Original Article

Design and validation of a virtual reality trainer for ultrasound-guided regional anaesthesia

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Summary

Virtual reality is a form of high-fidelity simulation that may be used to enhance the quality of medical education. We created a bespoke virtual reality trainer software using high resolution motion capture and ultrasound imagery to teach cognitive-motor needling skills necessary for the performance of ultrasound-guided regional anaesthesia. The primary objective of this study was to determine the construct validity between novice and experienced regional anaesthetists. Secondary objectives were: to create learning curves for needling performance; compare the virtual environment immersion with other high-fidelity virtual reality software; and compare cognitive task loads imposed by the virtual trainer compared with real-life medical procedures. We recruited 21 novice and 15 experienced participants, each of whom performed 40 needling attempts on four different virtual nerve targets. Performance scores for each attempt were calculated based on measured metrics (needle angulation, withdrawals, time taken) and compared between the groups. The degree of virtual reality immersion was measured using the Presence Questionnaire, and cognitive burden was measured using the NASA-Task Load Index. Scores by experienced participants were significantly higher than novices ($p = 0.002$) and for each nerve target (84% vs. 77%, $p = 0.002$; 86% vs. 79%, $p = 0.003$; 87% vs. 81%, $p = 0.002$; 87% vs. 80%, $p = 0.003$). Log–log transformed learning curves demonstrated individual variability in performance over time. The virtual reality trainer was rated as being comparably immersive to other high-fidelity virtual reality software in the realism, possibility to act and quality of interface subscales (all $p > 0.06$) but not in the possibility to examine and self-performance subscales (all $p < 0.009$). The virtual reality trainer created workloads similar to those reported in real-life procedural medicine ($p = 0.53$). This study achieved initial validation of our new virtual reality trainer and allows progression to a planned definitive trial that will compare the effectiveness of virtual reality training on real-life regional anaesthesia performance.

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Introduction

Simulation-based education is an essential component of an ultrasound-guided regional anaesthesia teaching curriculum; it is a fundamental teaching method to allow novices to gain proficiency in motor skillsets such as needle guidance [1]. Simulation models have included phantoms, cadavers, web-based online learning and sessions in dedicated simulation centres. More recently, technological advances have allowed the introduction of high-fidelity immersive virtual reality as a form of simulation. Immersive virtual reality describes the use of an occlusive head-mounted display unit that replaces all real-life sensory inputs with computer-generated visuals and audio. Hand-held controllers allow users to manipulate objects inside the virtual environment, such that a properly designed virtual reality system could replicate real-life skills.

Studies have previously investigated virtual reality simulators in regional anaesthesia. For example, computer tomographic scans were used to recreate a virtual spine allowing for web-based teaching of neuraxial ultrasonography [2], or in combination with haptic feedback to simulate the passage of an advancing needle through fascial planes for neuraxial [3] and coeliac plexus blocks [4]. In another study, magnetic resonance imaging scans were merged with ultrasound imagery to create a virtual simulation of the femoral region that included the femoral nerve [5]. Limitations of these studies include that they only describe the creation of the virtual reality system, they do not recruit any participants or assess the simulation [4, 5] and that all studies used older superseded technology (non-occlusive virtual reality, previous-generation low-resolution graphics) which led to user experiences that are dissimilar to real life.

In this study, we describe the design and programming of a current generation, immersive virtual reality trainer software to teach needling skills necessary for successful ultrasound-guided regional anaesthesia. We undertook three experiments with this new system: establishing initial construct validity of the trainer to discriminate performance between novice and experienced practitioners and plotting the trajectory of learning in all participants; measuring the level of immersion of our virtual environment and comparing with existing high fidelity virtual reality software; and exploring the cognitive workload imposed on users of the virtual reality trainer vs. comparable real-life medical tasks.

Methods

This was a prospective observational study performed in Liverpool Hospital, Sydney, Australia. This was a pre-planned validation of the virtual reality software before a future randomised controlled trial of virtual reality vs. traditional human training.

A pork meat phantom with embedded bovine tendon was constructed as per our previous work [6, 7]. This phantom closely resembles human nerve and muscle structures under ultrasound and allowed us to capture ultrasound images of needles inserted at multiple angles. Author AC then wore a motion capture suit (MTw Awinda®, Xsens, Netherlands) whilst scanning the pork phantom in all possible ultrasound planes of tilt, rotation, translation and heel–toe (Fig. 1a). Radiofrequency sensors embedded in the motion capture gloves and attached to the ultrasound transducer allowed three-dimensional spatial co-ordinates of the transducer to be captured at very high resolution (tilting of transducer accurate to 0.75° angles, rotational motion accurate to 1.5° angles, linear motion sensitivity refreshed at 1 kHz). Spatial co-ordinates of a 21G block needle (Stimuplex A®, B.Braun, Melsungen, Germany) inserted in-plane into the pork phantom were similarly captured. These positional data were time-synchronised with a concurrent and continuous video feed from the ultrasound machine (Edge, FujiFilm SonoSite, Bothell, WA, USA), matching the transducer three-dimensional position to ultrasound imagery.

This combined data library was used by the virtual reality trainer to display a life-like ultrasound video that faithfully replicated the movements of a virtual transducer and virtual needle in response to user inputs (Fig. 1b). To run the virtual reality trainer at highest resolution and zero lag with user inputs, we ran the software on a gaming laptop computer with a Core i7®-8750H processor running at 2.2 GHz (Intel Corporation, Santa Clara, CA, USA), 16 gigabytes memory and dedicated multithread graphics core (GeForce® GTX 1060, NVIDIA Corporation, Santa Clara, CA, USA). The virtual reality hardware used was an Oculus® Rift S (Meta Platforms, Menlo Park, CA, USA) occlusive head-mounted display and hand-held controllers (Fig. 1c). To complete the sense of total immersion, the needle guidance task was contextualised on a simulated patient in an operating theatre environment complete with haemodynamic monitors and audio track (Fig. 1d). The software was coded in C# and Unity Game Engine® (Unity Technologies, San Francisco, CA, USA), with user movement inputs via the hand controllers continuously tracked to six decimal points of precision using a 32-bit floating point value.

After the database was compiled, four positions along the embedded bovine tendon were selected and named as nerve targets 1–4. These positions were chosen to vary the

Figure 1 (a) Author AC wearing high-resolution motion capture hardware to create a video library of ultrasound images linked to spatial co-ordinates of a real-life ultrasound transducer. (b) The virtual reality software can use this database to faithfully display accurate imaging and needle position in response to movements of the virtual transducer and needle-holding hand. (c) Author AK demonstrating use of the virtual reality software. (d) Virtual reality simulation of operating theatre.

difficulty of needling for participants, there was variability in depth from surface (1.9–3.2 cm deep), nerve target cross-sectional area (0.33–0.65 cm^2) and anisotropy requiring transducer movements (±10° tilting from true vertical) to optimise images. The participant's motion controllers were represented by virtual hands that can grasp and hold the ultrasound transducer and nerve block needle. At each target nerve, the participant had to optimise the ultrasound image, then insert the needle in an in-plane approach to the target. The task was to choose an appropriate insertion point, advance and position the needle tip immediately above, withdraw, re-direct, re-advance and re-position the needle tip immediately below the nerve target.

The software precisely measured relative movements of both motion controllers to project an accurate graphical representation of the transducer and needle in virtual reality. These data were simultaneously recorded as three separate, objective metrics during each attempt (Box 1). The total raw score of 500 was normalised to a proportion of the performance score for ease of interpretation (higher scores equated to better performance). Scores were calculated by the software and immediately downloaded for analysis.

Participants were recruited via email advertisements sent to members of the Department of Anaesthesia and university medical student faculties at the Liverpool Hospital in April 2022. Eligible participants were those with no previous experience of ultrasound-guided regional anaesthesia, ultrasonography or regional anaesthesia procedures (novice participants) and those who had performed at least 50 ultrasound-guided regional anaesthesia procedures (experienced participants). After explaining the study protocol and obtaining written informed consent, participants were recruited into the study. Before virtual reality exposure, demographics and years of computer game use (including virtual reality game exposure) were assessed and the 21-item short form of the Depression Anxiety and Stress Scale (DASS) was completed by all participants.

Novice participants were shown a 10-min training video previously used in our work [6, 7] that explained the

Box 1 Performance score metrics.

- Angulation of the virtual needle from ideal in-plane (marks were deducted for needle trajectory away from 0° true perpendicular to the ultrasound plane of imaging, using the formula (90 – measured angle) × 200/90. Full marks were awarded if 0° and no marks if 90° out-of-plane)
- Withdrawal of the needle (marks were deducted for each withdrawal of the needle back to the insertion point, using the formula 200 – (number of withdrawals × 10). Full marks were awarded if there were no withdrawals and no marks if 20 withdrawals)
- Time taken from needle insertion to needle withdrawal after successful completion of the task, using the formula 100 – (time taken in seconds/2). (No marks were awarded if the maximum of 200 s was reached).

fundamentals of ultrasound physics, transducer movements and in-plane needle guidance under ultrasound. All participants were orientated to the virtual reality equipment and then allowed to explore the virtual reality trainer environment to familiarise themselves with the motion controllers and ultrasound scan the virtual patient. Participants were then instructed by a researcher to locate each nerve target and asked to perform an in-plane needle approach to the nerve. The researcher checked accurate placement of the needle tip above and below the nerve target; if the position of the needle was inadequate, the researcher asked the participant to re-attempt the task. This was done for all four targets and repeated 10 times per target resulting in a total of 40 attempts per participant. The study was conducted in an isolated room one-on-one with individual participants to avoid contamination with other participants.

To measure the perceived quality of immersion in the virtual environment, all participants completed the Witmer and Singer Presence Questionnaire [8] (version 3, Université du Québec en Outaouais Cyberpsychology Laboratory, Canada) after using the virtual reality trainer. To measure cognitive load when using the virtual reality trainer, all participants completed the National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire [9]. The NASA-TLX was run as an application on a smartphone (iOS version 1.03, NASA Ames Research Centre, Moffett Field, CA, USA) and is a subjective, human factors questionnaire that rates perceived workload on mental, physical, temporal, performance, effort and frustration domains. Values for the levels of presence expected in a high-fidelity virtual reality environment [10], and cognitive workloads expected in complex medical procedures [11], have been published which we used for comparative analysis.

The primary outcome was needling performance scores. The differences in score between novices and experienced groups for all attempts were analysed with repeated measures ANOVA. Learning curves in regional anaesthesia follow a power distribution [12]; a log–log scatter plot of performance scores (y-axis) vs. attempts (x-axis) and a best-fit linear regression line was inserted through all data points to graphically represent trajectory of learning for each participant. Raw scores for the Presence Questionnaire were converted into a proportion of the maximum possible score (0% = totally dissimilar to real-life, 100% = feels exactly like real-life). The NASA-TLX software was programmed to automatically convert raw domain scores into a pairwise weighted, single global score. t-Tests, Mann–Whitney U or chi-squared tests was used to analyse the differences between groups in demographic and baseline characteristics data, in each of the 4 nerve target performance scores, Presence Questionnaire normalised scores and the NASA-TLX-weighted global score. For this validation study, a convenience sample size of 15 participants per group was selected. We aimed to recruit 20 participants per group to account for withdrawals. All data were de-identified and analysed by a blinded statistician. Analysis was performed using SPSS version 24 (IBM Corp, Armonk, NY, USA), MedCalc version 20.115 (MedCalc Software, Ostend, Belgium) and Microsoft Excel version 2209 (Microsoft Corporation, Redmond, WA, USA). Statistical significance was determined by a two-tailed analysis, $p < 0.05$.

Results

A total of 21 novice and 17 experienced participants were recruited. Two experienced volunteers were excluded as they preferred out-of-plane approaches rather than in-plane needling; the remaining 15 participants' data were analysed. Demographics and pre-performance Depression Anxiety and Stress Scale of recruited participants are reported in Table 1. Experienced participants were older and predominantly male, but virtual and non-virtual computer gaming exposure and Depression Anxiety and

Table 1 Baseline characteristics of study participants. Values are mean (SD), number or median (IQR [range]).

	Novice n = 21	Experienced n = 15	p value
Age; y	21 (1)	42 (6)	<0.001
Gender; male	7	10	0.02
Computer gaming experience; y	0 (0–2 [0–13])	0 (0–1 [0–20])	0.43
Baseline DASS			
Depression	1 (0–2 [0–5])	0 (0–2 [0–7])	0.32
Anxiety	0 (0–1 [0–4])	0 (0–0 [0–2])	0.35
Stress	0 (0–0 [0–6])	0 (0–0 [0–0])	0.62

DASS, Depression Anxiety and Stress Scale.

Stress Scale scores immediately before virtual reality training were not statistically different between groups (all p values > 0.32).

Experienced participants performed significantly better than novices (p = 0.002, Fig. 2). Scores for experienced participants remained above 80% from attempt 3 onwards, while this threshold was not consistently achieved for novices. In both groups, performance scores significantly improved over time: novice, attempt 1 scores median (IQR[range]) 68 (54–82 [7–91])%, 95%CI 65–71 to attempt 40, 81 (81–88 [21–91])%, 95%CI 69–83, $p < 0.001$; experienced, attempt 1, 78 (70–87 [50–93])%, 95%CI 76–79, to attempt 40, 88 (85–92 [73–98])%, 95%CI 87–89, $p < 0.001$. Comparing performance at the individual nerve targets, experienced participants scored significantly better than novices for all four nerves: experienced vs. novices, target 1, 84 (82–89 [74–90])% vs. 77 (69–84 [64–86])%, p = 0.002; target 2, 86 (83–89 [78–93])% vs. 79 (74–84 [67–89])%, p = 0.003; target 3, 87 (85–91 [80–93])% vs. 81 (76–85 [67–89])%, p = 0.002; target 4, 87 (86–90 [78–92])% vs. 80 (74–86 [63–90])%, p = 0.003 (Fig. 2).

Three examples of different learning curves are provided in Fig. 3. The gradient of the best-fit regression line shows trajectory of learning, while standard error (SE) of the line is the variability of performance over time. Novice 8 is an example of strong learning growth with inconsistent performance: gradient 0.26 (95%CI 0.15–0.37), SE 0.06, adjusted $R^2 = 0.35$. Novice 20 showed a slowing trajectory with less variability in performance, suggesting an impediment to learning with a skills decay over time: gradient −0.03 (95%CI −0.4 to −0.01), SE 0.01, adjusted $R^2 = 0.19$. Finally, experienced 12 had gradient 0.01 (95%CI 0.01–0.02), SE 0.01, adjusted $R^2 = 0.21$, suggesting a flat learning curve and minimal performance variability. Log–log learning curves and raw data for all 38 participants are shown in online Supporting Information Appendix S1.

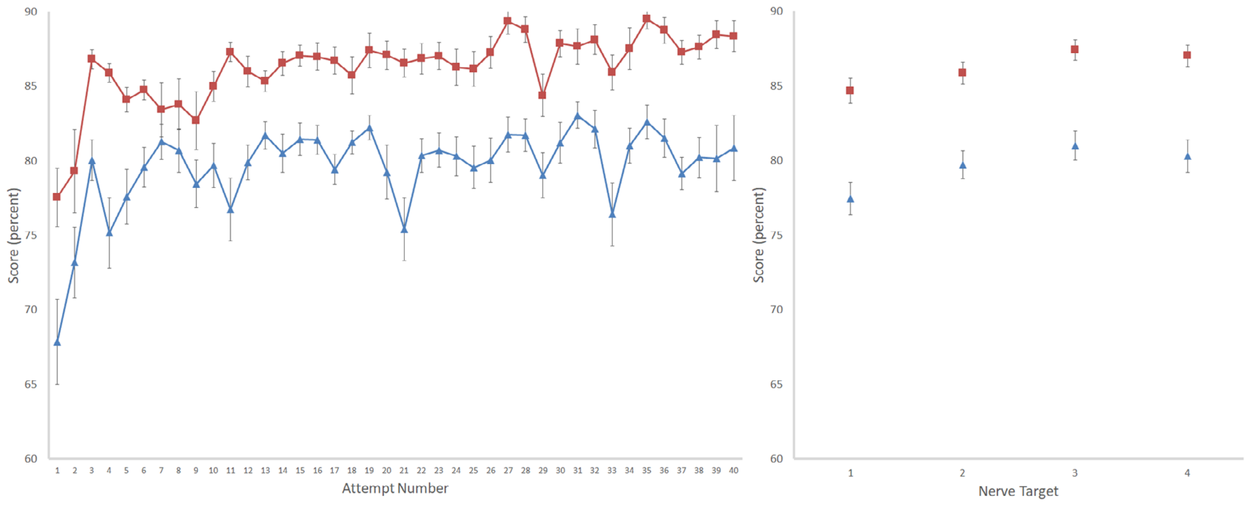

Figure 2 Performance scores between novices and experienced participants over 40 attempts (left), and at each of the four nerve targets (right). Blue triangles, novices; red squares, experienced. Bars represent 95%CIs.

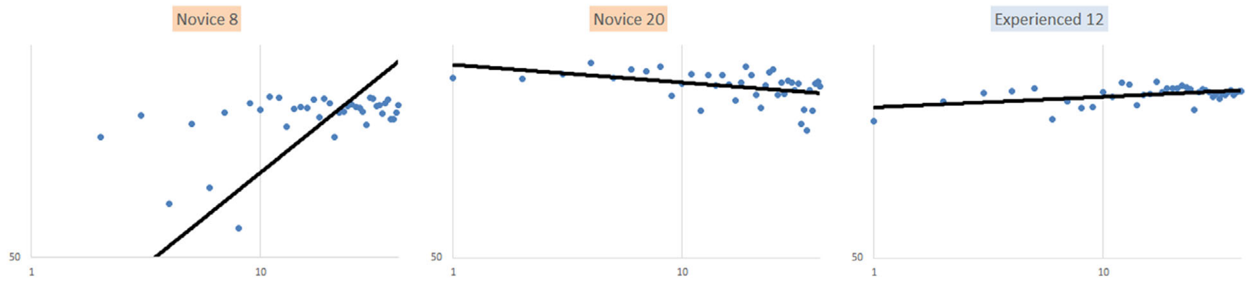

Figure 3 Examples of learning curves constructed for three participants, with best-fit regression line (dark line) overlaid on log–log transformed scatter plot of performance scores (y-axis) plotted against consecutive needling attempts (x-axis).

Table 2 Quality of virtual reality immersion and cognitive workload with use of the virtual reality trainer. Values are mean (SD) score out of 100.

Presence Questionnaire	Novice	Experienced	p value	All participants	Established values	p value
Realism	65 (14)	57 (15)	0.14	62 (15)	60 (25)	0.75
Possibility to Act	70 (11)	62 (19)	0.10	67 (15)	74 (22)	0.06
Quality of Interface	76 (17)	70 (15)	0.33	74 (16)	73 (25)	0.91
Possibility to Examine	62 (17)	56 (14)	0.31	60 (16)	73 (23)	0.002
Self-performance	71 (17)	65 (19)	0.39	68 (18)	79 (21)	0.009
NASA-Task Load Index (TLX) weighted global score	49 (16)	52 (16)	0.33	50 (16)	51 (15)	0.53

Presence Questionnaire scores are converted to perceived degree of immersion (0% = totally dissimilar to real-life, 100% = feels exactly like real-life). Significance testing between study groups, and between study participants vs. external established values for the Presence Questionnaire [10] and NASA-TLX [11].

Table 2 reports on participants' subjective experiences of the virtual reality trainer against real life (Presence Questionnaire) and against real-life cognitive workload (NASA-TLX). Experienced participants rated the level of virtual immersion lower in all five Presence subscales compared with novice participants, but the differences were not significant (all p values > 0.10). Perceived workload was similarly not significantly different between groups, p = 0.33. When compared with external reported scores, the virtual reality trainer was comparable with established high-fidelity virtual reality software in the realism, possibility to act, and quality of interface subscales (all p values > 0.06) but not as immersive in the possibility to examine and self-performance subscales (all p values < 0.009). The virtual reality trainer was not different from workloads experienced in procedural medicine (p = 0.53), which included both real-life and simulation tasks in endoscopy, laparoscopic surgery and clinical anaesthesia.

Discussion

Our virtual reality trainer programme, created to teach novices needling techniques relevant for ultrasound-guided regional anaesthesia, demonstrated construct validity, can provide information to create individualised learning curves, achieved acceptable levels of immersion and generated levels of task workload similar to real-life medical procedures. The results of this study provide initial validation of this virtual reality trainer and confidence for inclusion in future research and clinical use. Furthermore, other software upgrades may be considered including developing the programme to fully simulate a complete ultrasound-guided regional anaesthesia procedure or incorporating gamification [13] such as rewards and friendly competition that encourages learning [14].

A principle of human skills development is the requirement for thousands of hours of deliberate practice to gain expertise [15]. Fractionating a complex procedure such as ultrasound-guided regional anaesthesia into part-tasks allows training resources to be focused on specific skillsets. This allows faster learning and opportunity to pre-train novices to a minimum standard before clinical exposure [16]. There are multiple potential advantages of using high fidelity virtual reality to simulate nerves and needling behaviour compared with traditional training.

These include avoiding practice on commercial phantoms that degrade with repeated use or using biological phantoms with limited shelf-life; immediate performance feedback from the software as demonstrated by the individualised learning curves; scalability and cost-effectiveness as training of novices is limited only by availability of relatively inexpensive virtual reality hardware; avoiding known access bottlenecks due to limited teaching faculty; allowing home learning; and enjoyment of learning using a novel medium.

Our virtual reality trainer was able to discriminate between novice and experienced participants, an important element in validating the software [17]. The group learning curves also replicate previous studies in regional anaesthesia with novices improving more quickly than experienced before plateauing, whilst experienced participants begin and consistently perform with greater success [18, 19]. We also demonstrated that the software can construct learning curves at an individual level as a proof-of-concept. As the metrics required to build the learning curve are continuously measured, we can conceive future software versions providing a real-time learning curve for novices that would help them meet pre-clinical performance thresholds in the context of a competency-based curriculum [20].

We sought to create the virtual reality trainer with a high level of presence, a term referring to the multisensory and cognitive immersion felt by participants when they interact inside the simulated virtual reality environment. Previous studies suggest that for complex procedural tasks, higher levels of presence result in greater `buy-in´ of the simulation to depict real life, with better spatial memory outcomes [21, 22]. The Presence Questionnaire subscales measure how specific aspects of virtual reality interactions accurately mimic the real world [23]. While our virtual reality trainer scored well in most domains, two aspects were reported to be less immersive: possibility to examine (`How well can you pick up objects in virtual reality and closely scrutinise them?´) and self-performance (`How quickly did you adjust to using the controllers in virtual reality?´). We can accept this compromise for two reasons: our virtual reality trainer did not emphasise discovery and exploration of virtual objects but rather on the motor procedural task; and these two domains are relatively small contributors to overall immersion [24]. Nonetheless, the self-performance result suggests that participants will need a longer familiarisation period for the virtual reality equipment than we provided, which is an important consideration for future studies.

We also compared workloads imposed by the virtual reality trainer with real-life medical procedures using the NASA-TLX. This multidomain questionnaire has been widely used in over 10,000 studies and is the most accepted measure of workload during complex, multitasking human endeavours [11]. Participants rated the virtual reality trainer similar to 45 published medical tasks including endoscopy and laparoscopic surgery, suggesting that the virtual trainer is neither too easy nor too difficult and is accurately replicating life-like performance pressure. However, this initial summary will need corroboration with TLX scores specifically from regional anaesthesia procedures in future studies.

There are other limitations to this study. For an initial validation study, a small convenience sample size was used. The software was coded to measure and report pre-determined metrics, but the performance score is a composite and is more weighted towards angulation and withdrawals vs. time taken. Comparisons of presence and workload were made to previously published values, rather than to directly equivalent regional anaesthesia models in phantoms or clinical procedures. Together, these factors could bias the results towards a more positive outcome for the virtual reality trainer. For instance, experienced participants who have already performed many ultrasound-guided regional anaesthesia procedures rated the virtual reality simulation to be less immersive than their novice counterparts. While a computerised and automated measurement of metrics removes subjectivity of scoring by human observers, these are narrow in focus and more holistic endpoints that capture overall performance in ultrasound-guided regional anaesthesia including non-technical skills should be measured. Lastly, we did not formally measure cybersickness associated with virtual reality use, in which users report motion sickness-like symptoms including nausea, dizziness, eye strain, disorientation, fatigue and headaches. Cybersickness is more common with rapidly moving visual scenes or constant head movements, whereas our simulation was restricted to a relatively small imaging area and used more hand rather than head movements thus minimising this risk. There was no participant withdrawal from this study as a result of cybersickness, but future simulations which allow greater user freedom in the virtual environment should formally measure any side effects.

In conclusion, we created a bespoke software programme to teach ultrasound-guided needling skills in virtual reality. This virtual reality trainer allows participants to practice needling skills in an immersive, realistic simulation using real-life ultrasound imagery and replicating real-life transducer and needle movements. The software automatically collects and can provide immediate feedback on performance after each attempt which is one of many potential advantages of using virtual reality. This study provided initial validation of this software as a credible simulation-based training tool for ultrasound-guided regional anaesthesia.

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Supporting Information

Additional supporting information may be found online via the journal website.

Appendix S1. Supplementary data.

