The effect of distributed virtual reality simulation training on cognitive load during subsequent dissection training

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Background: Complex tasks such as surgical procedures can induce excessive cognitive load (CL) that can have a negative effect on learning especially for novices.
Aims: To investigate if repeated and distributed virtual reality (VR) simulation practice induces a lower CL and higher performance in subsequent cadaveric dissection training.
Methods: In a prospective, controlled cohort study, 37 residents in otorhinolaryngology received VR simulation training either as additional distributed practice prior to course participation (intervention) (9 participants) or as standard practice during the course (control) (28 participants). Cognitive load was estimated as the relative change in secondary-task reaction time during VR simulation and cadaveric procedures.
Results: Structured distributed VR simulation practice resulted in lower mean reaction times (32 % vs. 47 % for the intervention and control group, respectively, $p<0.01$) as well as a superior final-product performance during subsequent cadaveric dissection training.
Conclusions: Repeated and distributed VR simulation causes a lower CL to be induced when the learning situation is increased in complexity. A suggested mechanism is the formation of mental schemas and a reduction of the intrinsic CL. This has potential implications for surgical skills training and suggests that structured, distributed training be systematically implemented in surgical training curricula.
Keywords: cognitive load, temporal bone dissection, mastoidectomy, virtual reality simulation, surgical skills training.

Practice Points

- Excessive cognitive load (CL) can inhibit learning especially for novices.
- CL can be modified and optimized of benefit to learning.
- Repeated and distributed VR simulation training reduces CL and has positive effects on CL and performance in subsequent learning situations of higher complexity.
- Systematic distributed training should be implemented into surgical training.

Introduction

Surgical skills acquisition often represents a complex learning task, consisting of both cognitive and motor skills components that most often cannot be separated or reduced. Also, the traditional learning environments of the operating room (OR) or the dissection lab represent highly complex learning environments that add substantial demands on the trainee. Simulation-based training including box trainers for basic skills training and advanced virtual reality (VR) simulators for procedural training is increasingly being integrated into surgical training curricula. Regardless of chosen modality for surgical skills training, organization and instructional design should support effective learning and ensure surgical competency—and because especially novices are challenged when new and unorganized information and complex psychomotor skills during for example surgical skills training, learning theory and evidence should inform decisions on organization of training and instructional design. This includes building learning sessions so that complexity matches current skills and considerations on transfer of skills from one learning setting to more complex learning situations and finally to real life.

Cognitive load (CL) theory provides a contemporary framework relevant to surgical skills training. The main premise of CL theory is that working memory and information processing is limited which implicates that a CL exceeding the individual learner's cognitive capacities leads to a cognitive overload (Sweller 1988). Three different sources of CL are considered: the intrinsic load derived from the learning task itself, the extraneous load caused by the learning situation and the way the learning task is presented, and the germane load of the learning process (van Merriënboer and Sweller 2010). A cognitive overload impacts negatively on learning and especially the novice is at risk: unconsolidated skills and poorer mental schemata for organizing novel information and reducing the number of elements in working memory increases intrinsic load and extraneous load for example from fatigue or poor supervision (Sewell et al. 2017). In theory, reducing the intrinsic and extraneous CL promotes learning and skills acquisition and this has recently been corroborated by a large meta-analysis based on a broad range of studies on education and learning in which a lower CL was found to improve retention and transfer of multimedia learning (Xie et al. 2017). However, a high CL is not necessarily bad as increasing the germane load can have positive effects on learning (van Merrienböer, Kester and Paas 2006).

Different instructional design strategies can be implemented to reduce and modify CL (van Merriënboer and Sweller 2010) but are dependent on procedure and learning context (Andersen 2016c). In motor skills learning, distributed and repeated practice allows for memory consolidation (Shea et al. 2000) and in the framework of cognitive load theory, repeated practice supports the construction of mental schemata (germane load) for dealing with task intrinsic load (Brünken et al. 2003).

Measuring a construct such as CL is difficult and a number of different methods to estimate CL have been reported in the literature including validated questionnaires and objective measurements (Naismith and Cavalcanti 2015). The latter includes the dual-task paradigm where for example reaction time is measured in response to a visual, auditory or tactile stimulus (a secondary task) (Rojas et. al 2014) and we have used this method to estimate CL in previous studies (Andersen et al. 2016a, 2016b, 2016c).

In temporal bone surgery, the mastoidectomy procedure is an example of a complex learning task that has traditionally been trained using cadaveric temporal bones in a demanding learning environment—the dissection lab: the trainee needs to simultaneously handle the otosurgical drill and foot pedal, the suction/irrigation, and the operating microscope (motor skills) and navigate in a surgical field that includes important structures such as the facial nerve, the sigmoid sinus, the dura, the ossicles and the inner ear (cognitive skills). This exemplifies a procedure with a high number of interactive elements adding to intrinsic CL as well as extraneous load resulting from the learning environment that often includes multi-source instructions such as human instructors and textbook information separated from the task such as dissections manuals in which the information needs to be searched out. Therefore, VR simulation of the procedure has been established as a valuable learning tool for acquiring basic skills (Zhao et al. 2011, Andersen et al. 2016d). We have previously investigated the role of CL in relation to VR temporal bone surgical simulation and found:

1. A VR simulation environment induces a lower CL compared with the traditional cadaveric dissection environment (Andersen et al. 2016b).
2. CL decreases with repeated and distributed VR simulation practice but not if practice is massed (Andersen et al. 2016a).

However, there is a gap in knowledge on whether the lower CL obtained through repeated and distributed VR simulation practice also results in a lower CL during a more complex learning situation. In other words – do the mental schemas formed by repeated practice thereby reducing intrinsic CL aid in inducing a lower CL when complexity of the learning task increases? This has potential implications for organization of surgical skills training: If repeated and distributed simulation-based training promotes a lower CL and a better performance this would further support the implementation of such training into surgical curricula.

In this study, we therefore wanted to investigate the effect of repeated and distributed VR simulation practice of the mastoidectomy procedure on CL and performance during subsequent cadaveric dissection training.

Material and methods

Participants in the Danish national temporal bone courses in January 2016 and 2017, n=17 and n=20, respectively. Participants were post-graduate year 2–5 residents in otorhinolaryngology and relative novices regarding temporal bone surgery.

In relation to the temporal bone courses, all participants were invited for this prospective and controlled study and were offered additional structured VR simulation training before the four-day temporal bone course. The simulation training was only offered at the Simulation Centre at Rigshospitalet in the eastern part of Denmark (Konge et al 2015) and participants were offered no financial or time compensation for participation. A total of nine trainees accepted and completed the distributed VR simulation training before participation in the temporal bone course (Figure 1, flowchart). The remaining 28 temporal bone course participants agreed to serve as controls. All participants signed informed consent for participation in this research study.

For the VR simulation training, we used the Visible Ear Simulator developed by our group (Trier et al. 2008; Sorensen et al. 2009). The simulator consists of academic freeware software and features 3D stereo-graphics, haptic interaction with the Geomagic Touch (3D Systems, SC, USA) for drilling with force feedback, onscreen step-by-step guides for a number temporal bone procedures including mastoidectomy, and an integrated tutor-function that green lights the volumes to be drilled in correspondence with the selected guide.

The interventional VR simulation training consisted of distributed practice in the three months before the temporal bone course and was structured with five practice blocks of three identical procedures spaced by at least one week. The standard training during the temporal bone course, which both groups received, consists of 1.5 days of lectures, one three-hour VR simulation training block at the Simulation Centre identical to the practice block during distributed practice, followed by two days of dissection training whereof the first hour was reserved for performing a single anatomical mastoidectomy with posterior tympanotomy on a cadaver for this study.

During each VR simulation procedure and the single cadaveric dissection procedure, reaction time to a sound stimulus (measured in hundredths of seconds) was measured manually in repeated series of four at t=5 min and t=15 min (simulation) and t=5 min, t=15 min, t=30 min and t=45 min (dissection) using a commercially available reaction timing device (American Educational Products LLC, USA). Similarly, reaction time was measured immediately before and after each practice block/the dissection procedure to establish individual resting baseline. Mean reaction time for each procedure was calculated and divided by the mean reaction time at baseline, resulting in the relative reaction time for each procedure (in other words – the relative change in reaction time during procedure compared to baseline, unitless). The relative reaction time was used as a proxy for change in CL. Further, performances were assessed by rating virtual and dissection final products using a modified Welling Scale (max. 26 points) (Andersen et al. 2015) by two blinded raters for virtual performances and three blinded raters for dissection performances. The raters rated all performances of their respective modality.

Data were analyzed using SPSS (SPSS Inc., IL, USA) version 23 for MacOS X. Linear mixed models were used for repeated measurements of relative reaction time and estimated marginal means are reported. In the linear mixed models, time of measurement and session number were input as repeated measurements, and either group (intervention/control) or baseline (baseline/end-of-training sessions) as a fixed effect depending on comparison.

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

Results

Participants had comparable baseline characteristics (Table 1) such as age, gender distribution, years of training, previous simulation-based surgical skills training, and self-reported computer skills and gaming frequency. The intervention group on average practiced 432 minutes (SD 80.0 min; range 318–636 min) in the VR simulator during the distributed training program. During the temporal bone course, the participants on average completed a practice block (three identical procedures) in 111 min (SD 33.2 min; range 42–183 min).

Relative reaction time in VR simulation decreased significantly with repeated and distributed practice (linear regression, $p<0.002$) (Figure 2) similarly to what we have previously found. Unsurprisingly, the intervention group had a superior final-product performance in cadaveric dissection compared to the control group (12.8 points vs. 10.3 points, respectively, $p<0.01$).

The control and intervention groups had similar mean relative reaction time during their first VR simulation procedure (Table 2). At the end of the interventional training program, the relative reaction time had decreased 15 percentage points, which was statistically significant (linear mixed models, $p<0.001$) (Figure 3). As the main finding, this was found to induce a significantly lower relative reaction time during cadaveric dissection training for the intervention group compared with the control group (1.32 vs. 1.47, linear mixed models, $p<0.01$).

Discussion

In this prospective, controlled study of the effect of structured VR simulation training on CL and performance in subsequent cadaveric dissection training, we confirmed that repeated and distributed VR simulation practice reduces CL. Consequently, a lower CL was induced during cadaveric dissection compared with the control group in addition to final-product performance being higher in the repeated and distributed practice group. This suggests that the formation of mental schemas and resulting lower intrinsic CL from repeated and distributed practice the VR learning environment positively benefits subsequent training in the more complex dissection learning environment.

CL in relation to medical and surgical skills training has received increasing interest in the recent years and the number of high quality studies are growing. Repeated VR laparoscopic simulation practice of salpingectomy resulted in a decreased CL as estimated by validated questionnaires (Bharathan et al. 2013), similar to what we found in this and a previous study (Andersen et al. 2016a). Another recent study has demonstrated that experience and training as well as CL predict ultrasound image acquisition performance (Aldekhyl et al 2018).

Element interactivity, i.e. the number of elements needed to be processed simultaneously, is a main cause for intrinsic CL and can only be changed by modifying the task (van Merriënboer and Sweller 2010). In our case, the complexity of the learning task—performing a mastoidectomy—is lower in VR simulation than the similar task on the cadaver (Andersen et al 2016b): for example, in the VR simulator navigation and all instrument handling is performed using a single device (either the mouse or the haptic device) as opposed to the closer to real-life conditions of dissection where the otosurgical drill is held in the dominant hand and activated by a foot pedal, while the suction is simultaneously handled using the non-dominant hand, and the surgical field is viewed through the operating microscope. Other factors could affect element interactivity and reduce complexity in VR simulation including the on-screen step-by-step instructions, guidance by the simulator-integrated tutor-function, and the fact that the simulation does not include bone dust or water that needs to be suctioned.

In a study on lumbar puncture training, reduced complexity of the learning task and the learning environment was associated with a superior performance and lower CL during skills acquisition and intermediate retention, however, these results did not apply in a highly complex scenario (Haji et al 2016). In contrast, we found that the lower CL induced by repeated and distributed practice in a less complex learning task and VR environment supported a higher performance and lower CL in the more complex "wet" setting. Altogether, this could suggest that although "simpler" training may not by itself be sufficient in reducing CL if the end point task (cadaveric dissection) is complex, the additional effect of repeated and distributed practice can. This is supported by the literature on "automaticity": In VR surgical simulation it has been demonstrated that novices may achieve proficiency after relatively few practice sessions whereas improvement in secondary task performance needs substantially more practice (Stefanidis et al. 2008). Experts, on the other hand, have cognitive capacity to immediately perform well on the secondary task because they have experience and already have mastery of the familiar primary task and can perform it with automaticity (Stefanidis et al. 2009). In the lens of cognitive load theory, minimal CL is induced at the point of automaticity as exemplified in the ultrasound training study (Aldekhyl et al. 2018). Experience is highly dependent on repeated and distributed practice along with feedback, training on a variety of cases, and cognitive factors—all key elements of deliberate practice (Ericsson 2004).

Several instructional design principles for optimizing CL follow from the cognitive load theory (van Merriënboer and Sweller 2010) but only few studies have investigated these in relation to surgical skills training. In a previous study, we implemented the principles of worked examples and problem completion exercises with backward chaining as a means to reduce extraneous CL and increase performance in VR simulation training of mastoidectomy (Andersen et al. 2016c). However, the subsequent re-integration of part task exercises instead resulted in increased CL and inferior performance compared with a group that had been trained with the standard top-down instructions. Further, it seems that not only the instructional design influences on CL: A large questionnaire study of trainees performing colonoscopy found several interesting associations related to CL—for example that intrinsic load was reduced with learner experience, increased by learner fatigue, and increased with complexity of the procedure; extraneous load increased with fatigue; and supervisor engagement both decreased extraneous load and increased germane load (Sewell et al. 2017).

The entire learning experience and setting contributes to CL and must therefore be considered in the design of surgical skills training programs.

Studies from other surgical fields such as laparoscopy corroborates that distributed VR simulation training before an expensive (animal) training course increases performance (Bjerrum et al. 2015). Furthermore, a meta-analysis from 2013 has found a large effect-size of 0.66 of distributed learning (Cook et al. 2013). Together with the positive effect of distributed practice on CL when going from a simpler to a more complex learning environment, cadaver and animal lab training should—both from and educational and ethical point of view—be reserved for training after basic competency have been acquired with simulation-based methods.

Our study has several limitations. We had fewer participants in the intervention group than in the control group. This relates to recruitment of participants: First of all, the intervention training was only offered at our simulation center in the eastern part of Denmark, whereas participants in the national temporal bone course where geographically distributed with half of trainees situated in the western part of Denmark. Next, participants were offered no time or financial compensation and participation was on a voluntary basis. Combined, this could introduce a potential recruitment bias, favoring trainees from nearby training centers and those with the most interest in temporal bone surgery. Furthermore, there is the challenge of measuring a construct such as cognitive load. Several methods have been proposed in the literature and many are validated but each method has specific limitations. Currently, there is no gold-standard or superior method for estimating CL (Naismith et al. 2015, Naismith and Cavalcanti 2015). The method we chose—secondary task reaction time—is unable to distinguish between the different components of CL and should optimally draw on the same attentional resources as the primary task. On the other hand, secondary reaction time measurement offers the possibility for establishing baseline and calculating individual relative changes, and is effective in detecting even minor changes in CL (Andersen et al. 2016a, 2016b)

Our study contributes to current knowledge by demonstrating that the lower CL induced by repeated and distributed practice in a VR simulator has positive effects on CL and performance in a more complex learning environment. In the lens of cognitive load theory, a likely explanation being that repeated and distributed practice provides novices with experience and task familiarity, and assists in forming mental schemata, thereby reducing intrinsic load and optimizing germane load. Other training modalities and methods could have positive effects on learning and CL: for example, structured observation as preparation for learning has demonstrated a substantial effect in simulation-based skills training (Cheung et al. 2016). VR simulation has consistently been found to be beneficial in surgical skills acquisition and our findings add that VR simulation training has positive effects on CL in a subsequent learning task of high complexity. Altogether, this has implications for surgical skills training and should further promote the use of VR simulation as an integral part of training curricula when possible.

Conclusion

Consideration of CL in surgical skills training is highly relevant especially in the context of novice training as excessive CL is disadvantageous for learning. Different strategies can be used to lower CL and with this study, we demonstrate that not only does repeated and distributed VR simulation practice lower CL but this also that a lower CL was induced in a similar but more complex learning situation. Together with current knowledge on CL, this adds that surgical skills training can benefit from 1) training in a simpler learning environment such as VR simulation and 2) that repeated and distributed practice has positive effects on surgical technical skills performance and CL in subsequent learning situations of increased complexity.

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Declarations of interest

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Table 1. Baseline participant characteristics.

	Control group	Intervention group
No. of participants	28	9
Temporal bone course cohort, N		
2016	13	4
2017	15	5
Age, mean	36.8	36.3
Sex, N		
Male	13	3
Female	15	6
Years of training in Otorhinolaryngology, mean	3.9	3.9
Other experience with any VR simulation	50 %	100 %
Other experience with any surgical skills training	71 %	56 %
Self-rated computer skills (1–7 Likert scale), mean	4.1	4.1
Gaming frequency (1–5 Likert scale), mean	2.1	1.9

Table 2. Mean relative reactions times

	Mean	95 % CI	
VR simulation training			
Control group	1.21	1.17–1.24	p=0.09§
Intervention group			
Baseline	1.27	1.21–1.33	
End-of training	1.12	1.08–1.17	
Difference	0.15		p<0.001
Dissection training			
Control group	1.47	1.41–1.52	
Intervention group	1.32	1.23–1.42	
Difference	0.15		p<0.01

§ compared with intervention group baseline

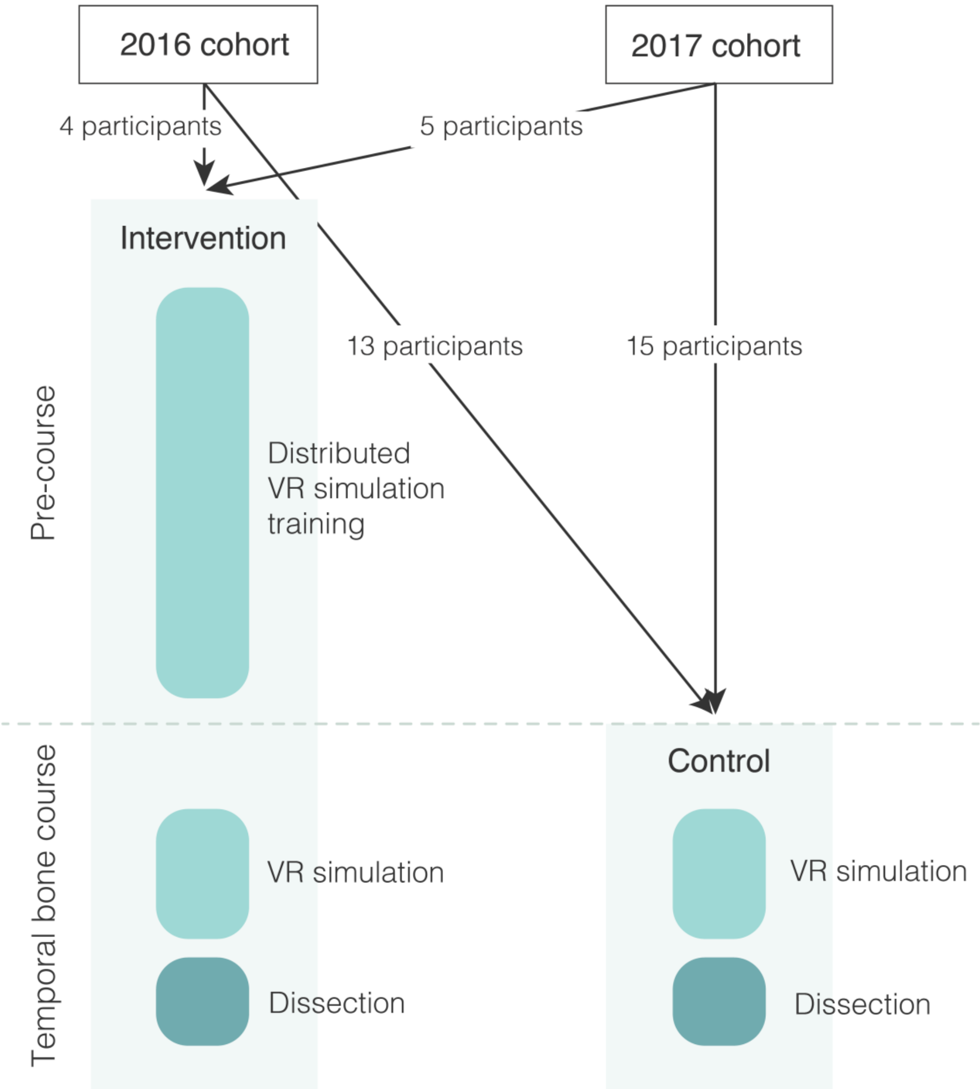

Figure 1. Flowchart.

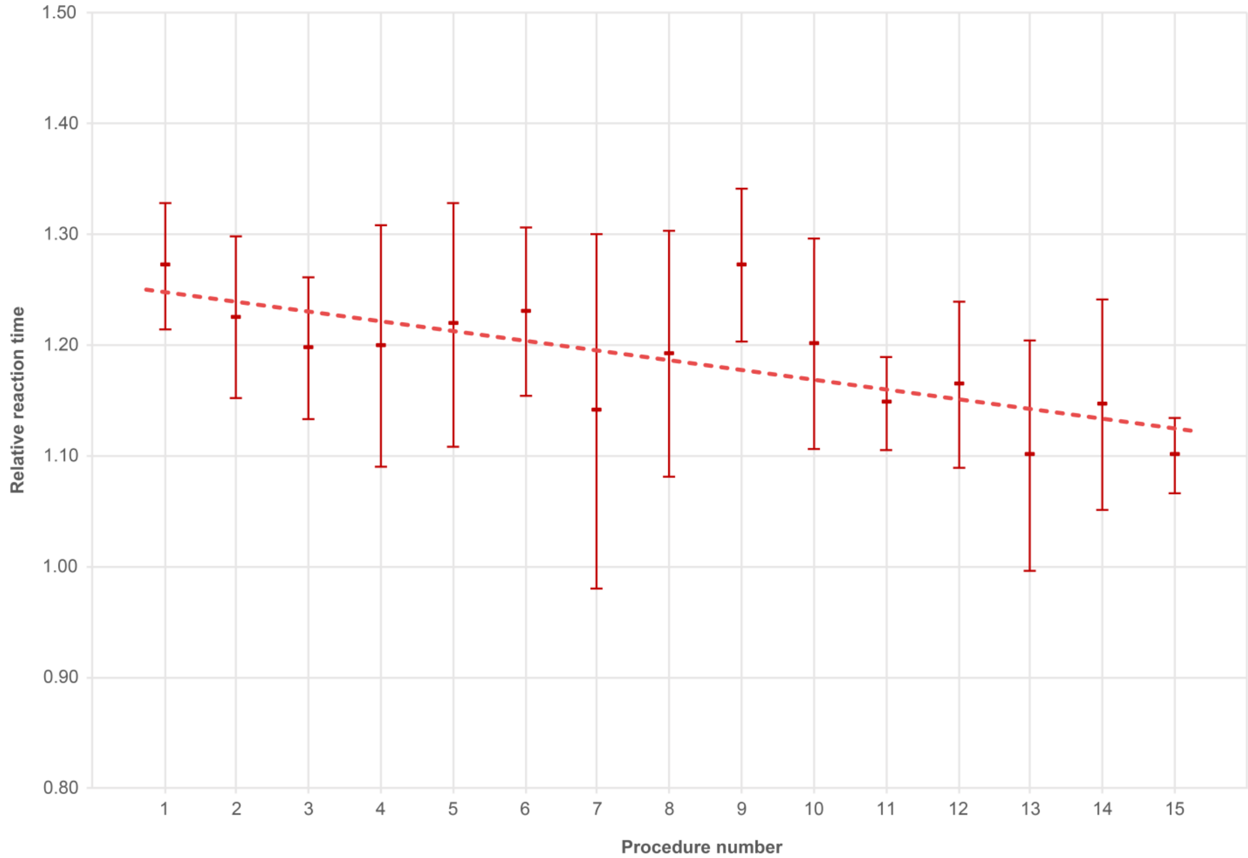

Figure 2. Means plot of relative reaction time during the pre-course VR simulation training.

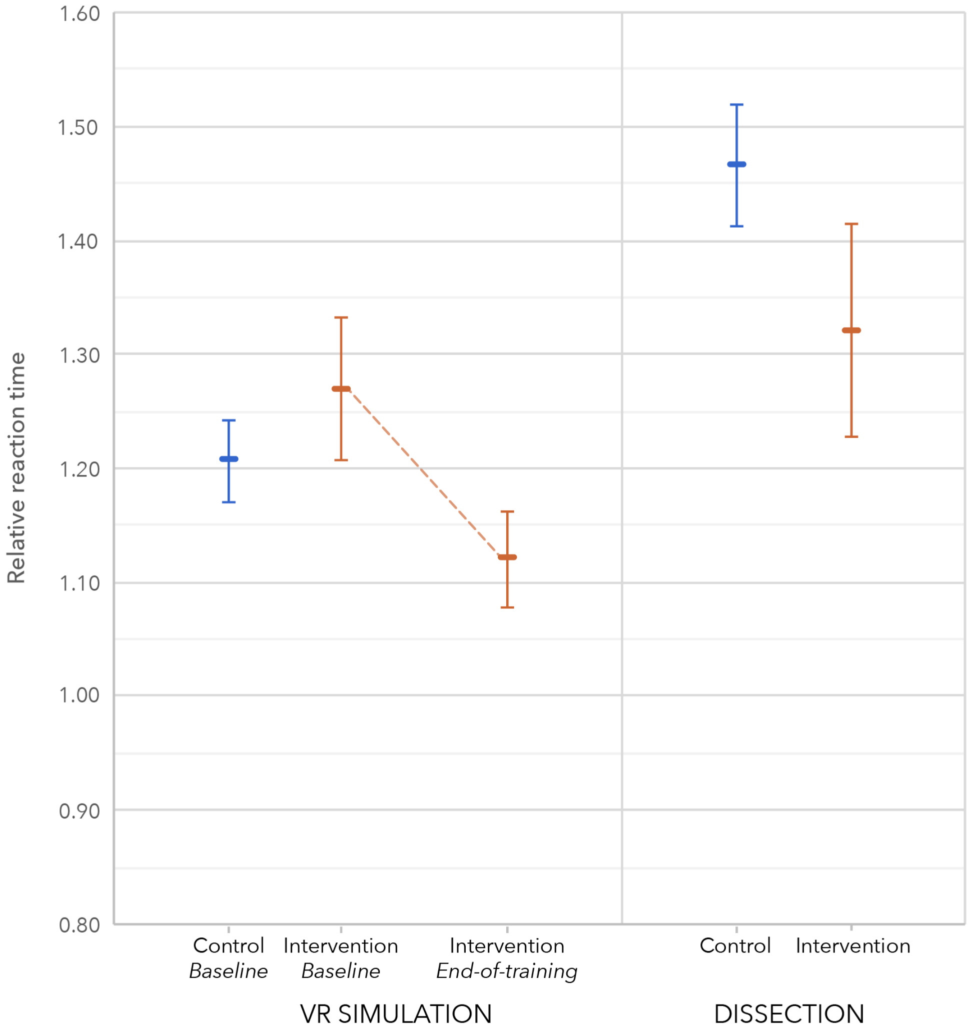

Figure 3. Means plot of relative reaction time during VR simulation and dissection for the control and intervention groups.