UPPSALA UNIVERSITET

WRITTEN REPORT

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Performance increase of non-experienced trainees on a virtual reality cataract surgery simulator

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Populärvetenskaplig sammanfattning

Ögats lins är den genomskinliga strukturen bakom iris som stödjer ögats ljusbrytning och ansvarar för att bilden som formas på näthinnan är i fokus. Katarakt definieras som nedsatt syn på grund av grumling i linsen som orsakar en optisk störning. Förstahandsbehandlingen för symptomgivande katarakt är kataraktkirurgi som innebär borttagning av ögats lins och ersättning av det men en syntetisk lins. Kataraktkirurgi innebär mycket små och exakta rörelser vilket gör operationen nära gränsen av vad en människa kan klara av. Forskning har visat att det kan ta upp till 1000 operationer för en ny kirurg ska nå sin fulla potential.

Utbildning av kataraktkirurger är tids- och resurskrävande. Förhoppningen är att man genom att använda en VR-simulator kan effektivisera utbildningen av blivande kataraktkirurger och minska antalet komplikationer som patienter drabbas av. Denna studie är ett delsteg i att uppnå detta. Tidigare forskning med simulatorn har visat att den efterliknar riktig kataraktkirurgi samt formulerat ett skicklighetsindex, ett betyg, som speglar hur bra en simulering är utförd. Detta arbete bygger vidare på detta genom att studera hur inlärningskurvan ser ut över en period av 10 konsekutiva dagar med 4 simulationer varje dag samt utforska vilken del eller aspekt av operationen är svårare än de andra.

10 läkarstudenter från Uppsala Universitet med god teoretisk kunskap men utan erfarenhet inom kataraktkirurgi rekryterades till studien. Resultatet visade att den första delen av operationen, där man öppnar upp linsen och bryter den i små delar var svårare än den senare delen av operationen där man tar ut linsens delar. En platå kunde observeras för den svårare delen efter ungefär 37 simuleringar. De andra delarna visade ingen platå eftersom deltagarna var lika bra som referensvärdet från början. Vidare förfining av skicklighetsindexet kan hjälpa till att bättre spegla skicklighetsförbättringen som kan åstadkommas genom att använda VR-simulatorn.

ABSTRACT

Introduction: Cataract is a leading cause of blindness globally. Phacoemulsification cataract surgery is the procedure of choice for management of cataract. The surgery has a steep and long learning curve. Using the PhacoVision® VR-simulator manufactured by Melerit AB the study aims to evaluate the performance increase in trainees naïve to cataract surgery and investigate whether any phases of the operation are more difficult than the others. **Method:** 10 medical students with previous knowledge regarding ophthalmology were admitted to the study. We employed the performance index previously formulated by Söderberg et al. encompassing 38 individual variables to assess the performance increase of the study participants spanning 10 consecutive days with 4 simulations each day. **Results:** The overall performance increase for the sculpting plus capsulorhexis phase fit the regression model which indicated an asymptote of 0.88 95% CI [0.24, 1.52] and a number of operations needed to reach 90% of the asymptote of 37 95% CI [16, 61]. The other data sets did not fit the regression model while review of the data showed that in many cases the study participants exhibited reference-level performance from the first simulations. **Discussion and Conclusion:** The forming of a high-level asymptote for the more demanding sculpting phase suggests that the trainees were plateauing. However, with some of the performance variables not taken into account due to limitations of the performance index the trainees might still stand to improve. The data further suggests that the evacuation phase is less demanding that the sculpting plus capsulorhexis phase.

1 INTRODUCITON

The optical lens is the clear anatomical structure situated in front of the vitreous body and behind the iris whose role is to help focus the light on to the retina by virtue of its shape clarity and refractive index. Embryologically it is formed from ectodermal tissue, and it contains epithelial cells which give rise to lens fibers throughout the entire lifespan. Thus, the lens becomes more compact and thicker with advancing age. A loss in the optical clarity of the lens is called a cataract.(Asbell et al., 2005). The word cataract is derived from the Latin *cataracta*, meaning "waterfall". To the naked eye of an observer the white foamy appearance of an advanced cataract bears semblance to the turbulent waters of a waterfall.(Jacobs, 2021)

In 2020 cataract was the leading cause of blindness in those aged 50 and above globally. Together with undercorrected refractive error, cataract is responsible for 50% of all global blindness and 75% of all global moderate and severe vision impairment (defined as presenting visual acuity from <6/18 to 3/60). (Steinmetz et al., 2021)

The etiology of age-related cataracts is to this day not fully understood and is likely multifactorial. Researchers have been able to identify risk factors which increase the risk of developing cataract. These include increasing age, diabetes mellitus, smoking, excessive UV-light exposure, obesity, and high blood pressure, among others. Consistent evidence suggests also that a higher level of education is associated with a lower prevalence of all cataract types. (Seddon et al., 1995)

The management of cataract has always required surgery. In fact, couching, which involves the use of a needle to dislocate the lens backwards into the vitreous cavity, is one of the oldest recorded surgical procedures, dating back all the way to 800 BC. By the mid-18th century intracapsular cataract extraction, i.e., the removal of the lens together with its capsule through an incision at the junction of the sclera and the cornea, had started to emerge. Fast forward to the second half of the 20th century and the advent of intraocular synthetic lenses which paved the way for the development and refinement of extracapsular cataract extraction (Leffler et al., 2020).

The extracapsular procedure involves removal of part of the anterior lens capsule, careful extraction of the lens though an incision at the junction of the sclera and cornea and aspiration of the residual lens tissue. This technique preserves the posterior part of the capsule and equatorial zonular attachment which facilitates superior anatomical location of the implanted intraocular lens. (Asbell et al., 2005)

Phacoemulsification is currently the procedure of choice for the surgical management of cataracts. First developed in 1967 by Kelman the procedure can be viewed as a form of extracapsular cataract surgery as it too leaves the posterior capsule and zonules intact. The main difference is that instead of extracting the entire lens through a relatively large limbal incision (between the sclera and cornea) approximately 11 mm wide, a much smaller, approximately 2-3 mm incision is made in the periphery of the cornea. (Asbell et al., 2005) Then, the crystalline lens is uncovered by precisely tearing an operculum in the anterior surface of the capsule using a forceps to apply an angular shear force. This procedure is called capsulorhexis (Asbell et al., 2005).

An ultrasonic probe (a phaco probe) is inserted and used to emulsify the lens nucleus through the high frequency vibrations of its metal tip and simultaneously aspirate the resulting fragments. Using a blunt cannula, the operator removes the remaining lens cortex adhering to the capsule. Finally, the intraocular replacement lens is inserted in a folded state and unfolded into place. The preservation of a fully intact posterior capsule is the critical quality factor of the surgery procedure (Asbell et al., 2005; Söderberg et al., 2011).

Cataract surgery has for many years been the most common surgical procedure in Sweden as well as in many developed countries. Over 99% of cataract operations Sweden today are performed using the well-established phacoemulsification technique.(Behndig et al., 2020)

Despite there being no complications reported in over 95% of the cataract surgeries performed in well developed countries, the procedure is of course not exempt from errors. The most common intra-operative complication is posterior capsular rupture with rates varying between less than one per cent and 4.1 per cent in most institutions. (Behndig et al., 2020) (Chan et al., 2010). This further consolidates an intact posterior capsule as the hallmark of well performed cataract surgery. This becomes even more apparent as one evaluates the performance of surgeons in the beginning of their career. The rates of capsular ruptures for surgeons in training has been reported to vary between 5-20% during their first 200 cases (Cruz et al., 1992; Robin et al., 1997; Tarbet et al., 1995) despite teacher intensive training.(Randleman, 2007; Thomas et al., 1994).

One study has found that the major obstacle in the residents’ exponential learning curve of phacoemulsification surgery is nucleus disassembly with the majority of intra-operative complications occurred at level of capsulorhexis and cortical removal steps.(Al-Jindan et al., 2020)

It has been reported among experienced surgeons that the rate of complications decreased exponentially reaching an asymptote after 400(Ng et al., 1998) or even 1000 cases(Martin & Burton, 2000).

A substantial amount of research suggests that motor skill or the performance of a certain task increases from an initially low level towards a high level asymptote while at the same time the rate of mistakes or erroneous movements decreases from an initially high level towards a low level asymptote(Spruit et al., 2014). Additionally, research suggests that actively engaging simulation games are a more effective form of teaching than a more passive instructional method (Sitzmann, 2011).

Science is advancing at a breakneck speed, especially in the field of information technology (IT). The evolution of processors has been following Moor's Law for more than 50 years now which has given us countless marvels of technology (Mack, 2011). One such marvel is the personal computer which is in current times more than capable of complex virtual reality simulations at an affordable price and convenient size (Khor et al., 2016). Virtual reality training simulators have been developed for a multitude of surgical procedures, including cataract surgery (Söderberg et al., 2011), laparoscopic surgery (Gurusamy et al., 2009), robotic surgery (Bric et al., 2016), orthopedic surgery (Aïm et al., 2016), and endoscopic surgery (Kühnapfel et al., 2000) to name a few. Additionally, a Cochrane review has found that virtual reality training is a welcome supplement to standard laparoscopic surgical training of apprenticeship and is at least as effective as video trainer training in aiding standard laparoscopic training (Gurusamy et al., 2009).

Prof. Söderberg's research team at Uppsala University together with Melerit AB, a Linköping-based Swedish medical technology company have developed a cataract phacoemulsification surgery simulator, PhacoVision® (Laurell et al., 2004; Söderberg et al., 2002). The PhacoVision® simulator consists of a trainee interface and an observer interface both connected to a powerful personal computer running the bespoke simulation software.

Previous studies conducted with the simulator have established with the help of experienced surgeons that the simulator authentically emulates cataract surgery (Söderberg et al., 2005). Relevant response variables to be measured during the simulations have been identified (Söderberg et al., 2006) and based on these selected variables a performance index was defined in order to reliably and objectively measure the progress of the trainees (Söderberg et al., 2007). Furthermore, the studies previously conducted measured the performance increase over a short period of time (a few days) and have not observed the formation of a high level asymptote, indicating that the trainees had not yet reached their full potential (Söderberg et al., 2011).

The aim of the current study is to evaluate the performance increase in trainees familiar with the anatomy and physiology of the eye, but naïve to cataract surgery, over the course of 40 simulations spanning at least 10 days. We are interested in whether a high-level asymptote will be observed in the participants performance index indicating that they are nearing their full potential of improvement using the simulator. We also aim to investigate which phase of the operation is more difficult between the sculpting plus capsulorhexis and evacuation phase and also whether any of the different parts of the procedure appear to be more difficult than the others.

2 METHODS

2.1 Study participants and recruitment

The study participants were 10 medical students from Uppsala University. Seven of them had recently undergone their clinical rotations in Ophthalmology while the remaining 3 had only undergone theoretical studies in Ophthalmology. They were recruited during the winter and spring of 2021 via an announcement on a social media message board for medical students in Uppsala. The announcement described the study, the level of engagement and preexisting knowledge required and explicitly stated that there will be no reimbursement for participation.

The participants were admitted to the study after an initial physical meeting with the study leader. The meeting consists of a standardized power-point presentation regarding cataract as a disease, cataract surgery and the study lay-out after which the participant reviews and signs a written consent form if they choose to partake in the study.

The criteria required for admission to the study were theoretical knowledge of the anatomy and physiology of the eye, no previous firsthand experience in microscope surgery, especially cataract surgery and agreement to the terms of the study. Experience with commercial virtual reality headsets was not a criterion but was inquired. None of the participants had had more than anecdotal experience with such headsets.

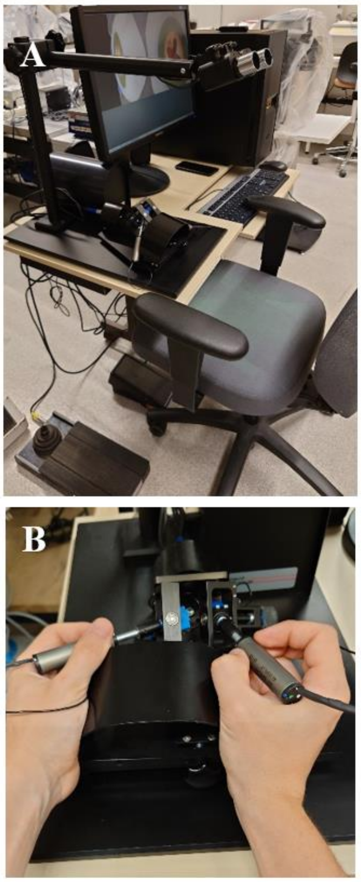
2.2 The simulator

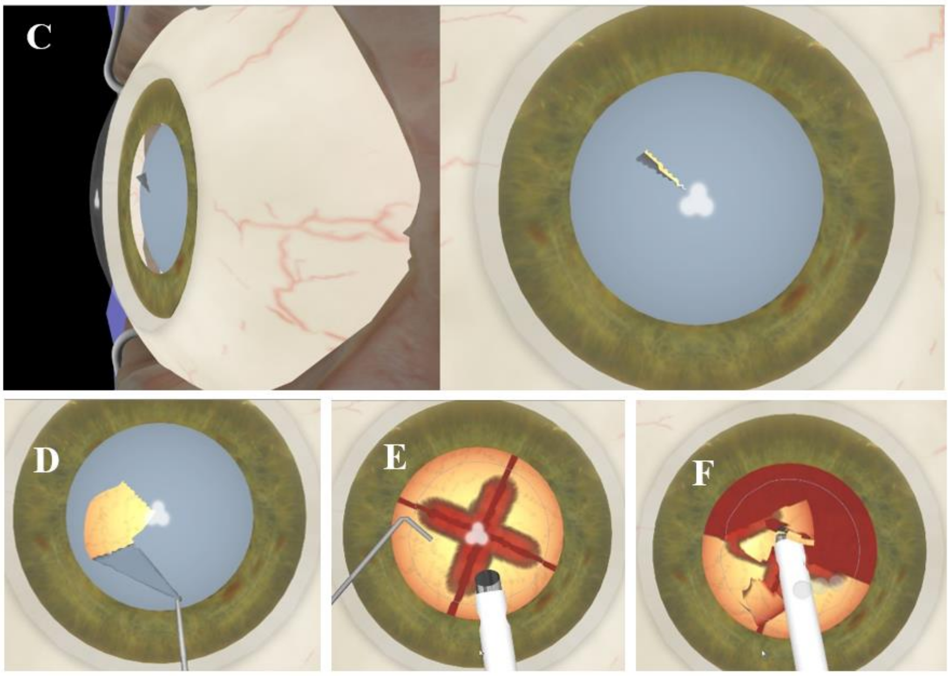
The simulator used in this study is the latest version of the PhacoVision® simulator, developed by Melerit AB, a Linköping-based Swedish medical technology company (Figure 1). It consists of a trainee interface and an administrator interface, both connected to a personal computer running the simulation software.

The trainee provides input to the simulator through a phacoemulsification/forceps handpiece, a lens manipulator handpiece, a commercial microscope pedal capable of moving the visual field in the x and y directions, zoom in and out and adjust focus and a phacoemulsification pedal which triggers irrigation in its first position, adds suction in its second position and further adds ultrasound energy in its third and final position. The trainee receives output from the simulator in real-time through two organic light emitting diode (OLED) screens housed in the two eye pieces of a mock microscope. This provides stereoscopic sight enabling better depth perception. Additional output is received audibly through two speakers and informs the trainee when the phaco probe is in irrigation, suction, and emulsification mode respectively and when damage is being done to the cornea, iris, or posterior capsule by the operator.

The administrator interface consists of a screen with two separate views of the operation field. One that is identical to the trainee view and one that is a profile view, slightly from the side, giving the administrator a better depth perception.

Figure 1





A. The simulator with the pedals underneath the table, the hand instruments, the microscope oculars, the screen for the administrator interface and a computer running the simulation and registering the results **B.** Detailed view of the hand instruments. The black arched metal piece on which the trainee is resting his hands represents the patient's forehead **C.** The simulation start point seen from the administrator perspective **D.** Capsulorhexis seen from the trainee perspective **E.** Cataract lens sculpted and cracked into four quadrants **F.** Evacuation of the cataract lens

Additionally, the administrator can set the patient and operation parameters (Table 1). These range from the size and characteristics of anatomical structures and instruments, the frequency, speed, and scope of the patient's movements to the incidence and number of bubbles created by the phaco probe.

Table 1. Table demonstrating the patient and operation parameters used in the simulator during this study

Patient parameter	Setting
Nucleus hardness (0-1)	0.65
Nucleus angular speed when dialled (degree/s)	1
Distance Tip – Irrigation port centre (0.5-4.0)	2
Bubles on/off (1=on, 0=off)	1
Average incidence of occurrence of bubbles (bubbles/min)	1
Average number of bubbles per group (bubbles/group)	3
Patient movement on/off (1=on, 0=off)	1
Average frequency of x-y patient field drift (times/min)	4
Maximum velocity for x-y patient field drift (mm/s)	2
Maximum x-y patient field drift (mm)	3
Maximum allowed x-y stretching of the zonulae	2
Maximum allowed z stretching of the zonulae at z before lost lens (mm)	2.5
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

2.3 Procedure and design

The study employed a longitudinal descriptive design. The virtual reality simulation procedure is divided into an initial sculpting phase and a subsequent evacuation phase. The sculpting phase begins with a preexisting corneal incision and an intact anterior capsule, stained blue. The trainee has a forceps in their dominant hand with which they perform capsulorhexis. After a completed capsulorhexis the administrator advances the simulation manually, switching the instruments in the trainee’s hands to a phaco probe in the dominant hand and a lens manipulator in the other hand. The trainee then proceeds to sculpt and crack the lens following a *divide and conquer* technique (Gimbel, 1991), whereby the trainee sculpts 2 ridges perpendicular to each other (effectively forming a “+“ sign) and subsequently cracks the lens across the ridges to obtain 4 individual quadrants.

At this point the administrator further advances the simulation manually, switching from the sculpting phase to the evacuation phase. The 4 lens quadrants obtained by the trainee are replaced with 4 standardized, pre-loaded quadrants. This swap is done to isolate the evacuation phase from the sculpting phase. Thus, the evacuation skill improvement is measured independently from the sculpting skill improvement as each evacuation phase for all the study participants started with the same computer-generated quadrants.

During the evacuation phase the trainee emulsifies and evacuates each quadrant individually. When there are no lens remnants left in the capsule, the simulation is manually terminated by the administrator.

Each of the 10 study participants underwent the study protocol outlined in Figure 2.

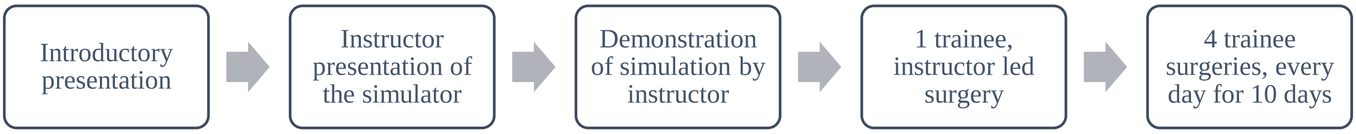


Figure 2. **Introductory presentation** detailing the study design, relevant anatomy, physiology, and pathology. **Instructor presentation of the simulator** covering the different parts of the simulator and their function. **Demonstration of simulation by instructor** covering each step of the simulation, demonstration of all the possible inputs and outputs of the simulator and valuable pointers and guidelines for a successful simulation. **1 trainee, instructor led surgery,** the trainee performs a surgery simulation, from start to finish, under close guidance and active feedback from the instructor. The surgery is paused at many stages to explain concepts and adequate procedure. The trainee is given the opportunity to experience all the possible outputs from the simulator, including damaging structures. The data from this stage is not registered. **4 trainee surgeries, every day for 10 consecutive days** under supervision of the instructor, however with minimal active feedback and opportunity to self-evaluate after the simulations by looking at the measured variables. A maximum total pause of 2 days was tolerated during the 10-day period.

2.4 Variables measured

The sculpting phase and the evacuation phase were evaluated separately. Totally 33 variables were measured for the sculpting phase and 31 variables for the evacuation phase. The reference value for each variable was obtained by averaging 10 consecutive values obtained by the instructor, who had previously performed more than 100 simulations and received continuous feedback from a MD PhD in Ophthalmology with detailed knowledge about the simulator (Table 2).

Table 2 showing and describing all parameters measured by the simulator. The variables are divided into

Parameter No.	Parameter name	Description	Reference values	
			sculpting phase	evacuation phase
Class 1. Overall Procedure				
1	Total Procedure Time	Total Time (s)	239.75	125.52
2	Capsulorhexis Time (s)	Time of capsulorhexis	41.65	N/A
3	Sculpting Time	Time with phaco mode sculpting on (s)	66.48	N/A
4	Evacuation Time	Time with phaco mode evacuation on (s)	N/A	75.72
5	Phaco Energy Used	Time integrated phacoemulsification power (mJ)	0.14	0.83
Class 2. Foot Pedal Technique				
6	PhacoPedalOff Defocus Time	Time of phacoemulsification foot pedal in position 0 (no irrigation, no aspiration, no phacoemulsification) and simultaneous phaco tip outside focus (s)	0	0
7	Irr Defocus Time	Time of phacoemulsification foot pedal in position 1 (irrigation mode) and simultaneous phaco tip outside focus (s)	0	0
8	AspIrr Defocus Time	Time of phacoemulsification foot pedal in position 2 (irrigation and aspiration) and simultaneous phaco tip outside focus (s)	0	0
9	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)	0	N/A
10	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)	N/A	0
11	Decentration Surgical Field	Time worked outside the optimal working viewing field (s)	20.87	5.46
Class 3. Phacoemulsification Technique				
12	Phaco Path Total	Total path traversed with the phacoemulsification handpiece tip (mm)	403.19	155.75
13	Phaco Path X	Path traversed with the phacoemulsification handpiece tip in X direction (mm)	110.32	65.23
14	Phaco Path Y	Path traversed with the phacoemulsification handpiece tip in Y direction (mm)	309.67	93.71
15	Phaco Path Z	Path traversed with the phacoemulsification handpiece tip in Z direction (mm)	156.77	63.12
16	Manipulator Path Total	Total path traversed with the nucleus manipulator tip (mm)	233.84	22.50
17	Manipulator Path X	Path traversed with the nucleus manipulator tip in X direction (mm)	116.03	11.36
18	Manipulator Path Y	Path traversed with the nucleus manipulator tip in Y direction (mm)	148.82	9.99
19	Manipulator Path Z	Path traversed with the nucleus manipulator tip in Z direction (mm)	101.79	12.06
Class 4. Capsulorhexis Technique				
20	Capsulorhexis forceps path total	Total path traversed with the forceps (mm)	126.58	N/A
21	Capsulorhexis forceps path X	Path traversed with the forceps in X direction (mm)	58.37	N/A
22	Capsulorhexis forceps path Y	Path traversed with the forceps in Y direction (mm)	84.51	N/A
23	Capsulorhexis forceps path Z	Path traversed with the forceps in Z direction (mm)	42.36	N/A
Class 5. Erroneous Manipulation				
24	BubbleBlockingViewTime (s)	Time that more than 3 adjacent bubbles are present (s)	16.27	22.65
25	No Irrigation Time	Procedure Time with the phacoemulsification foot pedal left in position 0 (no irrigation, no aspiration, no phacoemulsification) (s)	157.32	31.32
26	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	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	0
28	LensRemnants (mm)3	Detects if there are lens remnants at the end of the phaco procedure	N/A	0
29	EvacuationLevelHighTime (s)	Time when evacuation takes place > 1 mm above the iris plane	N/A	11.42
30	EvacuationLevelLowTime (s)	Time when evacuation takes place > 1 mm below the iris plane	N/A	37.15
Class 6. Damage to Ocular Structures				
31	FragmentCorneaTouchTime (s)	Time when lens fragment is in contact with cornea and the phacoemulsification tip simultaneously (s)	0	0
32	Phaco Cornea Touch Time	Time when phacoemulsification handpiece tip is in contact with corneal endothelium in any phacoemulsification foot pedal position (s)	0	0
33	Phaco Cornea Touch Energy On Time	Time that the phacoemulsification tip is in touch with the cornea and ultrasound energy is on (s)	0	0
34	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	0
Class 7. Damage to the Capsule				
35	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)	1.24	0
36	Phaco Beyond Posterior Capsule Time	Time with the phacoemulsification tip behind the posterior capsule (s)	0	0
37	Manipulator Beyond Posterior Capsule Time	Time with the nucleus manipulator tip behind the posterior capsule (s)	0	0
38	Zonula Stretch	Stretching of the zonulae (mm)	22.60	10.67

2.5 Data analysis

2.5.1 Performance index

Individual variable specific performance index

For each individual *i*, and each variable *j*, the *individual variable specific performance index*, $IVPI_{ij}$ was calculated using Equation 1. Thus defined, the *IVPI* is equal to 1 if the measured value *P* is the same as the reference *RP* (Table 2). Further the *IVPI* decreases if the measured value is higher than the reference and it increases if the value is lower than the reference. All the variables measured (Table 2) indicate a higher skill the lower their numeric value is, i.e., faster time, fewer movements, less time spent in unfavorable operating circumstances and less damage. Conversely, the *IVPI* indicates a higher skill the higher its numeric value is.

Equation 1

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

Individual class specific performance index

The *individual class specific performance index*, $ICPI_{ic}$ for each individual *i,* and each class *c* is defined (Equation 2) as the average of the individual variable specific performance indices, *1,2 …m* within one class (Table 2).

Equation 2

$$ICPI_{ic} = \frac{IVPI_{i1} + IVPI_{i2} + \ldots + IVPI_{im}}{m}$$

Individual overall performance index

The *individual overall performance index*, $IOPI_i$ for each individual *i*, is defined (Equation 3) as the average of all the individual variable specific performance indices, *1,2 …n* (Table 2).

Equation 3

$$IOPI_i = \frac{IVPI_{i1} + IVPI_{i2} + \ldots + IVPI_{in}}{n}$$

2.5.2 Nonlinear regression

Equation 4 was used 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 40 simulations where $IOPI_{improvement}$ is the difference between $IOPI_{Max}$ and the $IOPI$ after just the first simulation, N_i is the simulation number (i = 1, 2…40) and k is the learning rate. The nonlinear regression model used is a 3-parameter asymptotic exponential model.

Equation 4

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

For the data sets for which the regression model fit, Spearman's ranked correlation analysis was performed in order to assess the level of correlation between the performance increase and number of simulations.

3 RESULTS

All the values obtained for the IOPI and ICPI were plotted on scatterplots as functions of the number of simulations performed. Using 3-parameter asymptotic exponential regression analysis a curve was fitted to the data. The curve was used to calculate an asymptote and in some cases the number of simulations required to obtain 90% of the asymptote.

If the data did not fit the regression model the results are presented and interpreted descriptively.

3.1 Study population

The study enrolled 10 subjects aged 23 to 27 years old. There was no drop out from the study.

Out of the 10 subjects 7 were male and 3 were female. The subjects were all medical students at Uppsala University. 7 of the 10 had completed clinical rotations in ophthalmology, while the remaining 3 had recently undergone theoretical studies in ophthalmology.

3.2 Sculpting phase including capsulorhexis

3.2.1 Individual Overall Performance Index

The variables with a reference value of 0 do not produce an IVPI using Equation 1 and are thus not included in the calculation of the IOPI for the sculpting phase.

All the study participants reached and consistently scored a variable value of 0 for all the variables with a reference value of 0 towards the end of their training.

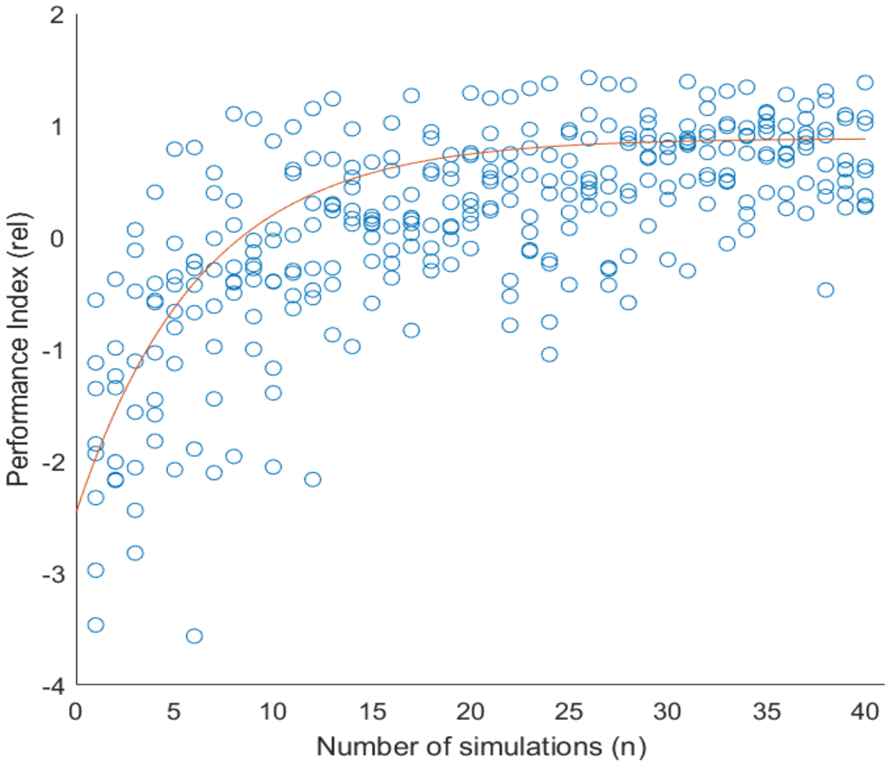


Figure 3. Scatterplot of the Individual Overall Performance index for the sculpting phase plotted as a function of the number of simulations. Red line shows best fitting to the data through 3-parameter asymptotic exponential model.

The level of the asymptote of the IOPI and the number of simulations needed to reach 90% of the asymptote for each subject are detailed in Table 3.

Table 3 The 95% CI for mean of IOPI asymptote and number of simulations needed to reach 90% of asymptote at each subjects included

Subject number	**Max IOPI (Asymptote) [95% CI]**	**Number of simulations to reach 90% of asymptote [95% CI]**
1.	1.18 [0.31, 2.06]	64 [22, 98]
2.	0.76 [0.44, 1.07]	28 [20, 35]
3.	0.44 [0.23, 0.60]	11 [7, 17]
4.	0.53 [0.07, 0.99]	26 [15, 35]
7.	0.65 [0.45, 0.85]	19 [10, 29]
8.	1.26 [-1.17, 3.68]	90 [20. 184]
9.	1.12 [0.57, 1.66]	53 [31, 79]
10.	1.15 [1.07, 1.23]	8 [6, 10]
Mean	**0.88 [0.24, 1.52]**	**37 [16, 61]**

The estimated asymptote level was 0.88; 95% CI [0.24, 1.52] and number of simulations to reach 90% of asymptote was 37; 95% CI [16, 61].

Spearman's correlation analysis revealed a moderately strong correlation coefficient of 0.65, P<.001.

The IOPIs as a function of the number of simulations for subjects number 5 and 6 is shown in Figure 4. The data from these subjects did not fit the regression model. They were not included in the regression analysis presented in Figure 3. Review of their data suggests that subject number 6 is a *non-learner* as they do not improve significantly during training and subject number 5 is a *slow learner* as they have not yet started a plateau after 40 simulations.

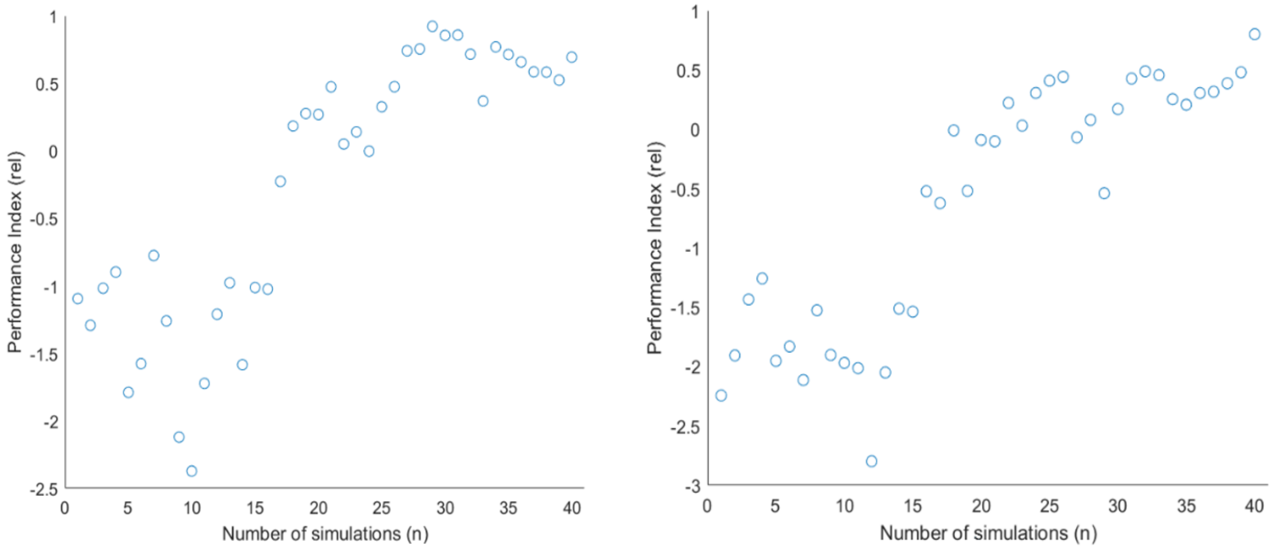


Figure 4. Scatterplot of the Individual Overall Performance index the sculpting for phase as a function of the number of simulations for subjects number 5 (left plot) and 6 (right plot).

3.2.2 Individual class specific performance index

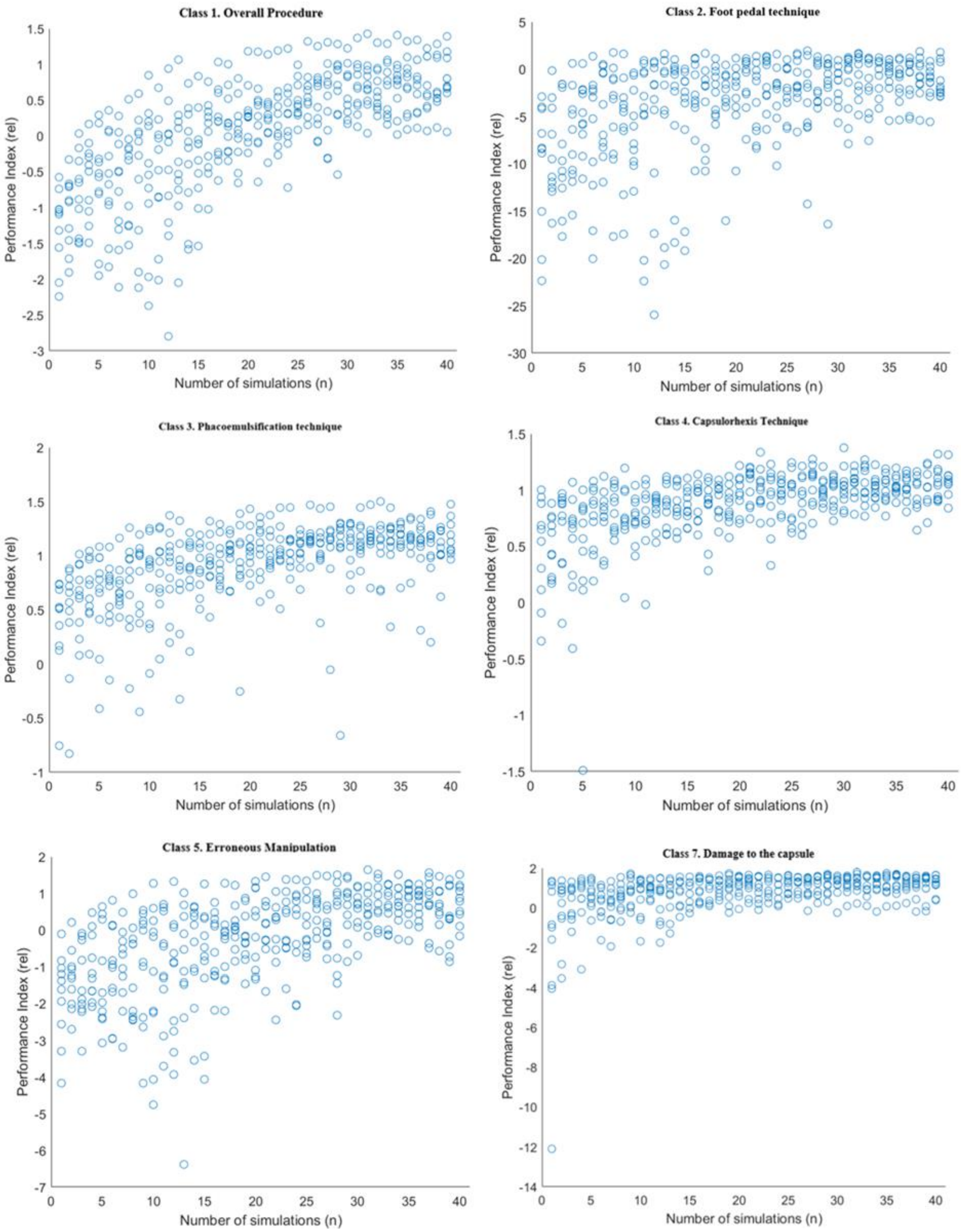


Figure 5. Scatterplot of the ICPI for the sculpting phase as a function of the number of simulations for each class in the sculpting phase.

The variables with a reference value of 0 do not produce an IVPI using Equation 1 and are thus not included in the calculation of the ICPI for the sculpting phase. All the variables in Class 6 had a reference value of 0 thus resulting in no ICPI for the class. All the study participants reached and consistently scored a variable value of 0 for all the variables with a reference value of 0 towards the end of their training.

Review of the data presented in Figure 5 shows that for Class 2, Class 4, and Class 7 the participants reached values of ICPI equal to 1 i.e., as good as the reference, virtually from the beginning of the study. Class 3 and Class 5 show some level of improvement, but the participants reached ICPIs of 1 and plateaued within their first 10 simulations while at the same time starting with high values. This indicates that these classes have a low level of difficulty as measured with the present performance index.

Class 1 shows a trend resembling the IOPI for the sculpting phase with almost all participants starting with lower values and trending upwards with the number of simulations and reaching a plateau at around an ICPI value of 1. This indicates that Class 1 has a higher level of difficulty as measured with the present performance index.

3.2.3 Capsular damage

The IVPI for capsular damage had a reference value of 0, hence produced no value. In order to assess this important variable, the incidence between the first 10 and last 10 surgeries was compared. The first 10 surgeries had an average incidence of capsular damage of 30%. The last 10 surgeries had an average incidence of capsular damage of 9%.

3.3 Evacuation phase

3.3.1 Individual Overall Performance Index

The variables with a reference value of 0 do not produce an IVPI using Equation 1 and are thus not included in the calculation of the IOPI for the evacuation phase. All the study participants reached and consistently scored a variable value of 0 for all the variables with a reference value of 0 towards the end of their training.

The individual overall performance index for the evacuation phase is illustrated in Figure 6 and further elaborated on in Figure 7 and Table 4.

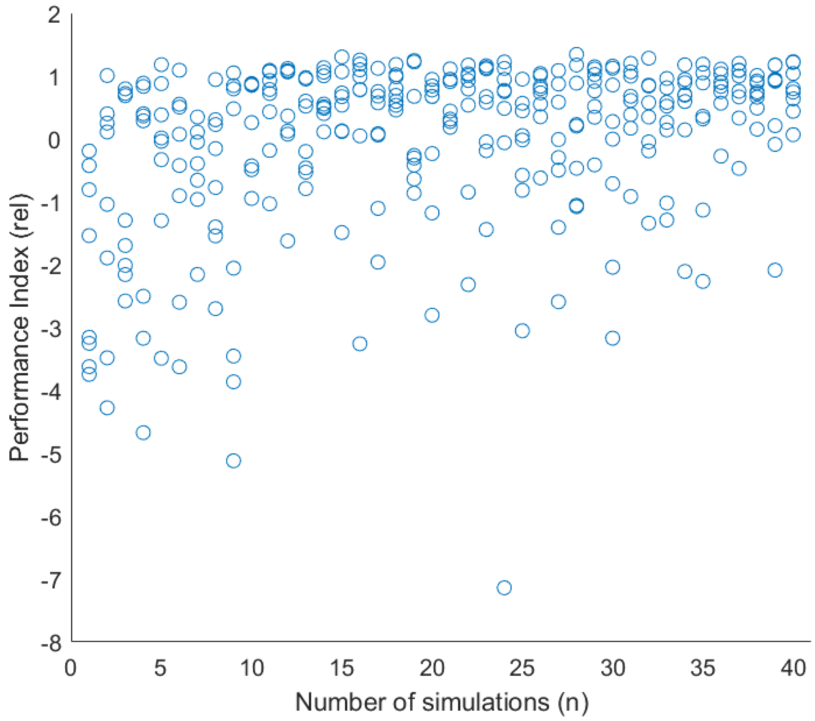


Figure 6. Scatterplot of the individual overall performance index for the evacuation phase plotted as a function of the number of simulations.

Participants reached IOPI of 1 within their first 5 simulations and quickly plateaued. This indicates a low level of difficulty.

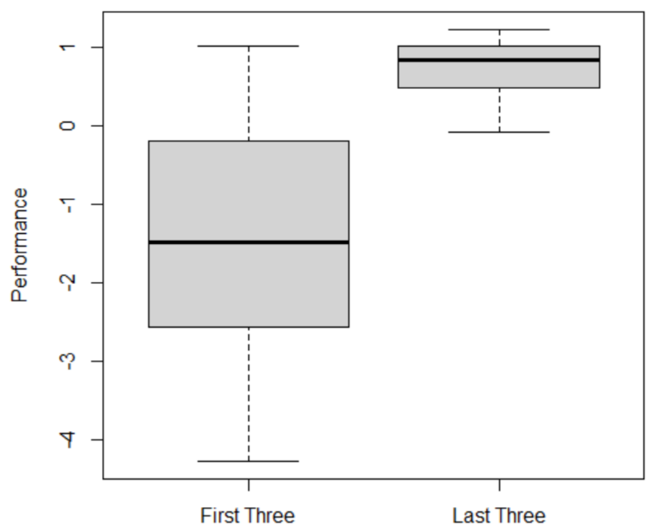


Figure 7. Boxplot ilustrating the mean IOPI for the evacuation phase for the first three simulations and last three simulations for all the study participants.

Table 4		
	First Three	**Last Three**
Mean	-1.49	0.75
Median	-1.49	0.85
IQR	2.21	0.49
SD	1.50	0.36
Min	-4.27	-0.08
Max	1.01	1.23

Table 4 presenting the mean, median, interquartile range, standard deviation, min-, and max-values of IOPI for the evacuation phase for the first three simulations and last three simulations for all the study participants.

3.3.2 Individual class specific performance index

The variables with a reference value of 0 do not produce an IVPI using Equation 1 and are thus not included in the calculation of the ICPI for the evacuation phase. All the variables in Class 6 had a reference value of 0 thus resulting in no ICPI for the class. All the variables in Class 4 (capsulorhexis) are only applicable in the sculpting phase and thus produce no ICPI for the evacuation phase.

All the study participants reached and consistently scored a variable value of 0 for all the variables with a reference value of 0 towards the end of their training.

Review of the data shows that for all the classes during the evacuation phase the participants reached values of ICPI equal to 1 i.e., as good as the reference, and reached a plateau virtually from the beginning of the study. This indicates that the evacuation phase has a low level of difficulty.

4 DISCUSSION

The aim of the current study was to evaluate the performance increase in trainees familiar with the anatomy and physiology of the eye, but naïve to cataract surgery, over the course of 40 simulations spanning at least 10 days. We were interested in whether a high-level asymptote will be observed in the participants performance index indicating that they are nearing their full potential of improvement using the simulator. We also aimed to investigate which phase of the operation is more difficult between the sculpting plus capsulorhexis and evacuation phase and also whether any of the different parts of the procedure appear to be more difficult than the others.

The study design and simulator parameters were accordingly adjusted to our aims.
The sculpting plus capsulorhexis and evacuating phases were measured independently. Furthermore, each evacuation phase started with a pre-loaded cracked lens in order to avoid any of the performance from the first phase carrying over to the second. On one hand this makes it more difficult to assess a trainee's overall performance for an entire cataract surgery, which would be closer to a real-world setting. On the other hand, it provides valuable insight into which part of the surgery is more difficult which arguably more important during training than an overall performance score as it enables more effective training, focusing on the more demanding procedures while not wasting time and energy developing already acquired skills.

The daily number of simulations was set to 4 based on previous experience from training with the PhacoVision® simulator suggesting that muscle and mental fatigue set in quickly especially in beginner trainees. One could argue that a more experienced trainee could easily do more than 4 simulations per day in order to further accelerate their skill increase, however this aspect is mostly negligible in the first 10 days of training. For a more long-term solution one could maybe adopt a time-based training schedule, for example, 2 hours every day.

The study length was limited to 10 days partly for practical reasons. Naturally, a longer study duration would elicit more representative data, especially since, as previously stated, cataract surgeons require years to reach their full potential. However, the trend observed in our data clearly suggests a plateau forming during the first 40 operations. This is most likely due to the lack of complexity in the simulator when compared to real cataract surgery, which was fully expected, though one could argue that another contributing factor was the lack of inter-patient variation. The patient parameters were carefully selected to balance the difficulty between the sculpting and evacuation phases while at the same time requiring a relatively high level of skill to perform flawlessly. Every simulation was performed on the same patient parameters, i.e., ocular size, spontaneous eye movements, lens hardness, bubbles formation rate and zonular strength (Table 1). This consistency is a prerequisite in the current study design; however, one could argue that it hinders the full potential of the simulator as a vital part of being a surgeon is the ability to adapt to the patient’s anatomy.

The current findings suggest that trainee overall performance index during the sculpting phase increases as a function of the number of simulations, following an exponential function with a high-level asymptote close to the reference value of 1 (Figure 3). The calculated Spearman’s correlation coefficient indicates that there is a moderately strong positive correlation between the overall performance and the number of performed simulations.

The two outliers, subject 5 and subject 6 behaved in a different manor to the other participants. Subject 6 appears to be a non-learner as the data suggests no significant improvement during the 40 simulations of the study. Looking at the data however one could argue that Subject 6 had an initial decrease in performance during the first 15 simulations only to reverse the trend and improve after that. This could be caused by a more explorative behavior innate to Subject 6 i.e., testing out alternative techniques, hand placements, microscope settings, et cetera, in the beginning of the study in order to familiarize oneself with the simulator and operation. This is however unlikely as the supervisor instructed all participants to follow the same procedure protocol and oversaw all simulations. A more likely explanation would be a lack of knowledge and/or interest in the task at hand, at least in the beginning. A nonnegligible risk with a VR-simulator training in the medical field is that the training is not taken as seriously as a real operation and is treated more akin to a video game. The subjects were instructed to treat the simulations as if it were a real operation however such a level of seriousness and dedication is not easily achieved and is perhaps not to be expected from all participants.

Subject 5 appears to be a slow learner as the data does not suggest that a plateau is being reached during the 40 simulations of the study. Examining the data however one could argue that the subject has reached an IOPI of 1 and is starting to consistently score an IOPI of between 0 and 1 during the last 10 simulations, indicating that the subject would most likely start to plateau decisively had the training continued. The same reasons for the lack of improvement presented for Subject 6 are likely explanations to the slow increase in IOPI of Subject 5. One could however also argue that for example a higher degree of cautiousness or a natural variation in the rate of motor-skill improvement could explain the slow improvement of Subject 5.

The class specific performance indexes for the sculpting phase showed a low level of difficulty for Class 2, Class 4, and Class 7 and a slightly higher level of difficulty for Class 3 and Class 5. The data further suggested an even higher level of difficulty for Class 1. The discrepancy in the performance increase of different classes can be partly attributed to an actual difference in difficulty, especially between Class 1, 3 and 4. The data clearly suggests that it is more difficult to perform capsulorhexis and sculpting in a shorter amount of time than it is to perform it with less movement of the instruments. This also reflects that the study participants showed cautiousness electing to perform the task in a slower manor in the begging while at the same time avoiding making unnecessary movements over the entirety of the 40 simulations.

Class 2, 5 and 7 were greatly impacted by the lack of IVPIs due to a reference value equal to 0. However as previously stated, all the study participants reached and consistently scored a variable value of 0 for all the variables with a reference value of 0 towards the end of their training. This indicates that these classes might have a lower level of difficulty or rather that the performance increase could be better described by a decrease in the incidence of negative events with an increasing number of performed simulations.

The trainee overall performance index increase during the evacuation phase appears to be less pronounced. The data did not fit the regression model as the participants quickly reached an IOPI of 1 and plateaued. There is however a clear trend towards less variation and better performance from the beginning of the training towards the end, exemplified by Figure 7 and Table 4. This finding could be a consequence of the evacuation phase being generally less technically demanding but more prone to random spikes in difficulty. During evacuation, fragments have a tendency to fall apart while being emulsified thus producing smaller fragments which are prone to being propelled in a random direction. If such a fragment gets stuck behind the iris or under the corneal incision the trainee is suddenly presented with a daunting task namely, a *rogue* fragment. An experienced surgeon would have no problem in such a situation, but the trainees faced a steep learning curve. As these situations arose randomly, the rate at which the trainees got better at dealing with them also varied significantly. The nature of the evacuation phase is therefore such that some trainees were able to perform as well as or even better than the reference from their first simulation while also performing much worse on their 30th or even 40th due to a *rogue* fragment lodged behind the iris. Figure 7 and Table 4 shows however that towards their last operations the trainees had developed enough skill and technique to better avoid creating such fragments and to deal with them in a faster and safer manor.

The class specific performance indexes for the evacuation phase showed that all participants reached values of ICPI equal to 1 i.e., as good as the reference, and reached a plateau virtually from the beginning of the study. This indicates that the evacuation phase has a low level of difficulty. This is in line with the what the IOPI data for the evacuation phase suggests, i.e., that the evacuation phase is generally less demanding, and that the performance increase is better reflected by increased consistency in values around the reference.

The fact that Equation 1 could not produce a performance index for the variables with a reference value of 0 negatively affected the ability to draw conclusions from the data. Important variables such as variables 36 and 37, indicating damage to the posterior capsule by the phaco probe or the manipulator, respectively were therefore not taken into account by the performance indexes. To compensate for this, the incidence of capsular damage was calculated for the first 10 and final 10 surgeries. This revealed a clear trend towards a lower incidence of capsular damage. The calculated incidence of 9% for the last 10 surgeries is in line with what was previously observed in cataract surgery aspiring residents (5-20%)(Cruz et al., 1992; Robin et al., 1997; Tarbet et al., 1995).

On one hand the current data points to a high-level asymptote manifesting itself around the 40 simulations performed by the trainees. On the other hand, considering the number of variables that were not taken into account for the calculation of the performance indexes one is inclined to think that the current data does not suffice to conclusively establish the number of simulations needed in order to truly reach 90% of the of the overall performance index asymptote. One needn't look further than the incidence of capsular rupture in order to ascertain that there is a ways to go until the trainees would reach rates of under 1% which is what is achieved and expected in modern cataract surgery centers (Behndig et al., 2020).

Anecdotal evidence from the reference trainee suggests that meaningful improvement can be achieved even after approximately 100 simulations, which is not at all surprising considering that surgeons have been shown to reach an asymptote in complications after as many as 1000 cases(Martin & Burton, 2000). Furthermore, the ability to freely control the simulation, repeat certain small steps on demand and adjust the patient parameters on the fly are extremely valuable tools, unique to a VR-simulator, that the trainees did not have access to.

5 CONCLUSIONS

We successfully evaluated the performance increase in trainees familiar with the anatomy and physiology of the eye, but naïve to cataract surgery and showed that a high-level asymptote does form for the sculpting plus capsulorhexis phase. This indicates that the trainees were nearing their full potential at performing the simulation. However, with many demanding variables not fully taken into account, e.g., capsular damage, the trainees might still have a great deal to learn from training with the simulator.

The data suggests that evacuation is generally less difficult than sculpting plus capsulorhexis as trainees reached performance index values of 1 for the evacuation phase very early on in the study. The evacuation phase does however provide a challenge in the form of spontaneous and significant increases in difficulty due to rogue fragments. Review of the class specific performance indexes for the sculpting phase suggests that performing a task in a shorter amount of time is more difficult than performing it in less movements, especially when there is a strong motivation to avoid erroneous maneuvers.

Extensive research (Gurusamy et al., 2009) has showed that virtual reality simulators can already be a valuable and cost effective tool in training aspiring surgeons. With advancing technique, declining costs of technology and increasing demand for high quality surgery, VR-simulators are likely set to become the golden standard in surgical training.

A further adapted performance index, which can take into account variables for which the reference value is 0, reflect a decrease in the incidence of negative events with an increasing number of performed simulations and perhaps even assign different weights to different parameters would serve to further uncover the full potential of the PhacoVision® VR-simulator.

As it stands today the PhacoVision® simulator, despite still being in a development stage, is a sophisticated tool which can serve to prepare aspiring cataract surgeons for the minute scale, intense focus required and massive learning curve of the most common surgical procedure in the modernized world.

6 REFERENCES

Al-Jindan, M., Almarshood, A., Yassin, S. A., Alarfaj, K., Al Mahmood, A., & Sulaimani, N. M. (2020). <p>Assessment of Learning Curve in Phacoemulsification Surgery Among the Eastern Province Ophthalmology Program Residents</p>. *Clinical Ophthalmology*, *Volume 14*, 113-118. https://doi.org/10.2147/opth.s241250

Asbell, P. A., Dualan, I., Mindel, J., Brocks, D., Ahmad, M., & Epstein, S. (2005). Age-related cataract. *365*(9459), 599-609. https://doi.org/10.1016/s0140-6736(05)17911-2

Aïm, F., Lonjon, G., Hannouche, D., & Nizard, R. (2016). Effectiveness of Virtual Reality Training in Orthopaedic Surgery. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, *32*(1), 224-232. https://doi.org/10.1016/j.arthro.2015.07.023

Behndig, A., Lundström, M., Serring, I., Lindström, A., Montan, P., Kugelberg, M., . . . Zetterberg, M. (2020). Årsrapport 2019 baserad på data från Nationella Kataraktregistret. In. www.kataraktreg.se/.

Bric, J. D., Lumbard, D. C., Frelich, M. J., & Gould, J. C. (2016). Current state of virtual reality simulation in robotic surgery training: a review. *Surgical Endoscopy*, *30*(6), 2169-2178. https://doi.org/10.1007/s00464-015-4517-y

Chan, E., Mahroo, O. A. R., & Spalton, D. J. (2010). Complications of cataract surgery. *Clinical and Experimental Optometry*, *93*(6), 379-389. https://doi.org/10.1111/j.1444-0938.2010.00516.x

Cruz, O. A., Wallace, G. W., Gay, C. A., Matoba, A. Y., & Koch, D. D. (1992). Visual results and complications of phacoemulsification with intraocular lens implantation performed by ophthalmology residents. *Ophthalmology*, *99*(3), 448-452. https://doi.org/10.1016/s0161-6420(92)31954-2

Gimbel, H. V. (1991). Divide and conquer nucleofractis phacoemulsification: development and variations. *Journal of Cataract & Refractive Surgery*, *17*(3), 281-291.

Gurusamy, K. S., Aggarwal, R., Palanivelu, L., & Davidson, B. R. (2009). Virtual reality training for surgical trainees in laparoscopic surgery. *Cochrane database of systematic reviews*(1).

Jacobs, D. S., MD. (2021). *Cataract in adults*. Wolters Kluwer. Retrieved June 26 from

Khor, W. S., Baker, B., Amin, K., Chan, A., Patel, K., & Wong, J. (2016). Augmented and virtual reality in surgery—the digital surgical environment: applications, limitations and legal pitfalls. *Annals of Translational Medicine*, *4*(23), 454-454. https://doi.org/10.21037/atm.2016.12.23

Kühnapfel, U., Çakmak, H. K., & Maaß, H. (2000). Endoscopic surgery training using virtual reality and deformable tissue simulation. *Computers & Graphics*, *24*(5), 671-682. https://doi.org/10.1016/s0097-8493(00)00070-4

Laurell, C. G., Söderberg, P., Nordh, L., Skarman, E., & Nordqvist, P. (2004). Computer-simulated phacoemulsification. *Ophthalmology*, *111*(4), 693-698. https://doi.org/10.1016/j.ophtha.2003.06.023

Leffler, C. T., Klebanov, A., Samara, W. A., & Grzybowski, A. (2020). The history of cataract surgery: from couching to phacoemulsification. *Annals of Translational Medicine*, *8*(22), 1551-1551. https://doi.org/10.21037/atm-2019-rcs-04

Mack, C. A. (2011). Fifty Years of Moore's Law. *IEEE Transactions on Semiconductor Manufacturing*, *24*(2), 202-207. https://doi.org/10.1109/tsm.2010.2096437
Martin, K. R. G., & Burton, R. L. (2000). The phacoemulsification learning curve: Per-operative complications in the first 3000 cases of an experienced surgeon. *Eye*, *14*(2), 190-195. https://doi.org/10.1038/eye.2000.52
Ng, D. T., Rowe, N. A., Francis, I. C., Kappagoda, M. B., Haylen, M. J., Schumacher, R. S., . . . Lee, B. B. (1998). Intraoperative complications of 1000 phacoemulsification procedures: a prospective study. *J Cataract Refract Surg*, *24*(10), 1390-1395. https://doi.org/10.1016/s0886-3350(98)80235-6
Randleman, J. B. (2007). The Resident Surgeon Phacoemulsification Learning Curve. *Archives of Ophthalmology*, *125*(9), 1215. https://doi.org/10.1001/archopht.125.9.1215
Robin, A. L., Smith, S. D., Natchiar, G., Ramakrishnan, R., Srinivasan, M., Raheem, R., & Hecht, W. (1997). The initial complication rate of phacoemulsification in India. *Invest Ophthalmol Vis Sci*, *38*(11), 2331-2337.
Seddon, J., Fong, D., West, S. K., & Valmadrid, C. T. (1995). Epidemiology of risk factors for age-related cataract. *Survey of Ophthalmology*, *39*(4), 323-334. https://doi.org/10.1016/s0039-6257(05)80110-9
Sitzmann, T. (2011). A META-ANALYTIC EXAMINATION OF THE INSTRUCTIONAL EFFECTIVENESS OF COMPUTER-BASED SIMULATION GAMES. *Personnel Psychology*, *64*(2), 489-528. https://doi.org/10.1111/j.1744-6570.2011.01190.x
Spruit, E. N., Band, G. P. H., Hamming, J. F., & Ridderinkhof, K. R. (2014). Optimal training design for procedural motor skills: a review and application to laparoscopic surgery. *Psychological Research*, *78*(6), 878-891. https://doi.org/10.1007/s00426-013-0525-5
Steinmetz, J. D., Bourne, R. R. A., Briant, P. S., Flaxman, S. R., Taylor, H. R. B., Jonas, J. B., . . . Vos, T. (2021). Causes of blindness and vision impairment in 2020 and trends over 30 years, and prevalence of avoidable blindness in relation to VISION 2020: the Right to Sight: an analysis for the Global Burden of Disease Study. *The Lancet Global Health*, *9*(2), e144-e160. https://doi.org/10.1016/s2214-109x(20)30489-7
Söderberg, P., Erngrund, M., Skarman, E., Nordh, L., & Laurell, C.-G. (2011, 2011-02-10). VR-simulation cataract surgery in non-experienced trainees: evolution of surgical skill. Ophthalmic Technologies XXI,
Söderberg, P., Laurell, C.-G., Simawi, W., Nordqvist, P., Skarman, E., & Nordh, L. (2006). Evaluation of response variables in computer-simulated virtual cataract surgery. Ophthalmic Technologies XVI,
Söderberg, P., Laurell, C.-G., Simawi, W., Skarman, E., Nordqvist, P., & Nordh, L. (2007, 2007-02-08). Performance index for virtual reality phacoemulsification surgery. Ophthalmic Technologies XVII,
Söderberg, P. G., Laurell, C.-G., Artzén, D., Nordh, L., Skarman, E., Nordqvist, P., & Andersson, M. (2002). Computer-simulated phacoemulsification improvements. Ophthalmic Technologies XII,
Söderberg, P. G., Laurell, C.-G., Simawi, W., Nordqvist, P., Skarman, E., & Nordh, L. (2005). Virtual reality phacoemulsification: a comparison between skilled surgeons and students naive to cataract surgery. Ophthalmic Technologies XV,
Tarbet, K. J., Mamalis, N., Theurer, J., Jones, B. D., & Olson, R. J. (1995). Complications and results of phacoemulsification performed by residents. *J*

Cataract Refract Surg, *21*(6), 661-665. https://doi.org/10.1016/s0886-3350(13)80562-7
Thomas, R., Braganza, A., Raju, R., Lawrence, & Spitzer, K. H. (1994). Phacoemulsification--a senior surgeon's learning curve. *Ophthalmic Surg*, *25*(8), 504-509.