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The effect of mental rotation skills training on ultrasound-guided task performance by novice operators: a rater-blinded, randomised, controlled study

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Abstract

Background: The effect of mental rotation training on ultrasound guided regional anaesthesia (UGRA) skill acquisition is currently unknown. In this study we aimed to examine whether mental rotation skill training can improve UGRA task performance by novice operators.

Methods: Volunteers with no prior experience of UGRA were enrolled in this randomised, controlled study. All volunteers underwent a baseline mental rotation test and their performance of a standardised UGRA task was independently assessed by two raters using composite error score (CES) and global rating scale (GRS). Volunteers with low baseline mental rotation ability were randomised to a mental rotation training group or a no training group. The UGRA assessment was repeated to determine the impact of the training intervention on task performance.

Results: Participants exposed to the training intervention made significantly fewer errors on CES and performed significantly better on GRS compared to those who did not receive the training intervention, even after controlling for their pre-training CES and GRS. This training effect was preserved for CES, but not GRS, when controlled for age, sex and mental rotation test scores.

Conclusion: A simple training intervention, based on the manipulation and rotation of 3-dimensional models, results in improved technical performance of an UGRA task in novice operators with low baseline mental rotation skills.

Introduction

The traditional approach to procedural skill acquisition, typified by the mantra *'see one, do one, teach one'*, is no longer valid in the modern anaesthesia learning environment.[1] The primacy of patient safety in clinical encounters, together with reduced patient exposure during postgraduate training programmes,[2] has led to the exploration of bench-model trainers, manikins, visuohaptic simulators and virtual reality simulators as tools to facilitate procedural expertise.[3] However, these tools are, themselves, associated with barriers to learning, such as equity of access, cost and the need for faculty and trainer development. It would, therefore, be advantageous to pre-train or supplement procedural skill acquisition with inexpensive, self-directed educational interventions to improve procedural skill.[4]

In this regard, mental rotation (defined as the visuospatial ability to manipulate mental representations of three-dimensional objects) is a prime candidate for intervention development.[5] This is based on evidence that mental rotation ability is predictive of performance in endoscopy,[6] ultrasound-guided regional anaesthesia (UGRA),[7] and radiological interpretation.[8] Furthermore, mental rotation skills training is associated with improved performance of mental rotation tasks,[9] which, in turn, have translated to improved novice performance of laparoscopic tasks.[10] Previous studies of mental rotation skills training interventions have either used direct practice with mental rotation problems, visualisation or manual manipulation on a computer screen using a joystick.[11–13] However, none has involved actual physical manipulation of an object, which is a key feature of procedural skill performance in medicine.

Thus, we have developed a novel educational intervention to build on the ideas of manipulation and visualization in order to determine whether mental rotation skills training is associated with improved performance of an ultrasound-guided needle task. Based on previous work,[7] [10] we hypothesise that mental rotation skills training would translate to improved technical performance of an ultrasound-guided needle task in learners with low mental rotation ability. Our primary objective was to compare the technical performance of this task between participants who had mental rotation skills training and those who had not.

Methods

Study design

This single-centre, rater-blinded, volunteer, prospective, randomised, controlled study was prospectively approved by the Faculty of Medicine & Health Sciences Research Ethics Committee, University of Nottingham (Reference: C15092015SoM) and conducted at the University Department of Anaesthesia, Queen's Medical Centre, Nottingham University Hospitals NHS Trust, Nottingham, UK.

Undergraduate students from Medicine or Science, Technology, Engineering and Mathematics courses (STEM) at the University of Nottingham were invited to participate using poster and social media advertising. Students who expressed a wish to participate were provided with a participant information leaflet and an invitation to attend the study. Students with previous experience of UGRA or mental rotation testing or training were excluded.

Study procedures

Following written informed consent on the day of study, a questionnaire was administered seeking baseline participant characteristics including age and gender. All participants, blinded to the study hypothesis, completed a standardised mental rotation test,[14] consisting of 24 problems with each requiring participants to mentally rotate four stimulus figures about their axes and match two of these figures to a single target figure (Figure 1). Participants were divided into those scoring more than 14 out of 24 on the initial mental rotation test (Group MRT-High), indicating an above average ability at mental rotation,[7] and those who scored 14 or less (Group MRT-Low).

All participants then watched an informational video[15] mapped to specific learning objectives, which demonstrated expert performance of standardised UGRA task[16] in an animal-tissue bench model.[17] Participants were instructed to replicate this UGRA task using a 38-mm highfrequency linear array ultrasound transducer (Fujifilm Sonosite Limited, Bedford, UK) and a 50 mm Stimuplex® Ultra 360 needle (B.Braun, Melsungen, Germany) on the same bench model (ultrasound task 1). Participants were independently assessed in this task by two anaesthetists experienced in UGRA who were blinded to participant mental rotation test scores. Each rater completed a validated composite error score (CES) [7 16 18] and global rating scale (GRS) [7 16 19] assessment of participant performance (see online supplementary materials). The raters had undergone specific training and practice in the use of these assessment tools. The CES was calculated by adding the total number of errors, number of needle passes and image quality score for each participant. A lower CES is associated with better accuracy and task performance. The GRS consisted of seven items each rated on a five-point scale. The GRS assesses more general behaviours and the overall performance of the participant. Upon completion of ultrasound task 1, MRT-High participants ceased study involvement. MRT-Low participants continued involvement and were randomised into two parallel groups by six-block design using an online random number generator:[20] those who would receive the mental rotation training intervention (group MRT-Low (Training)) and those who would not (group MRT-Low (No Training)).

Intervention

The mental rotation training intervention lasted 30 minutes and required participants to view in a mirror a two-dimensional image of a three-dimensional model constructed from Lego Duplo® bricks (LEGO System A/S, Billund, Denmark), and then to recreate the model with only the mirror image to view (Figure 2). After they had completed building the model, they were able to compare it directly with the original model. If they failed the task, they were asked to return to the mirror and make good any errors. This process was repeated until the participant completed the model correctly. Participants in the training group were given 30 minutes to repeat this process for up to ten models of increasing difficulty. Participants randomised to no training were taken to a separate room and asked to wait for 30 minutes.

Participants in both groups then repeated the same mental rotation test. Following this, both raters re-assessed participant performance in the same standardised UGRA task (ultrasound task 2). Both raters remained blind to group allocation. Study participation ceased once ultrasound task 2 was complete.

Statistical analysis

We used the Kolmogorov-Smirnoff test to test whether outcome data were normally distributed or not. Normally distributed data are presented as mean (SD), and non-normally distributed data are presented as median (Interquartile range (IQR)). We calculated the intra-class correlation (ICC) for each assessment to determine their inter-observer reliability. We assessed the internal consistency of each assessment by calculating Cronbach's alpha co-efficient and the associated standard error of the mean (SEM).

The primary outcome measure was the composite error score and the secondary outcome measures were global rating scale and mental rotation test score. We initially modelled count data for CES using Poisson models and if these were over-dispersed we used negative binomial modelling. Ordinary least squares models were used to analyse GRS data. To explore the effects of the training intervention on task performance we regressed post-intervention scores for CES and GRS to a training dummy (0 = not trained, 1 = trained) for participants in Group MRT-Low. In these models, we controlled for age and gender since both affect mental rotation[21] and therefore may influence outcomes.

Sample size calculation

Based on the effect size associated with laparoscopic skill acquision,[10] we calculated that 20 participants per group would be required to achieve a power of 0.90 with a p-value of 0.05 to detect a minimum primary outcome effect size of r = 0.3 – 0.5.

Results

A study flow diagram is shown in Figure 3. Cronbach's alpha (SEM) for CES was 0.732 – 0.769 (0.92 – 1.59) across both study periods and both raters. Cronbach's alpha (SEM) for GRS was 0.917 – 0.945 (0.82 – 1.01) across both study periods and both raters. The pre- and post-training ICC between the two raters were 0.96 (r = 0.94) and 0.95 (r = 0.95) for CES and 0.73 (r = 0.59) and 0.88 (r = 0.81) for GRS. As such, we summed the rater scores for each participant, for both assessments. There was only one rater for two participants in group MRT-Low (No training); these data were not analysed for CES or GRS.

Baseline characteristics

The mean (SD) age was 20.3 (1.6) years in group MRT-High, 21.7 (3.6) years in group MRT-Low (Training) and 24.0 (6.5) years in group MRT-Low (No training). There were 16 (72.7%) male participants in Group MRT-High, five (21.7%) males in group MRT-Low (Training), and four (20.0%) males in group MRT-Low (No training). CES was not normally distributed. Median (IQR) CES for ultrasound task 1 was 16.5 (7.8 – 23.0) for Group MRT-High, 19.0 (15.0 – 27.0) for group MRT-Low (Training), and 15.5 (7.8 – 20.8) for group MRT-Low (No Training). There was no difference in CES between the groups for ultrasound task 1 (Kruskall-Wallis; $X^2(2) = 4.93$, $p = 0.085$). Mean (SD) GRS for ultrasound task 1 was 34.0 (13.3) for group MRT-High, 24.9 (9.9) for group MRT-Low (Training), and 33.3 (11.6) for group MRT-Low (No training). GRS for group MRT-Low (Training) was significantly lower (indicated poorer task performance) than group MRT-High and group MRT-Low (No training) (one-way ANOVA; F = (2, 60) 4.21, $p = 0.019$). Mean (SD) scores for the baseline mental rotation test were 17.6 (2.4) for group MRT-High, 9.7 (3.0) for group MRT-Low (Training) and 9.0 (3.2) for group MRT-Low (No training). Baseline mental rotation score for group MRT-High was significantly higher than groups MRT-Low (Training & No training) (one-way ANOVA; F = (2, 62) 60.31, $p < 0.001$)

Mental rotation effects

Simple zero-order corrections (Spearman's Rho) showed that higher mental rotation scores at baseline were associated with a lower CES for ultrasound task 1, i.e. fewer errors (ρ = - 0.32, p = 0.012), and with a higher GRS for ultrasound task 1, i.e. overall performance (ρ = 0.40, p = 0.001). For ultrasound task 2, improved mental rotation scores were not associated with improved CES (ρ = - 0.26, p = 0.101). However, higher mental rotation scores were still associated with improved GRS for ultrasound task 2 (ρ = 0.31, p = 0.05).

Effect of training intervention on task performance

Summary data for the effect of the training intervention on CES, GRS and mental rotation test score are presented in Figure 4. Tables 1 & 2 summarise regression models for CES and GRS. The count data for CES were over dispersed (Pearson's dispersion = 8.22), therefore, these data were modelled using a negative binomial regression. Participants exposed to the training intervention made significantly fewer errors compared to those who did not receive the training intervention, even after controlling for their pre-training CES. Those who were younger also made significantly few errors. Likewise, participants exposed to the training intervention scored significantly higher GRS than those who did not receive the training intervention, even when their pre-training GRS was controlled.

To ensure the effects of the training intervention are not artefacts of controlling for age, sex, and mental rotation test scores, we ran a negative binomial regression for the post-training CES and ordinary least squares regression for the post-training GRS without the covariates. Participants exposed to the training intervention made significantly fewer errors measured by CES (B = -0.75 (SE = 0.18), p = 0.002, 95% CI = -0.94 – -0.21). However, there was no training effect on GRS (B = -0.27 (SE = 3.48), p = 0.997, 95% CI = -7.22 - 6.67).

Discussion

This study has shown that a simple training intervention, based on the manipulation and rotation of 3-dimensional Lego Duplo® brick models, leads to improved technical performance of an ultrasound-guided regional anaesthesia task in novice operators with low mental rotation skills. Specifically, this relates only to reduced error during task performance (CES), but not to the more general, overall performance of the task (GRS). Of note, the improvement in task performance related to the training intervention occurred independent of any gains in mental rotation ability, which did not improve beyond that achieved by test repetition alone. Previous studies have shown that mental rotation can be improved by engaging in spatial tasks, but these have been complex, intensive and sometimes lasting up to a day.[10] In contrast, our novel training intervention is simple, and not as time or resource intensive. This difference is likely to account for the failure of our intervention to improve mental rotation test scores in our study; to change mental rotation skills per se would require a more intensive and extensive training intervention. While our intervention was inspired by the concept of mental rotation, it was not designed to change mental rotation, rather it was designed to enhance ultrasound-guided needle task performance. Additionally, previous studies have not pre-selected people based on their mental rotation ability. The pre-selection of those who are low scorers restricts the overall range of possible change in mental rotation test scores.

We believe that the training intervention described in this study is generalizable to any procedural task that requires the manipulation and rotation of a medical device. Theoretically, any task that enhances spatial awareness skill should be beneficial to any other task that requires such skills. Therefore, in order to improve procedural task performance, learners could train on a very different task from that performed clinically. In this case, training with

Lego Duplo® brick models is generalizable to the much more complex spatial array of the ultrasound task.

We have confirmed previous findings that mental rotation test scores are predictive of composite error score and global rating scale score.[7] We had previously been unable to suggest a mental rotation test score below which training interventions would provide the most benefit to the learner in terms of procedural skill acquisition. Based on our findings, novice learners with a mental rotation test score less than 15 benefit from our simple training intervention. However, we are unable to state whether those individuals with higher mental rotation test scores would benefit and to what extent.

We have studied UGRA task performance by STEM undergraduates on an inanimate animal-tissue bench model in a non-clinical environment. Thus, it is unclear whether the performance gains we have measured would arise clinically in the hands of an anaesthetist in-training. In mitigation, previous studies have demonstrated that medical students' performance of an UGRA task is comparable to that of novice doctors in-training.[16 18] It is difficult to simulate the stress induced by initial clinical practice in UGRA, which is known to produce detrimental and variable effects on performance.[22–24] However, it is likely that we induced similar levels of stress in our participants due to the examination-like conditions imposed on them, added to their real-time assessment without feedback on their performance. We did not include summed composite error and global rating scale scores for participants 128 and 129 who were allocated to the non-training group. This was due to unanticipated, late unavailability of a rater. Unfortunately, we had exhausted our supply of available STEM undergraduates, such that we failed to recruit any further volunteers. Thus, we may have created a type-1 error due to a lack of statistical power.

On balance, we have demonstrated that a simple, low resource mental rotation skills training intervention can improve technical performance of an ultrasound-guided needle task in novice operators with low mental rotation ability. Based on our findings, mental rotation test screening of novice UGRA learners coupled with our training intervention could enhance expertise acquisition in UGRA for this group of learners. In the absence of screening, a more pragmatic approach might be to provide the training intervention to all UGRA novices, since it requires little resource. Future avenues of enquiry should examine whether our novel training intervention transforms to enhanced performance of other skills used in anaesthetic practice such as flexible videobronchoscopy[25] and whether such findings are mirrored in clinical practice.

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Authors' contributions

Study design/planning: J.G.H., N.M.B., E.F., R.A.M. Study conduct: D.W.H., R.K., S.S., R.A.M. Writing and revising paper: all authors.

Declaration of interests

D.W.H: none declared

S.S: none declared

R.K: none declared

E.F: none declared

J.G.H: is the associate editor-in-chief of the BJA. J.G.H. accepts fees for advising in civil, criminal and coronial medicolegal cases.

N.M.B: none declared

R.A.M: none declared

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Tables

Table 1. Negative binomial regression model for the effect of the training intervention on CES. Coefficients are unstandardized (95% CI). n = 41 consisting of group MRT-Low (Training) n = 23 and group MRT-Low (No training) n = 18. (SE = Standard error)

	Coefficient (SE)	p-value	95% CI
Training Intervention (0 = no training, 1 = training)	-0.60 (0.17)	< 0.001	-0.92 – -0.26
Mental rotation test score before training (MRT-1)	-0.05 (0.04)	0.259	-0.13 – 0.03
CES before training	0.01 (0.007)	0.161	-0.004 – 0.02
Age	-0.03 (0.02)	0.033	-0.06 – -0.002
Sex (0 = female, 1 = male)	0.121 (0.23)	0.590	-0.32 – 0.57
Mental rotation test score after training (MRT-2)	-0.008 (0.03)	0.785	-0.07 – 0.05
Constant	4.33 (0.54)	0.000	3.28 – 5.38
α	0.21 (0.05)		0.12 – 0.34
R^2	0.07		

Table 2. Ordinary least squares regression model for the effect of the training intervention on GRS. Coefficients are unstandardized (95% CI). N = 41 consisting of group MRT-Low (Training) n = 23 and group MRT-Low (No training) n = 18. (SE = Standard error)

	Coefficient (SE)	p-value	95% CI
Training Intervention (0 = no training, 1 = trained)	6.15 (2.99)	0.048	0.06 – 12.13
Mental rotation test score before training (MRT-1)	-0.32 (0.69)	0.648	-1.74 – 1.09
GRS before training	0.63 (0.15)	0.000	0.33 – 0.93
Age	0.39 (0.26)	0.144	-0.14 – 0.92
Sex (0 = female, 1 = male)	-5.35 (3.54)	0.140	-12.55 – 1.84
Mental rotation test score after training (MRT-2)	0.43 (0.48)	0.380	-0.55 – 1.40
Constant	3.45 (7.87)	0.664	-12.54 – 19.44
R^2	0.50		

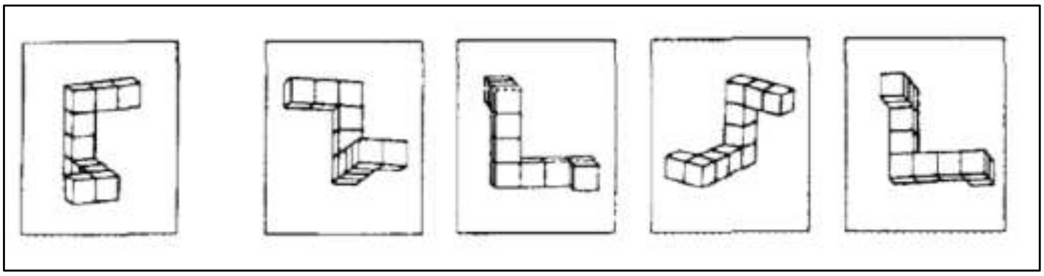
Legends to figures

Figure 1. Example item from mental rotation test. A target figure on the left and four stimulus figures on the right. The participant must find the two stimulus figures on the right which match the single target figure on the left. Reproduced with permission.[14]

Figure 2. Room set-up for performance of mental rotation training.

Figure 3. Study flow diagram.

Figure 4. Ultrasound task performance and mental rotation test score before the training intervention (ultrasound task 1) and after training (ultrasound task 2) in participants exposed to training (MRT-Low (Training); n = 23), and in those not exposed to it (MRT-Low (No training); n = 18). **Panel A** Boxplot of CES (median, (IQR)) and whiskers (1.5 x IQR) with outliers (*). **Panels B & C** Mean (95% CI) GRS and MRT score. Horizontal dashed lines represent the median (IQR) or mean (95% CI) CES, GRS or MRT score for participants in group MRT-High (n = 22). A lower CES score is associated with fewer errors during task performance. A higher GRS is associated with improved task performance. A higher mental rotation test score is associated with better mental rotation performance.



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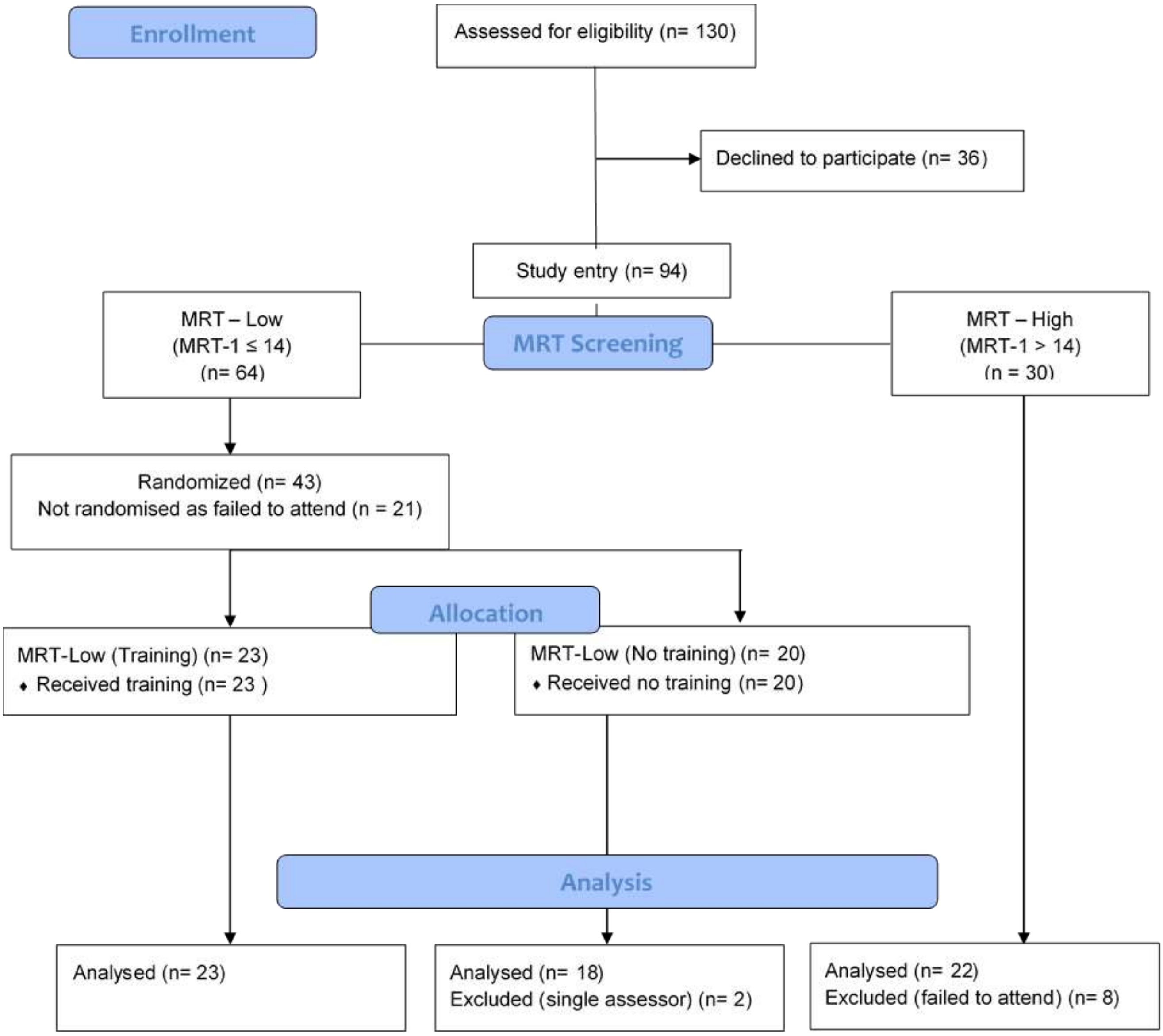

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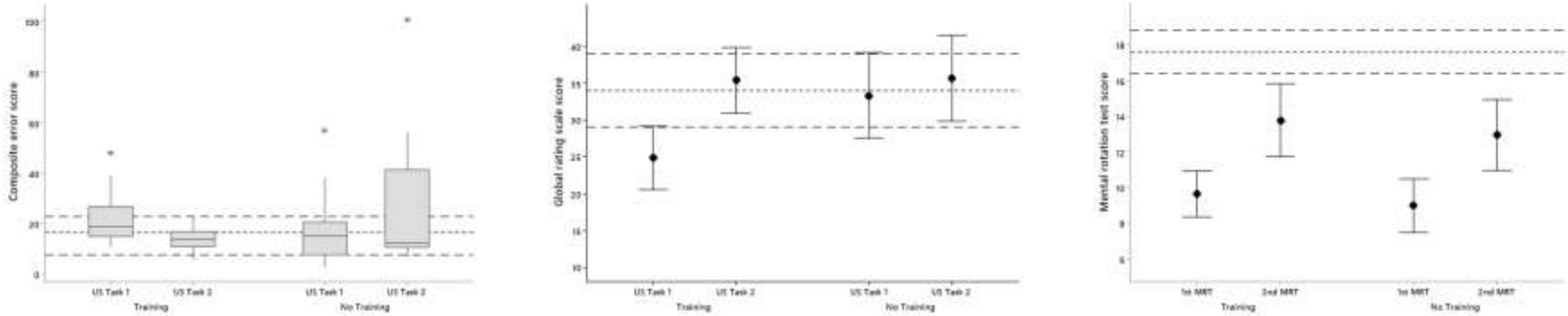

Panel A Composite error score **Panel B** Global rating scale score **Panel C** Mental rotation test score

Figure 4. Ultrasound task performance and mental rotation test score before the training intervention (ultrasound task 1) and after training (ultrasound task 2) in participants exposed to training (MRT-Low (Training); n = 23), and in those not exposed to it (MRT-Low (No training); n = 18). **Panel A** Boxplot of CES (median, (IQR)) and whiskers (1.5 x IQR) with outliers (*). **Panels B & C** Mean (95% CI) GRS and MRT score. Horizontal dashed lines represent the median (IQR) or mean (95% CI) CES, GRS or MRT score for participants in group MRT-High (n = 22). A lower CES score is associated with fewer errors during task performance. A higher GRS is associated with improved task performance. A higher mental rotation test score is associated with better mental rotation performance.