there is a great deal of global interest in the initiative and it has been recognized internationally, winning awards at the 2016 Saving Lives at Birth Grand Challenge and the 2017 VR for Impact ("About the LIFE Platform," 2018).

Osso VR, PeriopSim, and the LIFE Project clearly illustrate the shift towards digital simulators and training tools in surgical training and medical education at large. Additionally, these examples highlight an underlying assumption of modern medical education: high-complexity simulators result in better learning outcomes. However, there is little research that validates this assumption, explores the deeper relationship between complexity and learning, or establishes a framework for the optimal design of digital simulators in a surgical context.

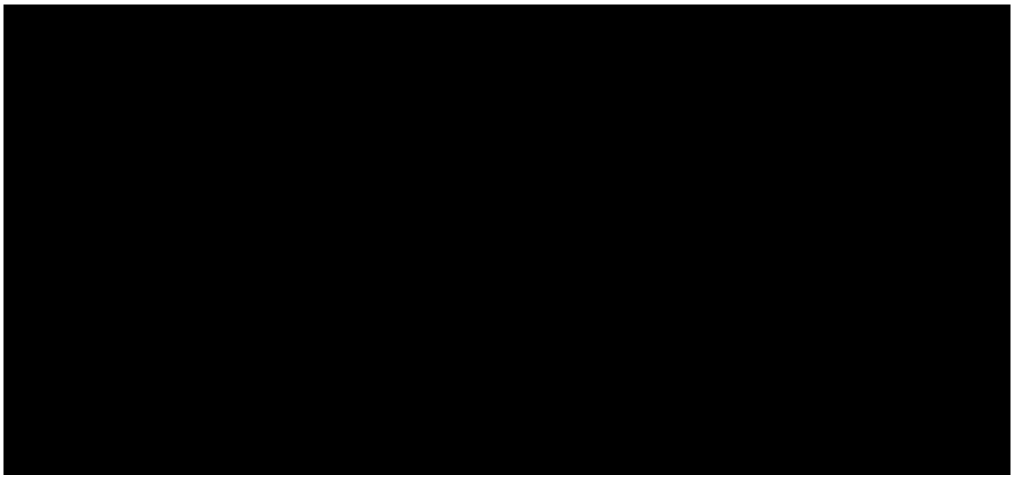

Figure 4: A video demonstrating the LIFE Project. The video can also be found at: https://videopress.com/v/0z6hUySN

2.3 Visual Complexity and Scaffolded Learning

The use of high-complexity models in surgical simulators is nearly ubiquitous; however, at least one study suggests that high-complexity models do not necessarily result in increased learning gains. Dankbaar et al. (2016) demonstrated that high-complexity medical simulators, while more effective at engaging and involving learners, may be distracting and impede content comprehension. This is particularly true for novice learners who may experience cognitive overload when learning new content in combination with exposure to high-complexity models.

Conversely, some studies in non-medical fields support the use of higher-complexity content for educational purposes. Jenkinson & McGill (2012, 2013) found that undergraduate students exposed to low- and high-complexity visual animations explaining a common misconception in biology courses better understood the content when presented with the high-complexity treatment. However, Jenkinson & McGill (2013) also determined that there was a limit to what students could infer from high-complexity visualizations alone. To help circumvent this limit, the authors suggested a need for a guided approach that directed student attention to relevant content. These findings illustrate the merits of high-complexity models during the learning process; however, they do not exclude the use of low-complexity models as potential supports.

Given the underlying assumptions regarding high-complexity surgical simulators and the work completed by Dankbaar et al. (2016) and Jenkinson & McGill (2012, 2013), it is worth considering how low- and high-complexity simulators might be used in tandem—specifically for novice learners. In their work, Jenkinson & McGill (2013) suggested a guided approach that used perceptual cues to create a visual “scaffold” for the learner. Traditionally, the concept of scaffolding in learning was described as a mentoring process in which someone with experience helped a learner succeed in tasks that where otherwise unattainable at their current competency level (Wood, Bruner, & Ross, 1976). As learning science has developed, the term scaffold has come to mean a form of support offered by peers, curricula structure, and software or tools—including visualizations in animations, serious games, and simulators—that are part of the learning scenario (Puntambekar & Hübscher, 2005). In addition, the purpose of scaffolded learning has expanded; it no longer just means helping learners accomplish a task, it also means helping learners retain knowledge for future use (Reiser, 2016; Sawyer, 2006).

In the approach hypothesized by Jenkinson & McGill (2013), the scaffoled learning they proposed was a series of visual cues within an animation. These cues would direct students to important content and over time be faded, or scaled down, as learners gained knowledge and no longer required supports. While the context is different, a similar scaffolded learning approach could be integrated within surgical simulations. Specifically, low-complexity models within a simulator could serve as a visual scaffold for novice surgeons and scaled to high-complexity models as their knowledge and understanding increases. To the authors knowledge, no such approach has been taken and validated when designing surgical simulators, offering a novel opportunity to study the impact of visual complexity when using simulators to train surgeons.

3 Research Goals and Objectives

3.1 Research Problem

Currently a gap exists in the practical education and training of physicians moving through surgical residency and fellowship programs. While physicians obtain the requisite technical knowledge and theory for complex and/or high-risk procedures, their practical experience with such procedures is often inadequate (Peeters et al., 2014). As a result, there is a great need for training models that allow physicians to learn in a low-risk environment without the use of real patients. Serious gaming and the integration of interactive and immersive technologies including VR, AR, and MR can help fill this gap in training; however, a great deal of research is still needed to determine the optimal design, development, and use of these models. In particular, the role of visual complexity in learning comprehension for different surgical tasks warrants further investigation.

3.2 Research Goals

The primary goal of this project is to investigate the impact of using visual complexity to scale difficulty and scaffold learning in surgical simulators, and determine if its use effects the understanding, learning gains, and knowledge retention of novice learners—specifically medical clerks and surgical residents with little exposure to TTTS and fetoscopic laser ablation. The secondary goal of this project is to construct a high-complexity visual library of 3D placental models for use in a complete surgical simulator to be developed in the future at Mount Sinai.

3.3 Research Objectives

The objectives of this project are:

I. To develop separate high-complexity and low-complexity immersive 3D models of the human placenta for use in VR to test anatomical and procedural knowledge for a TTTS surgery. The high-complexity models will strive for accuracy and hyper-realism in the recreation of the environment using more detailed textures and structural information. The low-complexity models will focus on substantially reducing one aspect of the high-complexity models (e.g. reducing the structural complexity of the placental vessels, using simple ambient lighting and reflective effects, or by using a low-realism rendering style akin to Sketch and Toon in Cinema 4D)

II. To evaluate the success of scaffolding learning in surgical simulator while teaching novice learners the anatomical and procedural knowledge needed for TTTS surgery by:
   a. Evaluating novice learner performance and learning gains through pre/post-tests in a group exposed to a low-complexity intervention, followed by the high-complexity intervention at a different learning session
   b. Evaluating novice learner performance and learning gains through pre/post-tests in a group exposed to a high-complexity intervention, followed by another high-complexity intervention at a different learning session

III. To record and document the process of taking 3D medical data sets and optimizing them for use in Unity and interactive models including VR, AR, and MR. This documentation will be used to provide a template for others working in the biomedical communications field.

IV. To complete the construction of a 3D visual library of placental models for later use in a full surgical simulator designed to teach fetoscopic laser ablation for TTTS treatment in the MFM unit at Mount Sinai.

4 Methods

4.1 Target Audience and Participants

The target audience for this project will be novice learners: medical student clerks and year one (R1) or year two (R2) surgical residents with little exposure to TTTS but who are interested in MFM.

4.2 Establishing Design Scope

The scope of my MRP is limited by time and available resources, and as a result the proposed low- and high-complexity simulators are simplified in nature. However, the MFM team at Mount Sinai is working towards the development of a more comprehensive simulator after the completion of this project. Working with the MFM team, I must ascertain the main goals of this full simulator, so that I can determine which design elements will be appropriate for use in my project. This narrowed scope will be used to guide the construction of the low- and high- complexity visual treatments and to ensure that the two models provide effective scaffolding of the concepts and tasks needed to learn TTTS surgical procedures.

4.3 Ethics Review and Approval

An ethics application will be submitted to both the Mount Sinai Research Ethics Board (REB) and University of Toronto REB in the summer of 2018. To complete the summative assessments outlined in the proceeding sections, the target audience will need to undergo formal testing to determine the success of the simulators. Both REB submissions may be necessary as staff from Mount Sinai and students from University of Toronto could undergo testing.

4.4 Formative Assessment

To develop a complete understanding of the TTTS surgical procedure, and of the challenges surgeons face while learning and performing the procedure, I will participate in a surgical observership at Mount Sinai during the summer of 2018. While completing this observership, I will conduct a needs assessment of the

MFM team at Mount Sinai to determine the direction and development of the proposed 3D models and eventual surgical simulator.

The needs assessment will consist of a guided focus group with the goal of collecting qualitative data and assessing:

I. What the surgical team feels current simulators are lacking
II. What they feel the primary goal/responsibility of surgical simulators should be
III. If the team feels high-complexity simulations are necessary to accomplish these goals/responsibilities; and if so, what elements of complexity (structural complexity, realistic lighting, realistic surfaces, etc.) are most/least important to simulator success
IV. The challenges they experienced while learning MFM and TTTS procedures and, more broadly, while learning surgical skills
V. Any additional information they feel is pertinent to the development of 3D placental models and a TTTS surgical simulator

4.5 Asset and Model Creation

The underlying structures of the models that will make up my final 3D library will be derived from CT and MRI data. As the final library requires many different placental models to mimic the in vivo variation seen in the OR, I will need to collect, extract, and potentially combine a substantial amount of surface geometry from these datasets using Horus during the summer and fall of 2018.

Once the required information has been extracted from 3D datasets using Horus, the 3D models will need to be further refined and built in ZBrush during the fall of 2018. The final requirement is for the library to be high-complexity and realistic; however, one of the models will be made to be low-complexity for use in the summative evaluation. Following refinement in ZBrush, the 3D models will be optimized for use in Unity, specifically for use in VR or similar immersive technology. This optimization will require research over the summer of 2018 and iterative testing during the fall and winter of 2018/2019. Specifically, challenges will need to be anticipated, and the technical and design goals (e.g. render time, responsiveness, user experience and interaction, realism, accuracy, etc.) of the final simulator will be prioritized.

4.6 Pilot Study Simulator Creation

High- and low-complexity 3D simulator with simple VR elements will be constructed for use in the summative evaluation. In this case, simple VR elements mean the ability to observe a 3D virtual environment from a static orientation. By limiting movement within the model overall complexity can be better controlled, cognitive overload separate from the simulator tasks (e.g. learners exploring the space and neglecting the primary goals of the simulator) can be limited, and the overall internal validity of the evaluation can be increased.

In the pilot simulator, participants will remain seated while in the virtual environment and “escorted” through the finalized 3D models. During the tour of the models, participants will be prompted with a series of multiple choice questions and simple skill tests (e.g. indicate the area that requires laser ablation to treat TTTS symptoms). The goal of these simulators will not be to test motor or technical skills but rather to assess participants’ anatomical understanding, knowledge of the procedure, and critical decision-making ability.

By excluding motor and technical skills, the simulation is simplified and exposes participants to a virtual environment without the need for true "interaction". While this will be different from fully interactive simulator to be completed by Mount Sinai in the future—lowering the external validity of the proposed project—it will allow for a controlled evaluation of scaled visual complexity. Additionally, considering the scope and timeline of an MRP a more simplistic simulator is necessary, and still useful in optimizing the construction of the full simulator.

4.7 Summative Assessment

The final step of this project will be to assess if scaling the visual complexity of surgical simulators—thereby scaffolding their learning by moving from lower to higher complexity representations—impacts the anatomical and procedural understanding of novice learners. This will take place during the winter and spring of 2019, and assessments may be completed by members of the Mount Sinai MFM team.

Within the selected participant group, three sub-groups will be created:

I. **Control Group**: will be exposed to a traditional intervention (e.g. a Power Point based lecture and assessment) that covers the same information taught in the visual treatments. During a second session this group will be exposed to the same lecture and assessment. The data from this group will help provide external validity by establishing if the use of a surgical simulator helps teach TTTS procedures, as would be expected given evidence from past studies.

II. **Test Group One**: will first be exposed to a low-complexity, 3D intervention and assessment with simple VR elements (visual treatment one). During a second session this group will be exposed to a high-complexity, 3D intervention and assessment with simple VR elements (visual treatment two). In additional to providing the project with increased external validity, data from this group will help refute or support the main hypothesis of the project: that scaffolding visual complexity will enhance leaning in novices.

III. **Test Group Two**: will first be exposed to a high-complexity, 3D intervention and assessment with simple VR elements (visual treatment two). During a second session this group will be again be exposed to a high-complexity, 3D intervention and assessment with simple VR elements. Data from this test group will help increase the external validity of the project and will also provide evidence for or against the projects null hypothesis: scaffolding visual learning does not enhance learning in novices; however, repeated exposure to the same treatment may increase knowledge retention and learning gains.

Each of the assigned sub-groups will be given a pre-test, post-test, and delayed post-test to establish the initial understanding of the participants, knowledge building, and learning gains resulting from the three treatments. Further research and coordination with content experts will be required to develop the pre-, post-, and prolonged post-test questions needed for the summative evaluation.

4.8 Usage

The data collected from the formative and summative evaluations will be used to direct the development of a TTTS surgical simulator at Mount Sinai following the completion of this project. Data from the evaluations will be used to determine the visual complexity—or the scaling of visual complexities—for the simulator.

5 Anticipated Significance

This project will direct and inform the development of a validated surgical simulator used to train surgeons in the completion of fetoscopic laser ablation therapy to treat TTTS. The surgical simulator will be used primarily at the MFM unit at Mount Sinai Hospital in Toronto, with the potential for distribution and remote use as a training tool for other MFM centers across the world. The summative evaluation completed during this project will expand the current understanding of how visual complexity impacts learning in surgical simulators, specifically regarding novice learners. The completion of this project will help inform the design and development of future immersive surgical simulators and serious games for medical education, ensuring that the time learners take to build their knowledge—regardless of their expertise— is well spent.

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