The effect of a distributed virtual reality simulation training program on dissection mastoidectomy performance

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Objective: To investigate the effect on final-product performance of a distributed, virtual reality (VR) simulation training program on cadaveric dissection performance and learning curves compared with standard VR simulation training during a temporal bone course.
Study Design: Educational interventional cohort study.
Setting: The national Danish temporal bone courses of 2016 and 2017.
Subjects: Post-graduate year 2–5 residents in otorhinolaryngology.
Intervention: Nine participants volunteered for additional VR simulation training (intervention) before the temporal bone course, with training blocks distributed (i.e. separated). The remaining 28 participants received standard VR simulation training during the temporal bone course (control).
Main Outcome Measure: VR simulation and cadaveric dissection final-product performances were analyzed by blinded raters using a 26-item modified Welling Scale.
Results: Distributed VR simulation training before the temporal bone course (intervention) significantly increased dissection final-product performance by 25 % compared with standard VR simulation training during the course (control) (mean scores 12.8 points vs. 10.3 points, $p<0.01$). Distributed and repeated VR simulation practice markedly decreased drilling time. Guidance by the simulator-integrated tutor-function significantly increased final-product performance by 2.3 points compared with non-tutored procedures but at the cost of increased drilling time.
Conclusion: Skills acquired in a VR simulation environment translates to cadaveric dissection skills and repeated and distributed VR simulation can be used to further increase performance compared with standard VR simulation training during a temporal bone course. Further dissemination of inexpensive VR simulators would allow all future temporal bone course participants to train locally before attending future centralized courses.

Introduction

Temporal bone surgical skills have traditionally been trained on human cadaveric temporal bones and while this is still considered gold-standard in training, the availability of human temporal bones, time for instruction and feedback by senior staff, and cost of maintaining appropriate facilities, have at many centers limited training opportunities for residents.[1] Initial temporal bone training before supervised surgery is therefore often restricted to temporal bone courses unless open lab facilities are available. This provides limited opportunity for the trainee to practice repeatedly to develop adequate and consolidated temporal bone skills, even though it is well-established that acquiring complex psychomotor skills such as technical surgical skills is dependent on consolidation of skills over time.[2]

New training resources such as physical models of the temporal bone of plaster or plastic, and virtual reality (VR) simulation of temporal bone surgery, have been developed to alleviate the limitations in training and provide opportunity for repeated practice. Several excellent VR temporal bone simulators are available[3–6] including academic freeware applications.[7,8] In the last decade, research on VR temporal bone surgical simulation has consistently demonstrated a positive effect on temporal bone skills and performance of novices.[9–11] In addition, high-quality evidence supports several reported assessment tools for valid competency assessment in mastoidectomy.[12–15] However, structured VR simulation training and assessment are rarely implemented into training programs.

A dose-response relationship between hours of simulation-based training and standardized learning outcomes has been demonstrated for a number of technical skills.[16] Studies on the learning curves of VR simulation training of the mastoidectomy procedure also demonstrate improved performance with increasing amounts of practice.[17,18] Furthermore, distribution of practice sessions in VR simulation training of mastoidectomy has been found to be superior to massed practice on both performance and retention of skills[17,19], in agreement with literature in the field of educational psychology. There is, however, still a gap in knowledge on the effect of repeated, distributed VR simulation training of the mastoidectomy procedure and transfer of skills to for example cadaveric dissection performance.

In this study, we therefore wanted to investigate the effect of a distributed VR simulation training program, with the hypothesis that this would lead to a significant improvement in final-product performance in subsequent cadaveric dissection mastoidectomy performance during a temporal bone course.

Material and methods

Setting and participants

17 and 20 otorhinolaryngology residents participated in the national temporal bone course at our institution in January 2016 and January 2017, respectively. Participation in the temporal bone course is a mandatory component of Danish otorhinolaryngology specialist training and each resident can participate only once. The residents were post-graduate year (PGY) 2–5 and had limited clinical experience with temporal bone surgery because the course is a prerequisite for supervised temporal bone surgery. Additionally, only a few residents had received temporal bone training at other temporal bone courses and none had performed real-life temporal bone surgery, and therefore, the participants were considered novices.

All course participants were invited for additional distributed VR simulation training (intervention) prior to the temporal bone course. Participants from both the eastern and western part of Denmark were invited but since the supplemental training was only offered at the Simulation Center as part of this study, and since no financial-, travel-, or time compensation was provided, only residents from the eastern part of the country accepted the invitation. A total of nine residents completed the distributed training program prior to the course. The remaining 28 residents agreed to serve as controls, receiving only standard VR simulation training offered during the course. All participants signed informed consent and completed a background questionnaire.

Study design

The study was a prospective, controlled study with structured, distributed VR simulation training during the 3-months period before the temporal bone course (intervention condition) for both cohorts. This was offered as a supplement to the standard three hours of VR simulation training during the course (control condition), which both intervention and control participants completed. All participants received 2 days of theoretical preparation before dissection during the 4-day temporal bone course. In all cases, VR simulation training preceded traditional cadaveric dissection training.

VR simulation platform

The Visible Ear Simulator, detailed in previous publications, is a freeware VR temporal bone surgical simulator featuring 3D stereo graphics and haptic interaction with force feedback for drilling using the Geomagic Touch (3D Systems, SC, USA). The simulator has an integrated step-by-step guide to mastoidectomy with text and images similar to a traditional dissection manual and it also features optional guidance by an integrated tutor-function that color-codes the volume to be drilled, in correspondence with the step-by-step guide. In this study, we used an experimental version of the Visible Ear Simulator version 2.0 that could save data from the virtual drillings.

VR simulation training

Participants in both the control and intervention groups were introduced to the VR simulator navigation and controls with a five-minute hands-on exercise before completing the first block of training.

For all participants, each block of training consisted of three identical procedures (anatomical mastoidectomy with posterior tympanotomy) on a single temporal bone model in the VR simulator (Flowchart, Fig. 1). Tutoring was controlled so the first procedure in each training block was guided by the color-coding tutor function (mandatory use) in addition to the step-by-step guide, and the following two procedures were guided only by the step-by-step guide. The VR simulation training followed the principles of directed, self-regulated learning (DSRL) and during the training, participants had access to technical assistance, but were provided with no structured feedback on performance.

The control group completed a single block of training during the temporal bone course, whereas the intervention group completed a total of six training blocks (Fig. 1) in a structured manner: five blocks during the three months immediately prior to the course in addition to a single block of training during the temporal bone course. Each of the training blocks were spaced by at least three days to ensure distribution of practice and training blocks were time limited to a maximum of three hours.

Cadaveric dissection training

The dissection training was performed on a fresh frozen, cadaveric, human head in a dissection tray shared between two participants, and with a setup consisting of an operating microscope, an otosurgical drill with various drill bits, and suction/irrigation. During cadaveric dissection training, all course participants were asked to perform an anatomical mastoidectomy with posterior tympanotomy identical to the procedure trained during simulation without feedback or guidance by faculty or peers. Participants were allowed to refer to a printed temporal bone dissection manual but were otherwise self-directed. Each participant was allowed one hour after which performance was evaluated before further dissection according to the course curriculum.

Outcome and statistics

The primary outcome was dissection final-product performance on a 26-item modified Welling Scale as described previously with binary rating of each item (0 for inadequate/incomplete and 1 for adequate/complete).[20] A sample-size calculation based on previous data suggested 16 participants would be needed in each arm to demonstrate a 10 % improvement in final-product score. Interim analysis after each course was planned a priori with termination of the study and reporting of data when difference in dissection performance was statistically significant with $p < 0.05$, which was after two temporal bone courses.

VR and dissection mastoidectomy final products were assessed: end-of-training VR simulation performances during the temporal bone course (corresponding to the 3rd procedure for the control group and 18th procedure for the intervention group) were assessed by two expert raters (SA and MS) blinded to participant, group, procedure number and cohort for comparison between the control and intervention groups, in addition to all pre-course training performances of the intervention group to establish the learning curves of repeated practice. Cadaveric dissection final products were assessed by three expert raters blinded to participant and group (SF, PC and MS).

Data were analyzed in SPSS (SPSS Inc., IL, USA) version 23 for MacOS X. The effect of the intervention was analyzed using linear mixed models with group (intervention and control) and rater as fixed factors, in addition to specimen as a random effect in cadaveric dissection (because two participants shared a cadaveric head). Likewise, for the effect of simulator-integrated tutoring in the repeated VR simulation practice (intervention group), a linear mixed model analysis was performed with procedure number, tutoring, and rater, as fixed factors.

Ethics

The regional ethics committee for the Capital Region of Denmark deemed this study to be exempt (H-15011780).

Results

Overall, the 2016 and 2017 cohorts had similar background characteristics (age, sex, years of training, participation in other temporal bone courses, experience with the Visible Ear Simulator, average computer usage outside work, self-rated computer skills, and gaming frequency) as did participants in the intervention and control groups. (Table I). 4 participants of the total 17 participants (24 %) in 2016 and 5 out of the total 20 participants (25 %) in 2017 volunteered for the pre-course intervention training program.

A boxplot of the final-product performance scores in cadaveric dissection and VR simulation training is presented in Fig. 2. Unsurprisingly, more training in the VR simulator led to a better end-of-training simulation performance (Table II). More importantly, the intervention group performed significantly better during their dissection mastoidectomy compared with the control group (mean 12.8 points vs. 10.3 points, $p<0.01$). This difference corresponds to dissection performance being increased by 25 % due to repeated and distributed VR simulation practice.

Examining the learning curves of the intervention group (Figure 3), final-product scores for procedures guided by the simulator-integrated tutor-function with green lighting seem to be better than those of unguided procedures (Figure 3A). This was found to be statistically significant with an effect estimate mean of 2.3 points (repeated measures linear mixed model, $p < 0.001$) of simulator-integrated tutoring. Further, final-product performance did not seem to improve substantially with repeated practice (Figure 3A). However, drilling time decreased markedly with repeated practice (Figure 3B) and when considering final-product score per minute as an overall performance measure (Figure 3C), performance increased following a classic, negatively accelerated learning curve. Guidance by the simulator-integrated tutor-function increased drilling time but also the final-product score altogether leading to a final-product score per minute nicely fitting the overall learning curve (Figure 3C).

Discussion

Structured VR simulation pre-course training significantly increased subsequent cadaveric dissection performance by 25 %. This corroborates that skills obtained in the VR simulation environment translates to the dissection environment, leading to an increased dissection performance. Further investigation of the learning curves of the intervention VR simulation training program, revealed that even though the final-product score improved only some with repeated practice, the time needed to obtain such a final product decreased markedly from around 58 minutes for the first procedure to 15 minutes for the 18th procedure. Considering both performance score and time, the overall performance (score per minute) followed a traditional negatively accelerated learning curve.

It is well-established that VR simulation can be used to improve cadaveric dissection performance[9–11] but only few studies have investigated repeated and distributed practice in temporal bone surgical training. Nash et al found that for their four medical student participants, automated VR simulator scores improved with repeated and distributed practice.[18] The automated score plateaued after 4 repetitions whereas drilling time in the simulator decreased during all the 6 repetitions.[18] Mowry et al found that for residents, skills on a timed cadaveric dissection exercise was correlated with the total number of previously drilled cadaveric temporal bones.[21] However, learning curves of repeated cadaveric temporal bone drilling were not established because this data was not available.[21] In a previous study, we investigated the learning curves of massed and distributed practice with and without simulator-integrated tutoring using medical students as study participants.[17] These results informed the new, structured training program investigated in the current study with training blocks consisting of three procedures and using the simulator-integrated tutor-function for the first procedure in each block. To date, this is the largest study on VR simulation training of *residents* with a *cadaveric dissection* outcome.

In the present study, we found a large positive effect of repeated and distributed practice on performance which concurs with contemporary literature on motor skills learning.[2] This further stresses that the massed practice of short and intense learning events such as temporal bone courses—from a learning perspective—provides suboptimal training compared with distributed training programs which allows for better development, consolidation, refinement and retention of skills.[22] VR simulation offers a relatively inexpensive platform for such repeated and distributed practice and a reasonable adjunct to traditional cadaveric dissection for optimizing the use of donated temporal bones for further training after basic skills have been acquired in the VR simulation environment.

Even though our structured training program significantly improved the cadaveric dissection performance, the mean VR simulation final-product score after repeated practice of 18 procedures was only 17.7 points out of the maximum of 26 points. The average trainee will probably need far more rehearsals than 18 to establish and consolidate skills at this level. Nevertheless, there may still be room for improvement in performance even after only 18 repetitions: fidelity through continuing technical and graphical advances of the VR simulator will likely contribute to this, but several other factors should be considered. In our study, performances guided by the simulator-integrated tutor-function were found to be significantly better than unguided procedures, similar to what we and others have reported previously.[17,23] In line with other reports, such feedback results in increased skills while provided but instant regression when unavailable.[24] The apparent learning curve plateau of mastoidectomy in VR simulation seems also to be attributable to cognitive factors[25] and should be considered when designing directed, self-regulated learning experiences[26] including self-directed VR simulation training in temporal bone surgery. More research on different learning supports and interventions for directed, self-regulated learning and countering the performance plateau are needed, especially those targeting cognitive factors.

There are several limitations to our study, which is a balance between rigor and feasibility. First of all, there is the premise of final-product analysis as the sole measurement of performance: final-product analysis only considers the end result but disregards the process—which may be important in regard to for example surgical risk. Furthermore, final-product assessment may not correlate well with more process–oriented assessment.[13] However, assessment of technique and process requires direct observation or video recording which is time consuming for raters and not feasible in the context of the more than 250 virtual and cadaveric dissection performances analyzed for this study. Further, our study recruited participants from all over the country for training at a single site on a completely voluntary basis. This potentially introduces a recruitment bias, favoring participants with the most interest in temporal bone surgery and with geographical convenience of training.

As a consequence of recruitment, a difference in the number of participants in the control and intervention groups was introduced. We planned to include several cohorts of course participants to allow for enough participants in the intervention group (based on the a priori sample size calculations) but terminated the inclusion of further cohorts after just two temporal courses because the planned interim analysis demonstrated such a large effect of the intervention on the cadaveric dissection performance. Although direct comparison between studies should be done with caution due to study differences, we have previously found that a mere two hours of self-directed VR simulation training immediately before dissection training improved dissection final-product performance by 52 %.[11] The present study suggests that there is an additional benefit of structured VR simulation training of repeated and distributed practice compared with a single block of simulation training during a temporal bone course

Altogether, the present study adds knowledge on the learning curve of repeated and distributed VR simulation training, the effect on subsequent dissection performance, and the performance of trainees rather than medical students.

In this study, the additional VR simulation training was offered as a voluntary and optional supplement to our temporal bone course and despite the lack of any form of compensation, 24 % of participants volunteered and completed the structured training program at the Simulation Centre before. Most participants in the control group expressed their interest in pre-course training at the time of invitation for study participation but mainly declined due to geography and trouble finding the time for participation. The low price of the necessary computer hardware to run the freeware VR temporal bone software should allow the simulator to be disseminated to most training departments, allowing for local training. Potential benefits of such local and self-directed VR simulation training are that it meets both the individual trainee's training needs and is conveniently available. Regardless, we think that training should be systematic, structured and based on evidence, and with this study we have provided data that such a training program is effective in improving cadaveric dissection final-product performance.

Conclusion

Structured VR simulation training of mastoidectomy with repeated and distributed practice increased subsequent dissection final-product performance by 25 % compared with a single block of VR simulation training during a temporal bone course. This corroborates that temporal bone skills acquired in a VR simulation environment translates to cadaveric dissection skills. Procedures guided by the simulator-integrated tutor-function where significantly better than unguided procedures, but whereas final-product performance itself was relatively stable, drilling time decreased. Consequently, final-product score per time followed a traditional negatively accelerated learning curve. Distributed VR simulation training is feasible in the context of a temporal bone course and allows participants to train deliberately before attending future temporal bone course.

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Table I. Participant characteristics

	Control group	Intervention group
	Count (%) / Mean (SD)	Count (%) / Mean (SD)
Number of participants	28 (76 %)	9 (24 %)
Age†	36.8 (3.9)	36.3 (4.9)
Sex‡		
Female	15 (54 %)	6 (67 %)
Male	13 (46 %)	3 (33 %)
Years of training†		
Otorhinolaryngology, years	3.9 (1.3)	3.9 (1.4)
Other surgical specialties, years	0.9 (1.5)	1.1 (0.7)
Participation in another temporal bone course‡		
No	25 (89 %)	7 (78 %)
Yes	3 (11 %)	2 (22 %)
Experience with the Visible Ear Simulator prior to the course, hours†	0.6 (1.5)	0.8 (1.6)
Average computer usage outside work, hours/week†	7.2 (7.3)	9.4 (7.4)
Self-rated computer skills (1–7 Likert scale)†	4.1 (4.3)	4.1 (0.8)
Gaming frequency (1–5 Likert scale)†	2.1 (1.3)	1.9 (1.4)

†Independent samples t-test, ‡Fisher's exact test. ns = not significant

Table II. Estimated marginal means

Modality	Group	Mean	95 % CI	Significance of Difference
Dissection§	Control group	10.3	8.7–11.8	
	Intervention group	12.8	10.8–14.9	
	Mean difference	2.6	0.7–4.4	p<0.01
VR simulation¶	Control group	13.3	12.0–14.6	
	Intervention group	17.7	15.4–20.0	
	Mean difference	4.4	1.8–7.0	p<0.005

§ Linear mixed model with rater and groups as fixed effects and cadaver specimen pairing as random effect.

¶ Linear mixed model with rater and group as fixed effects.

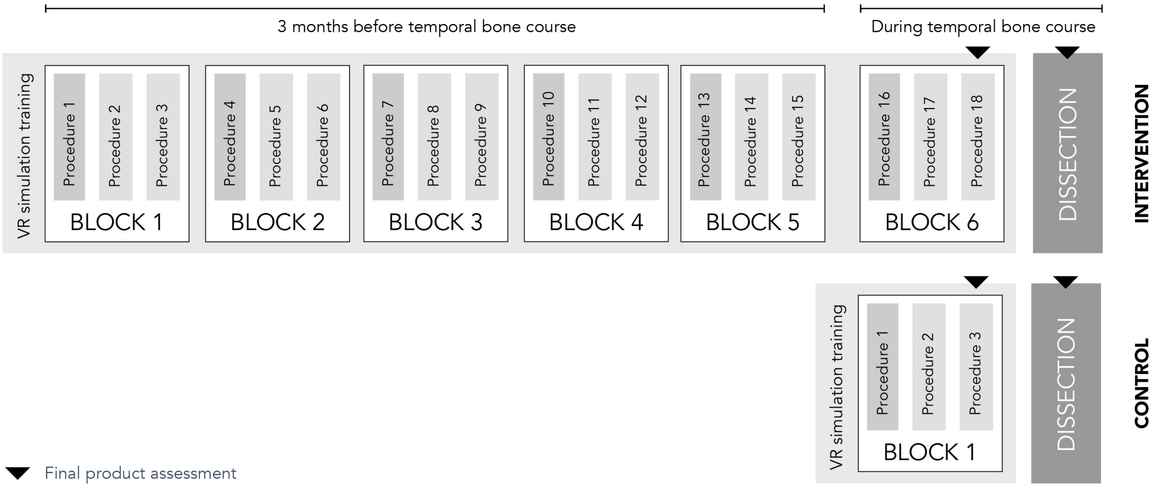

Fig. 1. Flowchart. The end-of-training VR simulation mastoidectomy performance and dissection mastoidectomy performance were assessed using final product analysis for comparison between the intervention and control groups.

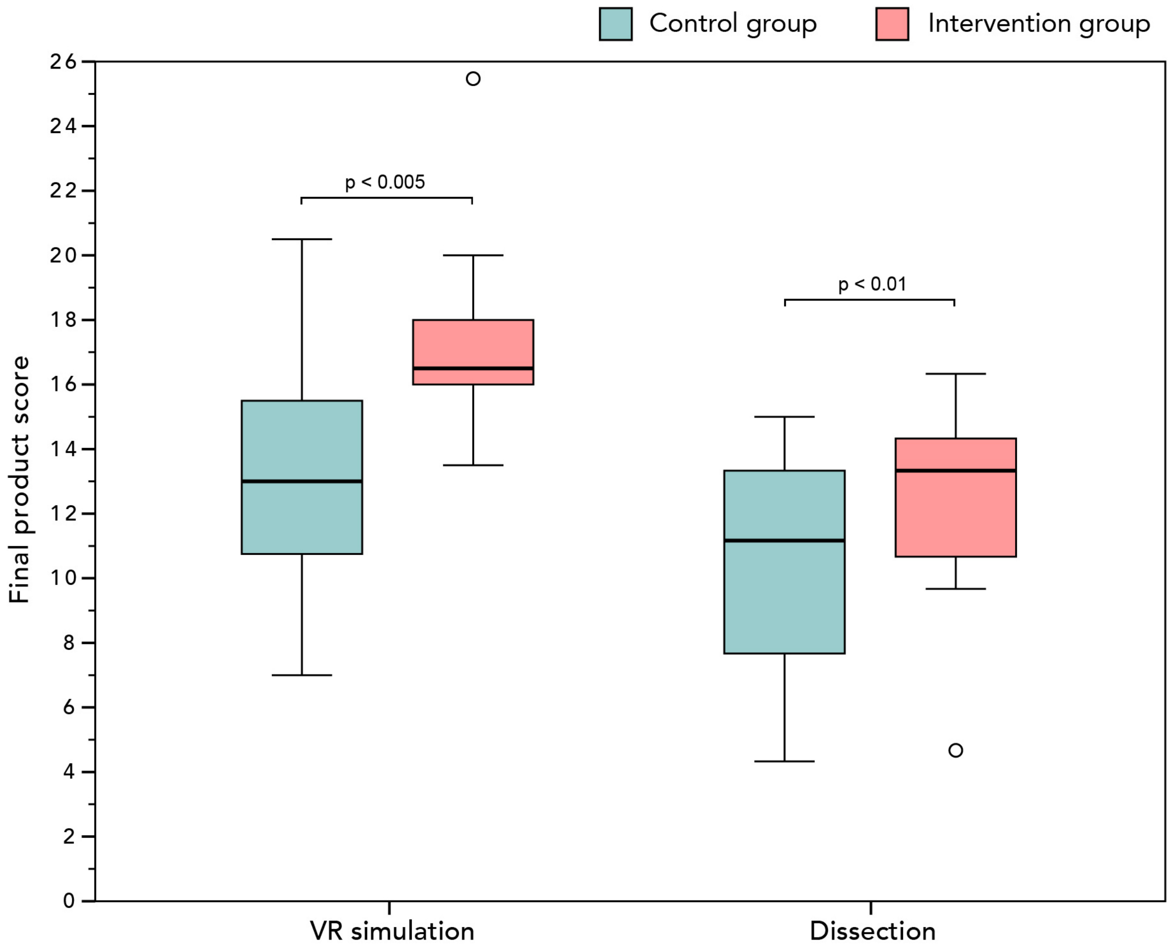

Fig. 2. Boxplot of end-of-training final product scores in VR simulation, and dissection final product scores, for the control and intervention groups.

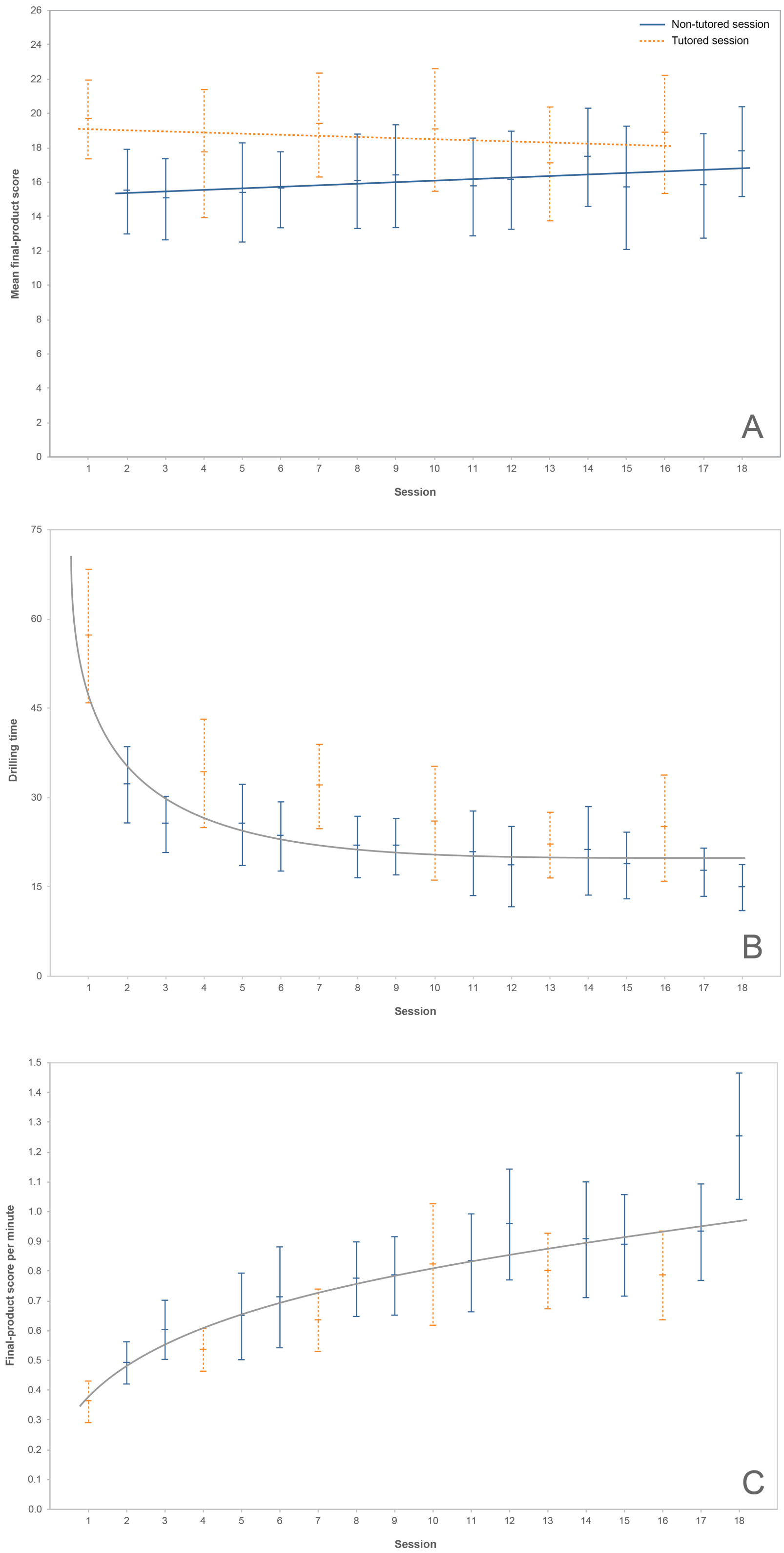

Fig. 3. Means plot and learning curves for the distributed training program (intervention): A) Final-product score, B) Drilling time. C) Final-product score per minute of drilling. Procedures guided by the simulator-integrated tutor-function (yellow) and unguided (blue).