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Learning curve for phacoemulsification with a virtual reality simulator

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Table of Contents

1 Populärvetenskaplig sammanfattning

Katarakt, eller gråstarr är en ögonsjukdom där linsen blir grumlig vilket innebär en nedsatt synskärpa. Katarakt är globalt sett den ledande orsaken till blindhet och behandlas med en operation där man tar ut den gamla linsen och sätter in en ny med hjälp av en teknik som använder ultraljudsvågor: phacoemulsifiering. I den här studien undersöktes ifall en simulator med virtuell verklighet kan användas i utbildningen av nya kataraktkirurger. 20 läkarstudenter fick öva på två delar av phacoemulsifiering med simulatorn i två efterföljande halvdagar och 35 variabler av deras utförande mättes automatiskt. Dessa variabler räknades ihop till ett övergripande prestandaindex för att undersöka om en inlärningskurva kunde ses vid de första 20 simulationerna för dessa läkarstudenter. Fem studenter hoppade av studien och fullständig data samlades in hos 15 studenter. Dessa studenter kunde delas in i två olika grupper, en grupp som lärde sig och en som inte gjorde det. Det var 6 läkarstudenter som uppvisade en statistiskt signifikant förbättringskurva för att kunna betraktas som att de lärde sig i den första delen av phacoemulsifieringen och 8 studenter i den andra. Deras inlärningskurvor var nästan linjära och ingen av dem uppnådde en asymptot i sitt lärande och skulle behöva öva mer med simulatorn för att nå dit. Den första delen av simuleringen gav mycket lägre prestandaindex i början av simulationerna men även lite lägre i slutet. Detta tyder på att denna del är mycket svårare att utföra och inlärningskurvan blev brantare i denna del men det var även fler som hamnade i gruppen som inte lärde sig på grund av väldigt spridda resultat. Syftet med studien var att undersöka hur simulatorn bäst ska användas, i denna studie användes simulatorn intensivt under två halvdagar och i framtiden borde man undersöka hur inlärningskurvan ser ut vid mer sporadisk användning av simulatorn.

2 Abstract

Purpose: To investigate the learning curve for phacoemulsification using a virtual reality simulator.

Methods: 20 medical students were introduced to the simulator and then registered 20 simulations of phacoemulsification each. The simulator automatically measured 35 variables during the simulation that were analysed together as a performance index.

Results: Two groups could be identified: a learning group and a non-learning group which were almost equal in size. These two groups mainly consisted of the same individuals in both phases of the procedure. The learning group generated almost linear learning curves without reaching an asymptote. The sculpting phase generated worse performance indices than the evacuation phase with large inter-individual differences. The results were quite scattered resulting in large confidence intervals, especially for the sculpting phase.

Conclusion: 20 simulations are not enough to show a learning curve with a steep inclination initially to later reach an asymptote and more training is needed with the simulator. Some people are more prone to learn with the simulator than others. The sculpting phase is harder to perform and requires additional practice.

3 Abbreviations

ICCE: intracapsular cataract extraction

ECCE: extracapsular cataract extraction

IOL: intraocular lens

VR: virtual reality

OSACSS: objective structured assessment of cataract surgical skill

LCD: liquid crystal display

IOPI: individual overall performance index

IVPI: individual variable specific performance index

ICPI: individual class specific performance index

4 Background

4.1 The eye

The eye is located within the orbital cavity and is therefore surrounded by the cranium to all sides allowing only limited space for the eye. Its main blood supply is from the ophthalmic artery deriving from the internal carotid artery which reaches the eye through the optic canal together with the optic nerve. The eyeball is made up of three outer layers with the cornea (the clear dome at the anterior portion of the eye) and the sclera (the white of the eye) being the outermost. The cornea is a thin transparent protective barrier. The sclera is a dense fibrous layer functioning as a protective barrier. The middle layer is the uvea, which contains the iris, the ciliary body and the choroid. The iris is a pigmented structure consisting of muscle fibers that can either dilate or constrict the inner aperture of the iris called the pupil. Between the cornea and the iris is the anterior chamber filled with aqueous humour. The ciliary body as an extension of the iris produces the aqueous humour. It also contains the ciliary muscle which consist of radial, circular and longitudinal muscle fibers. Inside the sclera is the choroid which consists of blood vessels in three layers. Inside the choroid is the inner layer, retina which consist of nervous tissue where the photoreceptors are located.

The lens is a transparent structure located in the posterior chamber behind the iris. The posterior chamber is confined between the iris anteriorly and the lens posteriorly and contains aqueous humour. The lens has a biconvex structure which means that the centre will be thicker than the peripheries and is about 4 mm thick at the thickest. The diameter is about 9 mm. (Riordan-Eva, 2017). The lens is encapsulated by a though capsule that can be divided into an anterior part and a posterior part. It is attached to the ciliary bodies on the side by zonulas. (Csillag, 2005). The lens is one of the most protein dense tissues in the body and these proteins are structured in a highly ordered and dense manner with little extracellular components. It is made up of a nucleus with fiber cells and surrounding cortical fibers with an epithelium layer anteriorly. The fiber cells contain large amounts of crystallins and have no nucleus nor many of the normal organelles such as mitochondria. All these properties give the lens its transparency (Hejtmancik and Shiels, 2015; Moreau and King, 2012).

Behind the lens the vitreous humour is located. The eye has a very delicate anatomy with several structures located close to each other and confined in the orbital cavity (Riordan-Eva, 2017) making surgery in this area very technically challenging (Laurell et al., 2004).

4.2 Cataract

The lens focuses the incoming light onto the retina and must therefore be transparent (Hejtmancik and Shiels, 2015). Cataract is an ophthalmologic disease where the lens is clouded and loses this transparency which will impair the acuity of the eye (Baumeister and Kohnen, 2018; Lam et al., 2013; Moreau and King, 2012). Cataract acquired at birth or before the child has turned one, is called congenital cataract. More commonly cataract presents itself later in life, which is referred to as senile cataract. Senile cataract can be further subcategorized into three groups depending on where cataract occurs: cortical, nuclear or posterior subcapsular (Baumeister and Kohnen, 2018). Cataract is the most common reason for blindness worldwide and the second most common reason for moderate to severe vision impairment after uncorrected refractive errors (Flaxman et al., 2017; Khairallah et al., 2015). In 2015 12,6 million people in the world were blind due to cataract and 52,6 million suffered from moderate to severe vision impairment due to their cataract. Cataract is a treatable disease but these numbers suggest that the treatment needs to reach out to a much greater number of people (Flaxman et al., 2017). In high income countries the proportion of people being blind due to cataract is lower than in other regions but it is still the second most common cause of blindness suggesting that an increase in treatment is necessary all over the world (Khairallah et al., 2015).

Nucleus fiber cells in the lens are enucleated which means that they will not be able to divide and are therefore very sensitive to environmental insults (Hejtmancik and Shiels, 2015; Moreau and King, 2012). The exact pathophysiological mechanisms behind the disease are unknown but the classical theory is that senile cataract occurs due to aggregates of proteins which, when large enough, will scatter the light coming into the lens and therefore cause a worsened acuity (Benedek, 1971). This theory is supported by more recent discoveries suggesting that the mechanism for senile cataract is very complex. There seems to be a gradual accumulation of several mild genetic mutations affecting either the lens crystallins or other proteins involved in the lens homeostasis (Shiels and Hejtmancik, 2017). This, in combination with environmental insults like UV radiation, exposure for heavy metals or other factors that increase reactive oxygen species will lead to a denaturation of the crystallins causing them to aggregate. Diabetic patients develop cataract earlier than the normal population and this can be explained by protein glycation which denature the α-crystallins (Moreau and King, 2012). Over the past 15 years several mutations affecting different proteins have been identified to play a role in the development of cataract but there is still a long road ahead to fully understand the pathophysiology behind the disease (Shiels and Hejtmancik, 2017).

4.3 Treatment of cataract

Cataract is treated with surgery where the lens is removed and a new artificial lens is inserted. There is no effective medical treatment (Baumeister and Kohnen, 2018; Moreau and King, 2012). In the first part of the 20th century the standard operating procedure was intracapsular cataract extraction (ICCE), a procedure where a 180 degrees incision was made along the limbus and the entire lens was extracted through this incision. During this period no new lens was inserted, and the patients had to wear thick spectacles lifelong without gaining perfect acuity even then. There was also a significant amount of serious complications related to this procedure e. g. vitreous loss and retinal detachment. The postoperative care at the hospital usually lasted over a week with full immobilization of the head. After the Second World War a new technique called extracapsular cataract extraction (ECCE) started to spread. In this technique the lens capsule remained more intact, a smaller incision of circa 10-11 mm could be made and an intraocular lens (IOL) could be inserted onto the intact posterior capsule allowing the patient to see without thick spectacles. However even this technique showed to have its limitations since it was hard to fully extract all cortical matter of the lens resulting in opacification of the posterior (Linebarger et al., 1999). To avoid several complications and to reduce post-operative care a shorter, less invasive surgery was desired. Cataract surgery was revolutionized in 1967 when Dr. Kelman invented a new technique for the procedure called phacoemulsification. The technique uses an ultrasonic probe to break up the lens into four quadrants which are then emulsified. The technique requires only very small incisions in the eye that do not require sutures to heal which has shortened the post-operative care substantially (Kelman, 1994), reduced post-operative astigmatism (Linebarger et al., 1999) and made cataract surgery possible to perform as an outpatient surgery (Spiteri et al., 2010).

In cataract surgery today most patients do not need general anaesthesia, retrobulbar or topical anaesthesia will be enough (Lam et al., 2013). This reduces complications related to general anaesthesia (Linebarger et al., 1999). The surgery consists of four major steps: corneal incision, capsulorrhexis, nuclear extraction and IOL implantation. The incisions are made through the cornea and are today as small as 2,8 mm (Lam et al., 2013). After the incision an opening in the anterior capsule called capsulorrhexis is created using continuous curvilinear capsulorrhexis. This is accomplished using a cystosome to create a small tear in the centre of the anterior capsule and then pull the flap radially with forceps to create a circular opening. When the anterior capsule is open the nuclear extraction can begin. This step uses Dr Kellman's phacoemulsification probe to break the lens with ultrasonic waves and then emulsify the pieces. There are different techniques for this. One common technique is called divide and conquer. In this technique the phacoemulsification probe creates two grooves passing though the centre at a 90 degrees angle to one another. The phacoemulsification probe and a manipulator are then used to crack these grooves dividing the lens into four quadrants. Subsequentially each quadrant can be emulsified by the probe. Other techniques for phacoemulsification are the stop and chop, phaco chop and trench divide and conquer techniques. In the last step a foldable IOL is implanted onto the posterior capsule using a lens injector (Lam et al., 2013; Linebarger et al., 1999).

To reach the lens the surgeon must first go through the cornea, then the aqueous humour of the anterior chamber and next the pupil, careful as not to damage the iris or any other structure on the way. Finally, the anterior capsule must be opened. It is crucial that the surgeon does not go too far since the vitreous humour is right behind the posterior capsule (Csillag, 2005). This anatomy requires the surgeon to be very precise and makes cataract surgery very technically challenging with the risk of complications. Intra-operative complications related to cataract surgery are posterior capsular tears, zonular rupture and suprachoroidal haemorrhage. Most commonly being posterior capsule tears with an incidence of between less than one percent to 4,1% can lead to lens drop and vitreous loss which in turn can cause retinal detachment and cystoid macular oedema. The most common post-operative complication is posterior capsule opacification due to lens epithelial cells being left in the lens capsule which causes loss of acuity with an incidence of between 5-50% within the five first years after cataract surgery. Other post-operative complications include corneal decompensation, raised intraocular pressure, astigmatism and endophthalmitis. Endophthalmitis is a feared complication but it is fortunately very rare with risk factors being posterior capsule tear, long surgical time and inexperience of the surgeon. (Briszi et al., 2012; Chan et al., 2010; Linebarger et al., 1999). The complication rate is highest in the first surgical cases of a resident and then drops with more experience (Briszi et al., 2012; Kaplowitz et al., 2018; Sen et al., 2019). The finding that a dramatic drop described as an inflection point in the learning curve occurs at about 70 cases (Kaplowitz et al., 2018) implies the importance of proper training of residents before they can start operating on real patients.

4.4 The education of cataract surgeons

Historically the teaching method for learning cataract surgery has been the master-apprentice version where the trainee has observed several surgeries operated by a more skilled surgeon and then try it themselves on patients (Lam et al., 2013; Ann Sofia S. Thomsen et al., 2015). The patients are awake during the procedure since local anaesthesia is used in the majority of cases (Lam et al., 2013; Smith, 2005), which gives the experienced surgeon few opportunities to comment on mistakes during the procedure. This compromises patient safety together with the fact that novice surgeons have a higher complication rate in their first cases and the experienced surgeon has limited access to the operating field due to small spaces in the operating room and cannot easily prevent mistakes made by the novice (Laurell et al., 2004). Lately there has been a legal and ethical discussion about the use of patients for training purposes and more safe methods for teaching cataract surgery are needed (Ann Sofia S. Thomsen et al., 2015). The education of a cataract surgeon today consists of wet lab simulations, micro-surgical skills courses (a combination of lectures and practise in wet labs) and in some cases virtual reality simulators before they can start performing parts of the procedure in an operating room under the supervision of an experienced cataract surgeon. In wet labs the trainee can practise surgical procedures on animal eyes, human cadaver eyes or synthetic eyes without the pressure of the real life scenario and without being able to damage any still functioning eyes (Kaplowitz et al., 2018; Smith, 2005; Spiteri et al., 2010). There are however limitations to this learning method. Human cadaver eyes are the most similar eyes to cataract eyes but they are harder to obtain and their corneas are usually oedematous with poor visibility into the anterior chamber which is crucial for phacoemulsification and capsulorrhexis. Enucleated animal eyes are cheaper and easier to obtain but have additional limitations from cadaver eyes since they have a harder, less elastic nucleus in the lens (Smith, 2005) and a bigger anterior chamber (Kaplowitz et al., 2018). This signifies that the phacoemulsification step of the surgery cannot be practised in an efficient way in these eyes (Smith, 2005). The phacoemulsification step in cataract surgery is considered to be the hardest step of the surgery (Sen et al., 2019; Smith, 2005) with the highest complication rate (Kaplowitz et al., 2018) which should imply that this step must be practised more before transferring the skills into the operating room.

4.5 Virtual Reality Simulators

A new, safe method using virtual reality (VR) simulation for learning surgical skills before going into the operating room has been developed and research within this area started in the beginning of the nineties (A. Sagar et al., 1994). VR can be defines as a “computer-generated representation of an environment that allows sensory interaction, thus giving the impression of actually being present” (Spiteri et al., 2010). The benefits of VR simulators as part of the learning process have been observed in other fields and are today used in several fields, both medical and non-medical. The aviation industry was early to start using flight simulators to teach their pilots and this raised the interest for VR simulation to teach surgery (Lam et al., 2013; Spiteri et al., 2010). Today there are VR simulators available for training in several surgical fields e. g. in laparoscopic (Alaker et al., 2016), endoscopic (Mahmood et al., 2018), endovascular (Rudarakanchana et al., 2015) and arthroscopic surgeries (Middleton et al., 2017).

There are currently three trademark VR simulators for cataract surgery: EYESi® (VRmagic) (Staropoli et al., 2017), MicrovisTouch® (ImmersiveTouch) (Sikder et al., 2015) and PhacoVision® (Melerit AB) (Laurell et al., 2004). All simulators can simulate most of the steps included in a cataract surgery but only MicrovisTouch has included haptic feedback in the simulator which the majority of ophthalmologist believe could help create a more life-like simulation (Sikder et al., 2014). The EYESi simulator has been more thoroughly researched than the other two and is currently used in many residential curriculums throughout the world (Staropoli et al., 2017). Several early studies have shown improvements in surgical skills outside the operating room when training on a virtual reality simulator. Feudner et. al studied 31 medical students and 32 ophthalmic residents randomized into two groups, one receiving training with a VR simulator and one receiving no training at all and compared their improvement on capsulorhexxis in wet labs. They could show a significantly greater improvement for the group that had trained with the VR simulator than for the control group (Feudner et al., 2009). When comparing training on a VR simulator with other training methods conflicting results have been found with some studies showing VR training to be superior to other training methods and some showing no significant difference (Ann Sofia S. Thomsen et al., 2015). Selvander et al. studied the learning curve when 35 medical students performed ten simulations on either the cataract navigation training module or the capsulorhexxis module on the EYESI simulator and then two simulations on the other module. A learning curve could be shown for the overall performance on the navigation module and some specific variables for both modules with initial rapid improvement and a plateau but not for the overall performance on the capsulorhexxis module. However, a significant improvement between the first and last simulation could be seen for the overall capsulorhexxis module. This indicates that the simulator can be beneficial as a part of the initial training for cataract surgeons. (Selvander and Åsman, 2012).

A previous study of the PhacoVision simulator on medical and optometric students as well as experienced cataract surgeons (Söderberg et al., 2007) defined reference values for measurement variables and found that an asymptote was reached after 20 simulations. A pilot study where ten medical students performed 20 phacoemulsification procedures divided into a sculpting phase and an evacuation phase on the PhacoVision simulator after an introduction indicated that two groups, learning group and non-learning group, could be considered in further experiment.

Later studies have showed varied results in complication rates and surgical skills when the skills acquired from a VR simulator are transferred to the operating room. A retrospective study with a relatively large sample size showed a significant reduction in complication rates after training with the simulator as a complement to conventional training (Staropoli et al., 2017), while another study was not able to show a significant reduction in complication rates but a shortened learning curve for the simulator-trained group (Pokroy et al., 2013). Thomsen et al showed in a prospective study that training with the simulator improved surgical skills measured with a standardized Objective Structured Assessment of Cataract Surgical Skill (OSACSS) rating scale compared with no training on the simulator but did not analyse the complication rate for the surgeons. They also concluded that novice (no full cataract surgeries performed at baseline) and intermediate (1-75 cataract surgeries performed at baseline) surgeons benefit the most from training on a virtual simulator. Experienced and expert surgeons with more than 75 surgeries prior to the study did not show significant improvements after training with the simulator. The conflicting results may be due to the many retrospective studies without a control of affecting variables and small sample sizes (Thomsen et al., 2017). In the study conducted by Pokroy et. al the authors discussed the possibility that the nonsimulator-trained group might have had more natural talent for cataract surgery or the opposite where the experienced surgeon might have taken over larger parts of the surgeries and therefore resulted in fewer complications and the inability to differ between these two possible reasons due to the retrospective design (Pokroy et al., 2013). Many studies do not use any standardized methods to assess surgical skills and have different introductions to the simulators which could also results in differing results. The study made by Thomsen et al had a prospective design but lacked a control group limiting the feasibility of the results (Thomsen et al., 2017). All these studies conclude that VR simulators should be used as a complement to the conventional training and not by itself.

Aside from teaching a surgery procedure the simulators have the possibility to objectively evaluate surgical skills to decide whether a resident is ready to start operating on patients (Ann Sofia Skou Thomsen et al., 2015). This has later been used in studies and it has been concluded that a proficiency-based learning where the trainee performs simulations until set, evidence-based criteria are reached is superior to a time-based simulation training since all trainees start with different skills, abilities and motivation to learn and will do so at different rates. Simulators are also able to give immediate feedback to the trainee which is a major advantage in learning (Gallagher et al., 2005; Zevin et al., 2012).

Another possible advantage with VR simulators is to study the impact of surgery on a surgeon and training the surgeon while working under unfamiliar conditions such as using the non-dominant hand, be under extreme fatigue or while using beta blockers. These types of studies are not possible to perform on patients due to ethical reasons and simulators provide a safe alternative. (Sikder et al., 2014). This could further improve the surgeon’s technical skills and prepare the surgeon for such events.

4.6 Aim of study

Even though there have been several studies on the EYESi simulator and how the skills acquired in the simulator transfer to the operating room there is a need for more prospective studies with larger sample sizes and control groups to evaluate the efficiency of the simulator (Thomsen et al., 2017). The other two simulators available: PhacoVision and MicrovisTouch are very poorly researched and further studies on these must be conducted. To incorporate a simulator into a surgical curriculum there must be studies showing a construct or concurrent validity for the simulator (Sikder et al., 2014) and which predefined criteria should be met by the resident before he or she can start operating on patients so that a proficiency-based training can be practiced (Zevin et al., 2012). For PhacoVision Söderberg et. al showed that an experienced surgeon performed better in all variables tested than students with no prior experience of cataract surgery proving a construct validity for the simulator (Soderberg et al., 2005) and defined reference values for the simulator (Söderberg et al., 2007). It is also necessary to research the learning curve and how the simulator is best used before it can be widely spread (Spiteri et al., 2010).

The aim of this study is to investigate the learning curve for performance index for medical students using the PhacoVision simulator.

The hypothesis of this study is that a non-linear learning curve will be found that shows an initial rapid improvement in performance index towards an asymptote.

5 Method

5.1 Participants

Altogether, 20 medical students at Uppsala University were recruited to the study thorough a common platform for all medical students. The inclusion criteria were to be a medical student and to have started the ophthalmology course, without any form of prior experience of cataract surgery, either with the simulator or otherwise. The exclusion criteria is that the participant could not spend two consecutive half days in the lab for any reason. All participants spent two consecutive half-days in the ophthalmology lab at Uppsala University Hospital. On the first day they received a standardized introduction to the simulator, a short lecture on the anatomy of the eye and the cataract surgical procedure and they were showed a short film of a normal cataract surgery. Before registration started the participants were all demonstrated the procedure 1-2 times on the simulator by an instructor that was an experienced user of the simulator after which they practised the procedure themselves 4-5 times. The first two practise procedures the instructor provided active feedback to the participant and the remaining practice procedures the participants practised alone but with the opportunity to ask as many questions as they wanted and with the feedback generated by the simulator after each procedure where 35 different variables were automatically recorded and could be accessed by the participant. A table listing all variables measured with reference values developed by Söderberg et. al may be found in the appendix (“Melerit PhacoVision Manual,” 2006; Söderberg, 2009). The introduction, demonstration of the simulator and the active feedback when training with the simulator were all given by the same instructor. An ethical approval was not required for the study since it is a master’s thesis and will not be published.

5.2 PhacoVision® simulator

The PhacoVision® simulator was developed by Laurell et. al in association with Melerit AB, Linköping, Sweden in the beginning of the 21st century. The simulator uses simulation software (M-base, Melerit AB, Linköping, Sweden) that works on top of Cosmo3D/Optimizer (Silicon Graphics Inc., Mountain View, CA). A special module has been created on top of M-base for phacoemulsification. The simulator consists of a computer, a 3-dimensional visual display of the eye, two handpieces and two foot-pedals (Figure 1). The handpieces, a phacoemulsification probe and a manipulator, each have four degrees of freedom: all 3 space dimensions and rotation. The foot-pedals work as follows: One foot-pedal controls focus, zoom and movement of the simulator-generated visual display and the other foot-pedal controls the irrigation, aspiration and emulsification functions of the phacoemulsification probe. The simulator-generated visual display is seen by the user through a microscope and may as well be seen by a person sitting next to the user on the computer screen (Laurell et al., 2004).

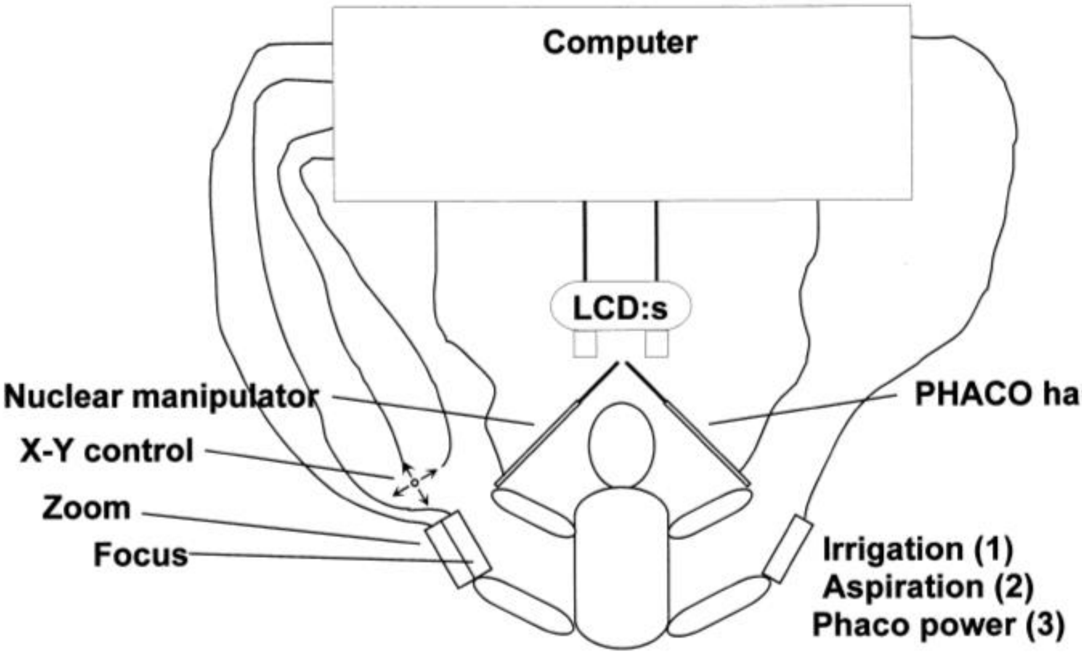

Figure 1. Schematic figure of the PhacoVision simulator. All input from the surgeons movements is analysed in the computer and displayed in the simulator-generated visual display of the eye using liquid crystal displays (LCD:s) in real time. (Laurell et al., 2004)

5.3 The procedure

All participants performed the phacoemulsification step of a cataract surgery. The steps prior to phacoemulsification in a normal cataract surgery were simulated to already have been performed with two incisions in the cornea for a phacoemulsification probe and a manipulator to enter the eye and a capsulorrhexis so that the lens could be reached. The patient parameter settings are demonstrated in table 1. The phacoemulsification step was divided into two parts by the simulator: the sculpting phase and the evacuation phase. 20 simulations were recorded, and 35 variables measured for each phase and participant divided over two consecutive days. In the sculpting phase the phacoemulsification probe was set with a high effect and pulse intensity of the ultrasound energy and low vacuum. The participants used the divide and conquer technique in which the lens is divided into four quadrants using ultrasound waves administered by a phacoemulsification probe to create four grooves in the lens all originating from the centre of the lens with a 90 degrees angle between each groove. When the grooves had been created the phacoemulsification probe and a manipulator were placed in the grooves and pulled apart to crack the grooves thus creating four separated quadrants. In the evacuation phase the settings on the phacoemulsification probe were changed to a low effect and pulse intensity of the ultrasound energy and a high vacuum. The participants brought up the lens quadrants one by one to the iris plane and then emulsified them using the phacoemulsification probe (Lam et al., 2013; Linebarger et al., 1999) (Figure 2).

Table 1. Table demonstrating the settings of patient parameters used in the simulator

Patient parameter	Setting
Nucleus hardness (0-1)	0.5
Nucleus angular speed when dialled (degree/s)	1.0
Distance Tip – Irrigation port centre (0.5-4.0)	2.0
Average incidence of occurrence of bubbles (bubbles/min)	1
Average number of bubbles per group (bubbles/group)	4
Average frequency of x-y patient field drift (times/min)	1.0
Maximum velocity for x-y patient field drift (mm/s)	2.0
Maximum x-y patient field drift (mm)	4.0
Maximum allowed stretching of the zonulae before lost lens (mm)	1.5
Maximum allowed zonular load (normal = 1)	1.0
Pupillary diameter (mm)	7.0
Force required to produce cracking (rel)	1.0
In frontal plane counter clockwise angle between 12 a'clock and phacoemulsification handle axis (degrees)	10.0
In frontal plane counter clockwise angle between 12 a'clock and manipulator handle axis (degrees)	290.0
Rhexis diameter (mm)	5.6
Anterior chamber depth (mm)	3.0

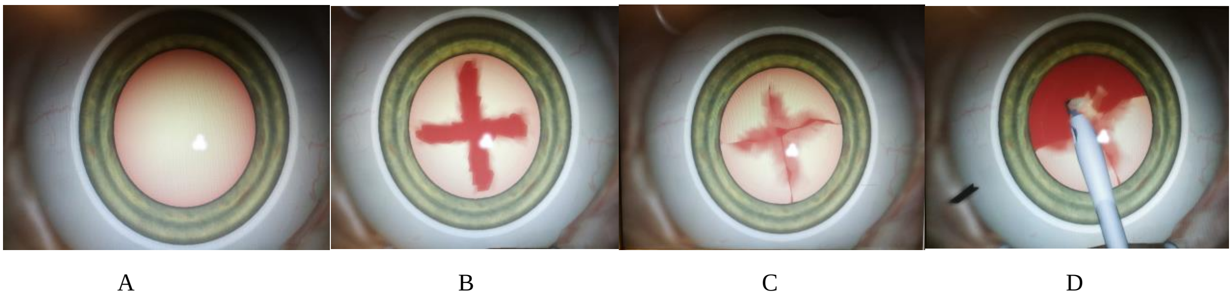

Figure 2. Pictures of the simulator-generated visual display of the eye in different steps of the simulation. (A): The image of the eye generated at the start of the surgery. (B): Four grooves have been sculpted creating a cross-sign through the lens. (C): The grooves have been cracked into four separate quadrants. (D): Emulsification of a quadrant in the evacuation phase with the phacoemulsification probe.

5.4 *Experimental design*

This study was a prospective, non-blinded experimental study. Since it was an early study on the subject a large sample size was not necessary, and 20 participants were enough to receive a sufficient power. The study was non-blinded due to the difficulty with the design. All participants received the introduction and demonstration of the simulator as well as active feedback from the same experienced simulator user. The data was anonymized with each participant receiving a participant number and the personal information of the participants was linked to the participant number in a separate document.

5.5 Data analysis

An overall performance index was calculated for each phase (sculpting and evacuation) based on the 35 variables automatically measured by the simulator in each simulation. The 35 variables were divided into 6 classes, Class 1 Overall Procedure, Class 2 Foot Pedal Technique, Class 3 Phacoemulsification Technique, Class 4 Erroneous Manipulation, Class 5 Damage to Ocular Structures, and Class 6 Damage to the Capsule, respectively (App. 1). The performance index was compared to the database reference values for each parameter defined by Söderberg et. al. (Söderberg, 2009). The individual overall performance index (IOPI) was calculated as the average of all individual variable specific performance indices (IVPI) of that individual for a simulation (Eq. 3). The IVPI was calculated as the average of the three iterations for that variable compared to the database reference value for that variable. The answer was subtracted from the number two so that the IVPI would equal one if it was the exact same as the reference value (Eq. 1). The individual class specific performance index (ICPI) was calculated as the average of all IVPIs of an individual belonging to that class (Eq. 2). The database reference values were found by Söderberg et. al by calculating the average of the variable when measured in a reference group.

$$IVPI_{ij} = 2 - \frac{RP_j}{P_{ij}}$$

Eq. 1. Equation for calculating the individual performance index (IVPI) for individual i and variable j. The performance (P) for individual i and variable j was calculated as the average of three iterations of the variable j. This performance is compared to the database reference value (RP) for variable j.

$$ICPI_{ic} = \frac{\sum_{j=1}^{m} IVPI_{ij}}{m}$$

Eq. 2. Equation for calculating the individual class specific performance index (ICPI) for individual i. The equation is based on the individual variable performance index (IVPI) for individual i and variable j. m = the number of variables measured within the class.

$$IOPI_i = \frac{\sum_{j=1}^{n} IVPI_{ij}}{n}$$

Eq. 3. Equation for calculating the individual overall performance index (IOPI) for individual i. The equation is based on the individual variable performance index (IVPI) for individual i and variable j. n = the number of variables measured.

The raw data collected from the simulator was converted into a Matlab file where the equations above were programmed to be calculated on all data. Nonlinear regression was used to calculate the learning curve for the overall performance indices of the participants as a function of the maximum performance index assuming an asymptote is reached as showed by Söderberg et. al on optometric students (Söderberg et al., 2008) (Eq. 4).

$$IOPI = IOPI_{Max} - IOPI_{improvement} * exp^{-k*N_i}$$

Eq. 4. Equation for calculating the best fit nonlinear regression for the improvement of the individual overall performance index (IOPI) of an individual as a function of the maximum individual overall performance index ($IOPI_{Max}$) over the course of 20 simulations where N_i = the simulation number (i = 1, 2…20) and k = the learning rate.

6 Results

The purpose of this study was to investigate the learning curve for phacoemulsification simulation on the PhacoVision® simulator. A preliminary analysis was made with a scatter plot of the IOPI as a function of the number of simulations for both the sculpting phase and the evacuation phase. Two groups could be distinguished, a learning group and a non-learning group. In the learning group a positive trend showed the IOPI generally increasing over the course of the simulations (Figure3). In the non-learning group no trend of increase were showed (Figure 4).

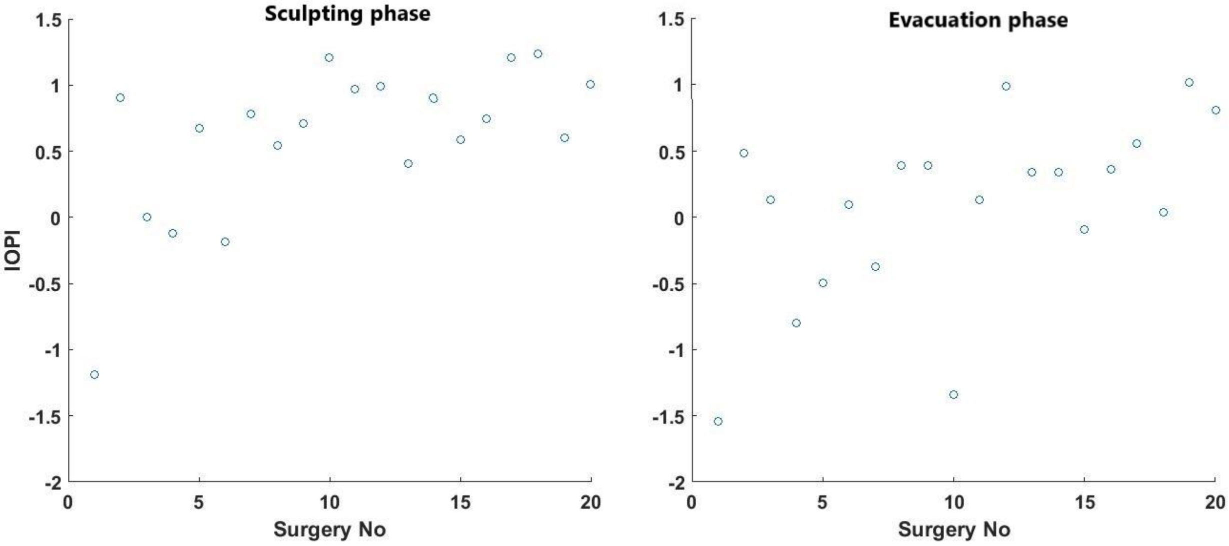

Figure 3. A scatter plot demonstrating the IOPI for each of the 20 simulations for an individual in the learning group.

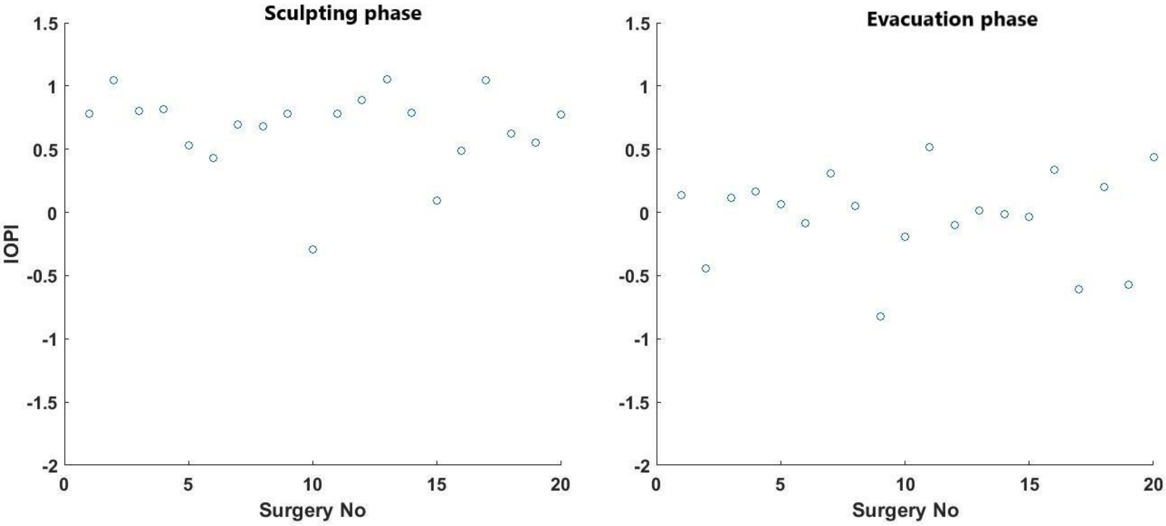

Figure 4. A scatter plot demonstrating the IOPI for each of the 20 simulations for an individual in the non-learning group.

It could also be seen that the participants did not reach an asymptote after the 20 simulations resulting in the need to modify the equation for the nonlinear regression with the asymptote set to 1 (Eq. 5).

$$IOPI = 1 - IOPI_{improvement} * exp^{-k*N_i}, \text{ or } \ln(1 - IOPI) = \ln\left(IOPI_{improvement}\right) - k * N_i$$

Eq. 5. Equation for calculating the best fit nonlinear regression for the improvement of the individual overall performance index (IOPI) of an individual over the course of 20 simulations with the asymptote set to 1. N_i = the simulation number (i = 1, 2…20) and k = the learning rate.

6.1 Drop-out

20 medical students were recruited to the study and 15 students finished the study. 5 students dropped out for different reasons including medical reasons, headache from the sounds of the simulator and back pain. It should be noted however that the manipulator handpiece in the simulator came loose after the first two participants and was fixed to a suboptimal state for the consecutive four participants. For these four participants the manipulator handpiece was not perfectly calibrated which made the cracking of the grooves substantially harder resulting in longer operation times, more movement with the instruments and more damage to the structures of the eye. Out of these four participants two dropped out of the study.

6.2 Sculpting phase

Applying Eq. 5 it was shown that 6 subjects belonged to the learning group for sculpting phase. The learning curves of these participants were almost linear with almost the same inclination over the whole curve (Table 2). In the sculpting phase the participants achieved very diverse IOPIs with the single worst IOPI ranging between -40 to -0.3 for different participants and the best IOPI ranging between -2 for some participants and above the reference value for others. Some participants did achieve an IOPI value above the reference (Figure 5) however these IOPI values were too few and spread out for them to be valued as an asymptote.

Fel! Hittar inte referenskälla.

Subject no	95%CI for inclination coefficients, k $\times 10^{-2}$	95%CI for improvement, $IOPI_{Improvement}$	Residual standard deviation
2	5.3±1.7	20.4±1.2	2.7
5	4.0±2.5	15.0±1.4	3.3
8	2.2±1.5	8.6±1.2	1.6
9	1.1±0.67	6.0±1.1	0.45
12	0.70±0.46	6.0±1.1	0.30
15	1.9±1.4	11.1±1.2	1.6

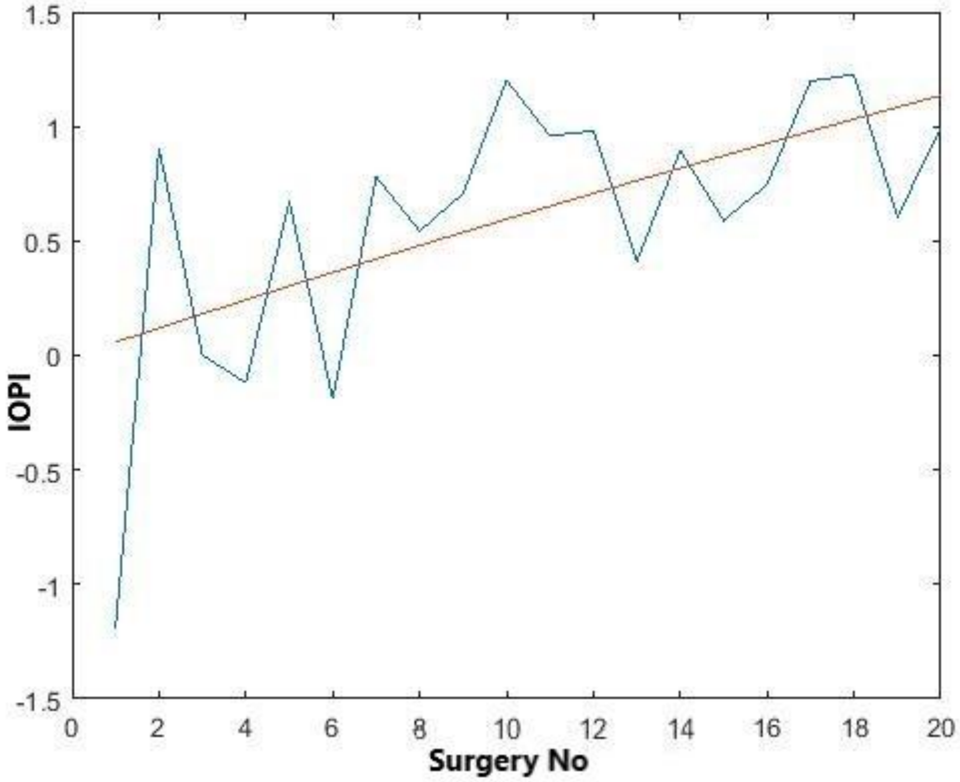

Figure 5 An example of the best fit curve for a learner in the sculpting phase using Eq. 5.

Applying Eq. 6 it was found that 9 subjects were non-learners since none of the inclinations coefficients (k) were significant. The estimated inclination coefficients for the non-learning group are demonstrated in Table 3.

$$IOPI = IOPI_{initial} + k * N_i$$

Eq 6. Equation for calculating the best fit curve for the IOPI in the non-learning group over the course of 20 simulations. N_i = the simulation number (i = 1, 2…20) and k = the learning rate.

Fel! Hittar inte referenskälla.

Subject no	95%CI for inclination coefficients k $\times 10^{-2}$
1	-40.4±95.0
3	28.0±34.0
4	0.14±9.1
6	-9.8±13.4
7	-0.59±2.7
10	5.5±10.7
11	-18.1±25.2
13	-1.8±3.7
14	11.4±57.9

6.3 Evacuation phase

For the evacuation phase it was estimated that 8 subjects belonged to the learning group by fitting to Eq. 5. The learning curves of these participants were almost linear with almost the same inclination over the whole curve and a flatter curve than for the learning group in the sculpting phase (Table 4, Figure 6).

Fel! Hittar inte referenskälla.

Subject no	95%CI for inclination coefficients, k $\times 10^{-2}$	95%CI for improvement, $IOPI_{Improvement}$	Residual standard deviation
2	0.97±0.95	6.4±1.1	0.68
3	1.0±0.58	6.4±1.1	0.41
5	0.94±0.74	6.8±1.1	0.55
6	0.86±0.63	6.1±1.1	0.44
8	0.73±0.71	5.8±1.1	0.46
9	1.1±0.77	6.6±1.1	0.56
12	0.59±0.60	6.1±1.1	0.40
13	0.52±0.41	6.1±1.1	0.27

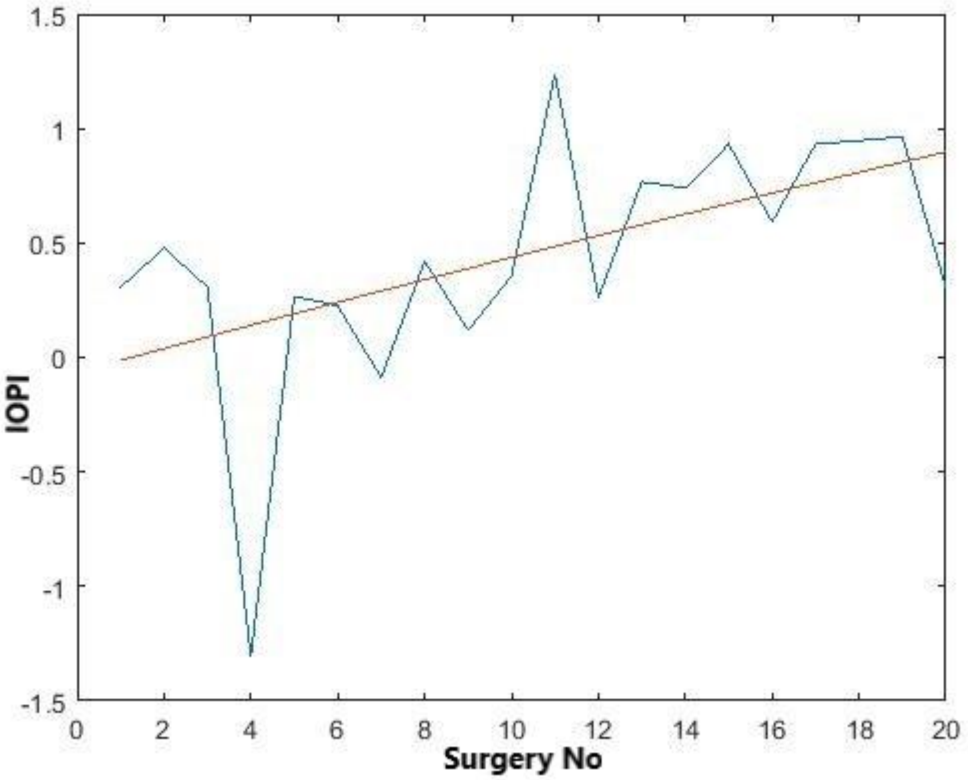

Figure 6 An example of the best fit curve for a learner in the evacuation phase using Eq. 5.

With fitting to Eq. 6, it concluded that 7 subjects were non-learners since none of the inclinations coefficients (k) were significant. The estimated inclination coefficients for the non-learning group are estimated (Table 5).

Fel! Hittar inte referenskälla.

Subject no	95%CI for inclination coefficients k $\times 10^{-2}$
1	-2.1±14.6
4	-2.1±3.5
7	-0.09±3.0
10	1.7±6.0
11	3.4±3.6
14	-3.1±8.1
15	3.0±4.2

6.4 Classes

The ICPI was calculated for each participant to estimate if certain parts of the simulation were easier to learn than others (App. 2-7). It was found that for the sculpting phase the results varied between the classes with the highest ICPIs for Class 5, damage to ocular structures where almost all the participants reached an ICPI above the reference value (=1) in the majority of simulations for the last 10 of the simulations (Figure 7).

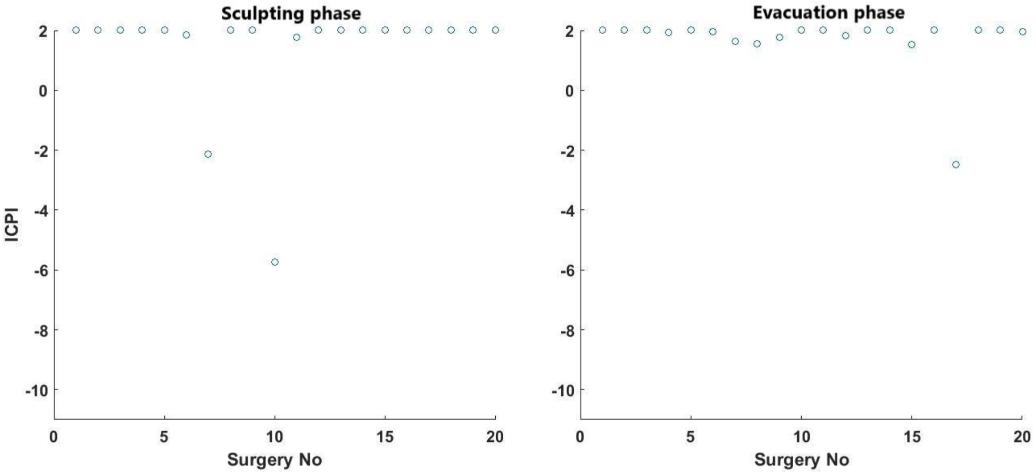

Figure 7. ICPI for the 20 simulations for one participant for class 5, damage to ocular structures.

High ICPIs were also seen in Class 2, foot pedal technique (Figure 8) and Class 4, erroneous manipulation where the majority of the participants reached an ICPI above 0 in the majority of simulations for the last 10 of the simulations.

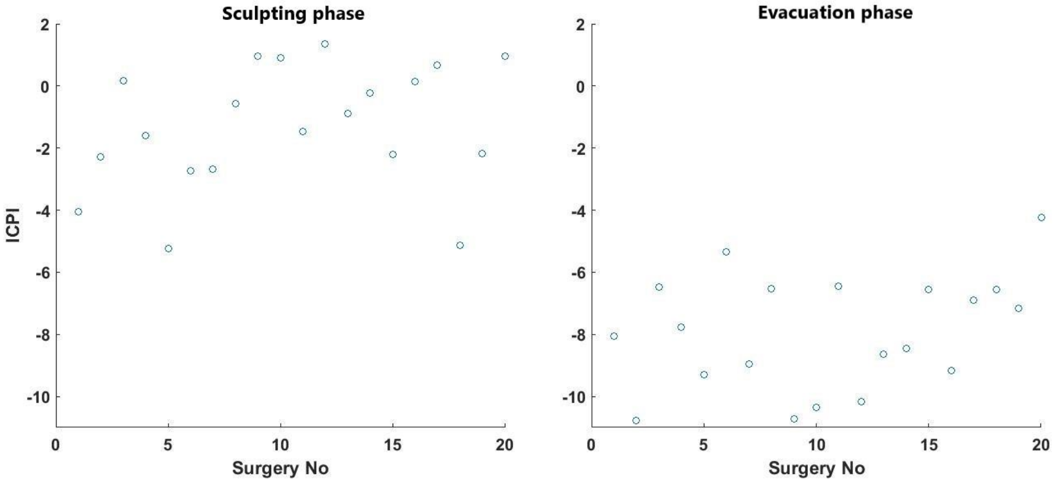

Figure 8. ICPI for the 20 simulations for one participant for class 2, foot pedal technique.

In Class 6, damage to the capsule the ICPIs were much spread with some participants showing ICPIs far from reaching -2 while 2 participants reached above the reference value. In the evacuation phase all the participants reached an ICPI above the reference value in the majority of simulations for the last 10 of the simulations for every class except for Class 2, foot pedal technique where none of the participants reached an ICPI above -2 in the majority of simulations for the last 10 of the simulations.

7 Discussion

7.1 Main findings

From the data it can be concluded that 6 out of the 15 participants that finished the study were learners in the sculpting phase and 8 out of the 15 participants were learners in the evacuation phase. 5 out of the 6 learners in the sculpting phase were also learners in the evacuation phase showing that some participants were more prone to learn than others. The learning curves of all learners were quite linear which was in contrast with the hypothesis. In the hypothesis it was believed that the learning curves would be clearly exponential with a fast learning in the beginning to later flatten out toward an asymptote. Thus, it indicates that 20 simulations were not enough to learn the phacoemulsification procedure. This is supported by the fact that no participants reached an asymptote for either the sculpting phase or the evacuation phase.

The reason why the participants achieved very diverse IOPIs and why some were more prone to learn than others might be the quite diverse study group. Since the study group consisted of medical students and not ophthalmology residents the skills and abilities at baseline as well as the interest and motivation might have varied substantially within the group. To learn such a complex procedure a great deal of attention is required, which might have varied between the participants since some participated in the study during a free day (presumably being well rested with good attention) while some participated after a whole day of classes. Because of this great inter-individual variation, the participants were at very different levels at the end of the experiment and even if the experiment had continued the participants would probably have reached an asymptote at very different stages. This indicates that a proficiency-based model of teaching would be of greater value than a time-based one in such a diverse group.

7.2 Sculpting

In general, the IOPIs for the sculpting phase were much lower for the first simulations than those for the evacuation phase. Higher IOPIs for the last simulations had also been achieved in the evacuation phase for most participants but this difference was not as great. This indicates that the sculpting phase is much harder to perform in the simulator and might need additional focus in the learning process. This could also be why the confidence interval for improvement was much greater from the sculpting phase (Table 2) than from the evacuation phase (Table 4).

The finding that the ICPIs varied greatly between the different classes indicates that either some of the specific class techniques were harder or that not enough focus was put on some of the specific class techniques. In Class 5 where the best ICPI could be reached for sculpting it could be argued that the asymptote was reached since the reference value was earlier set as the asymptote value.

However, when looking at the first ten simulations in this class the majority had reached the reference value as well indicating that there was no learning process in this class, the participants could immediately perform above the reference value after the initial few training sessions, indicating that the parameters of this particular class were fast to master (Figure 7). In Class 2 and 4 an overall trend of improvement could be seen between the simulations indicating good learning potential for these classes. In Class 4 total 7 participants even reached an IOPI above the reference value and it could therefore be argued that these participants reached the asymptote. A reason for the big spread in Class 6 might have been that some participants had more trouble cracking the grooves and therefore made the grooves deeper and wider to facilitate the cracking. When making the groove deeper the risk of damaging the posterior capsule increases substantially since the distance between the phacoemulsification probe and the posterior capsule decreases. Studies have suggested that some variables are more valuable to measure than others to gain a good estimation of the level of skills of the trainee. Time, for example, has been suggested to be a poor variable to measure while errors are good variables since these are important to avoid in an operating room (Gallagher et al., 2005). The Class 1, overall procedure, which mainly measure time might therefore not be as important as the other classes. The ICPI are good to further demonstrate the level of the student in different parts of the simulation and in the future an IOPI where some variables are considered more important than others might need to be developed. The ICPI may also be used as an additional evaluation tool in the learning process since it shows which parts of the simulation are the hardest for the student so that the student may focus more on these and receive extra help with them.

7.3 Evacuation

In the evacuation phase many participants had a much flatter best fit curve than in the sculpting phase. This resulted in several participants being sorted into the non-learning group as their confidence interval became too large to prove an improvement. A reason for the flatter curves might be that the participants performed well from the beginning and therefore could not improve as much as in the sculpting phase. Most participants had no value for IOPI worse than -2 and many were close to reaching the asymptote at the reference value, it is probable that only a few more simulations would be enough for most participants to reach an asymptote in this phase.
All the participants reached the asymptote (if the asymptote is defined as an IOPI above the reference value in the majority of the last ten simulations) in each specific class except for the Class 2 where none of the participants achieved a good result (defined as an IOPI above -2 in the majority of the last ten simulations). The Class 2 measures the foot pedal technique and how much of different parts of the procedure the microscope image is out of focus or decentralized. No

explanation has been found for this deviation in the results since the technique is used in the same way with no further difficulties compared to the sculpting phase. Furthermore, the ICPI values for the same class in the sculpting phase were very good. One possible reason however might be that the participants were restless in this last part of the procedure and lost focus on the foot pedals, but this does not explain while such good results were seen in the other classes for the evacuation phase. The fact that the results were poor for the second class might be the reason while the IOPI did not reach an asymptote in the evacuation phase for any of the participants.

7.4 Results in comparison with previous results

The reference value defined by Söderberg et al. was not reached by most participants in this study in either the sculpting phase or the evacuation phase indicating a worse overall IOPI than in the study by Söderberg et al. In their study they also found that an asymptote was reached after 20 simulations which this study could not demonstrate. A reason for these divergent results despite a similar study design might be that the study conducted by Söderberg et. al had a more thorough introduction with an instructional video on the PhacoVision® simulator as well as they had an experienced cataract surgeon as the instructor instead of an instructor only experienced in the simulator but not in the operating room (Söderberg et al., 2007). Their study also included both medical and optometric students as well as expert cataract surgeons instead of only medical students in this study. In line with a pilot study two groups of learners and non-learners were defined in this study but the learning group was bigger in this study. A possible explanation might be more careful information to the participants about the need to be cautious of the simulator and treat it as a patient. A problem with the simulator is that it may be easy to lose focus since there are no consequences if something goes wrong.

More extensive research has been made on the EYESI® cataract simulator. Selvander et. al could not prove a significant learning curve for the capsulorhexxis module even if there was an improvement between the first and last simulation (Selvander and Åsman, 2012). These results are in line with the non-learning group of this study. Their study only tested ten simulations however, perhaps if their study had been expanded to 20 simulations similar results with a learning group as well would have been seen. On the cataract navigation training module however, they could prove a learning curve but this module might be considered too easy to compare with the results of this study since it is an introductory module to the simulator. A similar module would however probably be of value even in the PhacoVision® simulator. These mixed results support findings in this study that the initial learning curve using a cataract simulator is quite uneven and more simulations are needed to reach an asymptote for more advanced modules. For the majority of the participants in this study an improvement in IOPI could be seen between the first simulation and the last. This goes in line with early findings on the EYESI® simulator for the phacoemulsification module and other modules where an improvement could be seen with repeated training on a simulator (Feudner et al., 2009; Ann Sofia S. Thomsen et al., 2015).

7.5 Method discussion

A pilot study found that the participants could be divided into two groups, a learning group and a non-learning group. To receive a sufficient power of the data at least ten participants were needed in each group resulting in 20 medical students being recruited. Out of these, five dropped out of the study due to various reasons but mainly impatience, loss of focus and a bad working environment. No compensation was offered to the participants and only the motivation to learn a microsurgery showed not to be enough for some. It could be argued that micro surgery is not for everyone or that 20 simulations in a row over a period of two half-days was too intensive. Two of the participants dropped out when the manipulator handpiece was sub optimally calibrated resulting in the simulation to be substantially harder to perform. The study design partly followed a proposed curriculum for using VR simulators as training devices including a standardized introduction giving the participants the relevant knowledge, explaining the procedure and common errors, training of skills with immediate feedback of errors and terminal feedback after each trial (Gallagher et al., 2005). Each participant performed 20 simulations because of previous findings showing that 20 simulations are needed to reach an asymptote (Söderberg et al., 2007). The results from this study however show that more simulations are needed before the asymptote is reached since no participants reached the asymptote after the 20 simulations. Several of the participants commented on the difficulty of the procedure and wished for a training program where the difficulty gradually increased and only a few skills were trained primarily to include the whole procedure in the end. This training method has been studied and described in literature and is referred to as shaping. It has been demonstrated that shaping is a very efficient training method (Gallagher et al., 2005) and incorporating this into the PhacoVision® simulator could be of value. Medical students were used as participants in this study since this allowed for more participants. Ophthalmology residents are the actual target group for PhacoVision® and would have been interesting to study, but they are less accessible due to a busy schedule and would decrease the study group substantially. Medical students are often very eager to learn and have the basic knowledge required for performing a cataract surgery. It has also been proven that novice and intermediate cataract surgeons (no prior or intermediate prior experience) benefit the most from training with a VR simulator and are therefore of greatest interest to study (Thomsen et al., 2017). The fact that all medical students that participated in the study had commenced the ophthalmology course meant that all had the relevant knowledge required about cataract, treatment and the anatomy of the eye. Most medical students at Uppsala University has the opportunity to attend one or several cataract surgeries and had therefore seen how the surgery is performed in the operating room. A performance index that included all variables was calculated for each simulation and analysed instead of each individual variable since many of the variables dependent and no valuable conclusions would be possible to make from them individually.

7.6 Strengths and limitations

A strength to this study was that all participants received the same introduction since it was given after a standardized document and by the same instructor. They all had the same opportunity to practice before the registrations of the simulation and no one had any prior experience of cataract surgery. Since all participants were trained by the same instructor there was no bias in the introduction and training of the simulator. Nevertheless, since the instructor had no prior experience of teaching cataract surgery with the simulator there might have been a bias between the early participants and the last ones since the instructor might have developed better teaching techniques during the study. The instructor met all participants as well as analysed the data with the impact that the study was not blinded, another solution was not possible due to limitations in staff. The data however was automatically collected by the simulator with no bias. During the data collection the manipulator handpiece was sub optimally calibrated for two of the participants that finished the study. This fact however cannot be seen in their results as they do not deviate from the rest. The simulator itself has its limitations since it cannot simulate a real cataract surgery precisely. One example of this is that the simulator has no built-in haptic feedback which made it very hard for the participants to know exactly how deep into the lens they were with the instruments. Another example is that “bad” behaviours can be taught by the simulator as opposed to the desired good ones and these are later very hard to erase (Gallagher et al., 2005). For example, the participants might have used the computer screen instead of the microscope to watch the displayed image of the eye while they were operating or held the instruments in a way that would not be possible in an operating room. The participants were told carefully not to do some of these known bad behaviours, but others might exist that are not yet known to the instructor. This might have led to falsely high performance indices and worse preparation for a real operating room surgery. A possible solution would be to use an expert cataract surgeon with extensive experience from the operating room as instructor who would be able to identify these bad behaviours at an early stage and prevent them.

7.7 Conclusion

The conclusions from my study are that:

- There are two distinct groups using the PhacoVision® simulator: a learning group and a non-learning group and some individuals seem more prone to learn with the simulator
- The learning curves of the learning group are almost linear without them reaching an asymptote
- 20 simulations with the PhacoVision® simulator are not enough to reach an asymptote and a proficiency based model would be a better way to reach it
- The sculpting phase seems to be harder to perform and should receive additional practice

A larger study with more participants and more simulations is necessary to find the whole learning curve which eventually reaches an asymptote. To compare these results future studies should be made on other possibilities to use the simulator, for example an interval training model, the shaping technique or a proficiency-based learning model. When the best method for using the simulator has been found for phacoemulsification the studies have to be expanded to test the remaining steps of a cataract surgery (incision, capsulorhexxis and IOL insertion). Further into the future studies should be made to compare simulator training to the conventional methods of training such as wet labs and research how well the skills acquired in the simulator are transferred to the operating room. Studies on this topic on the EYESI® simulator show promising yet conflicting results (Pokroy et al., 2013; Staropoli et al., 2017) indicating that similar studies on the PhacoVision® simulator are necessary and have promising outcomes.

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10 Appendix

App 1. Table showing and describing all parameters measured by the simulator with reference values. The reference values marked in red have not yet been decided and the parameters affected were therefore not analysed in the performance index. The bold text in the parameter column indicates a new class and the parameters listed below that class belongs to said class ("Melerit PhacoVision Manual," 2006; Söderberg, 2009).

Parameter name	Description	Reference value in sculpting phase	Reference value in Evacuation phase
Class 1 Overall Procedure			
Total Procedure Time	Total Time (s)	228.38	236.04
Sculpting Time	Time with phaco mode sculpting on (s)	90.45	
Evacuation Time	Time with phaco mode evacuation on (s)		52.75
Phaco Energy Used	Time integrated phacoemulsification power (mJ)	1.88	0.25
Class 2 Foot Pedal Technique			
Off Defocus Time	Time of phacoemulsification foot pedal in position 0 (no irrigation, no aspiration, no phacoemulsification) and simultaneous phaco tip outside focus (s)	7.49	10.39
Irr Defocus Time	Time of phacoemulsification foot pedal in position 1 (irrigation mode) and simultaneous phaco tip outside focus (s)	2.04	2.50
AspIrr Defocus Time	Time of phacoemulsification foot pedal in position 2 (irrigation and aspiration) and simultaneous phaco tip outside focus (s)	2.73	2.50
Sculpting Defocus Time	Time of phacoemulsification foot pedal in position 3 (irrigation, aspiration and phacoemulsification), phacoemulsification in sculpting mode and simultaneous phaco tip outside focus (s)	16.52	
Evacuation Defocus Time	Time of phacoemulsification foot pedal in position 3 (irrigation, aspiration and phacoemulsification), phacoemulsification in evacuation mode and simultaneous phaco tip outside focus (s)		0.87
Decentration Surgical Field	Time worked outside the optimal working field (s)	17.52	41.89
Class 3 Phacoemulsification Technique			
Phaco Path Total	Total path traversed with the phacoemulsification handpiece tip (mm)	296.21	307.91
Phaco Path X	Path traversed with the phacoemulsification handpiece tip in X direction (mm)	157.74	168.66
Phaco Path Y	Path traversed with the phacoemulsification handpiece tip in Y direction (mm)	183.76	190.54
Phaco Path Z	Path traversed with the phacoemulsification handpiece tip in Z direction (mm)	117.88	111.13
Manipulator Path Total	Total path traversed with the nucleus manipulator tip (mm)	133.62	171.97
Manipulator Path X	Path traversed with the nucleus manipulator tip in X direction (mm)	94.96	123.46
Manipulator Path Y	Path traversed with the nucleus manipulator tip in Y direction (mm)	49.54	64.05
Manipulator Path Z	Path traversed with the nucleus manipulator tip in Z direction (mm)	55.99	64.20
Class 4 Erroneous Manipulation			
Bubble Occlusion Time	Time that more than 3 adjacent bubbles are present (s)	31.50	67.86
No Irrigation Time	Procedure Time with the phacoemulsification foot pedal left in position 0 (no irrigation, no aspiration, no phacoemulsification) (s)	25.36	41.46
Manipulator Behind Iris Time	Time with the phacoemulsification foot pedal in position > 1 (irrigation, aspiration and or phacoemulsification) and the manipulator tip in position hidden by iris (s)	0.04	0.27
Phaco Behind Iris Time	Time with the phacoemulsification foot pedal in position > 1 (irrigation, aspiration and or phacoemulsification) and the handpiece tip in position hidden by iris (s)	0.54	0.04
Class 5 Damage to Ocular Structures			
Piece Cornea Push Time	Time when lens fragment is in contact with cornea and the phacoemulsification tip simultaneously (s)	0.00	0.28
Phaco Cornea Hit Time	Time when phacoemulsification handpiece tip is in contact with corneal endothelium in any phacoemulsification foot pedal position (s)	0.45	0.36
Phaco Cornea Hit Energy On Time	Time that the phacoemulsification tip is in touch with the cornea and ultrasound energy is on (s)	0.00	0.00
Iris Damage Time	Time when phacoemulsification handpiece tip is in contact with iris with phacoemulsification foot pedal in position > 1 (irrigation, aspiration and or phacoemulsification) (s)	0.07	0.16
Class 6 Damage to the Capsule			
Phaco Rhexis Damage Time	Time of phacoemulsification handpiece tip in contact with rhexis border during operation with phacoemulsification foot pedal in position > 1 (irrigation, aspiration and or phacoemulsification) (s)	6.91	1.76
Phaco Beyond Posterior Capsule Time	Time with the phacoemulsification tip behind the posterior capsule (s)	0.11	0.06
Manipulator Beyond Posterior Capsule Time	Time with the nucleus manipulator tip behind the posterior capsule (s)	0.04	0.08
Zonula Stretch	Stretching of the zonulae (mm)	11.75	35.74

App 2. Table showing the number of participants reaching above different values of the ICPI in the majority of the last ten simulations for the first class, overall procedure.

Class 1, overall procedure	Sculpting phase	Evacuation phase
Number of participants reaching a value above -2 in the majority of the last 10 simulations	12	15
Number of participants reaching a value above -1 in the majority of the last 10 simulations	8	15
Number of participants reaching a value above 0 in the majority of the last 10 simulations	2	15
Number of participants reaching a value above 1 in the majority of the last 10 simulations	0	15

App 3. Table showing the number of participants reaching above different values of the ICPI in the majority of the last ten simulations for the second class, foot pedal technique.

Class 2, foot pedal technique	Sculpting phase	Evacuation phase
Number of participants reaching a value above -2 in the majority of the last 10 simulations	14	0
Number of participants reaching a value above -1 in the majority of the last 10 simulations	12	0
Number of participants reaching a value above 0 in the majority of the last 10 simulations	11	0
Number of participants reaching a value above 1 in the majority of the last 10 simulations	2	0

App 4. Table showing the number of participants reaching above different values of the ICPI in the majority of the last ten simulations for the third class, phacoemulsification technique.

Class 3, phacoemulsification technique	Sculpting phase	Evacuation phase
Number of participants reaching a value above -2 in the majority of the last 10 simulations	12	15
Number of participants reaching a value above -1 in the majority of the last 10 simulations	7	15
Number of participants reaching a value above 0 in the majority of the last 10 simulations	1	15
Number of participants reaching a value above 1 in the majority of the last 10 simulations	0	15

App 5. Table showing the number of participants reaching above different values of the ICPI in the majority of the last ten simulations for the fourth class, erroneous manipulation.

Class 4, erroneous manipulation	Sculpting phase	Evacuation phase
Number of participants reaching a value above -2 in the majority of the last 10 simulations	13	15
Number of participants reaching a value above -1 in the majority of the last 10 simulations	12	15
Number of participants reaching a value above 0 in the majority of the last 10 simulations	9	15
Number of participants reaching a value above 1 in the majority of the last 10 simulations	7	15

App 6. Table showing the number of participants reaching above different values of the ICPI in the majority of the last ten simulations for the fifth class, damage to ocular structures.

Class 5, damage to ocular structures	Sculpting phase	Evacuation phase
Number of participants reaching a value above -2 in the majority of the last 10 simulations	15	15
Number of participants reaching a value above -1 in the majority of the last 10 simulations	15	15
Number of participants reaching a value above 0 in the majority of the last 10 simulations	14	15
Number of participants reaching a value above 1 in the majority of the last 10 simulations	14	15

App 7. Table showing the number of participants reaching above different values of the ICPI in the majority of the last ten simulations for the sixth class, damage to the capsule.

Class 6, damage to the capsule	Sculpting phase	Evacuation phase
Number of participants reaching a value above -2 in the majority of the last 10 simulations	7	15
Number of participants reaching a value above -1 in the majority of the last 10 simulations	6	15
Number of participants reaching a value above 0 in the majority of the last 10 simulations	4	15
Number of participants reaching a value above 1 in the majority of the last 10 simulations	2	15