Changes in attentional resources during the acquisition of laparoscopic surgical skills

M. Thomaschewski 1,2,3*, M. Heldmann 2,3, J. C. Uter 2, D. Varbelow 1, T. F. Münte 2,3 and T. Keck 1

1Department of Surgery, University of Lübeck, Lübeck, Germany
2Department of Neurology, University of Lübeck, Lübeck, Germany
3Institute of Psychology II, University of Lübeck, Lübeck, Germany

*Correspondence to: Department of Neurology, University Medical Centre Schleswig-Holstein, Campus Lübeck, 23538 Lübeck, Germany (e-mail: thomas.muente@neuro.uni-luebeck.de)

Abstract

Background: Increasing familiarity and practice might free up mental resources during laparoscopic surgical skills training. The aim of the study was to track changes in mental resource allocation during acquisition of laparoscopic surgical skills.

Methods: Medical students with no previous experience in laparoscopic surgery took part in a 5-week laparoscopic training curriculum. At the beginning and end of the training period, one of the training tasks was combined with a secondary auditory detection task that required pressing a foot switch for defined target tones, creating a dual-task situation. During execution of the two concurrent tasks, continuous electroencephalographic measurements were made, with special attention to the P300 component, an index of mental resources. Accuracy and reaction times of the secondary task were determined.

Results: All 14 participants successfully completed the training curriculum. Target times for successful completion of individual tasks decreased significantly during training sessions (P < 0.001 for all tasks). Comparing results before and after training showed a significant decrease in event-related brain potential amplitude at the parietal electrode cluster (P300 component, W = 67, P = 0.026), but there were no differences in accuracy (percentage correct responses: W = 48, P = 0.518) or reaction times (W = 42, P = 0.850) in the auditory detection task.

Conclusion: The P300 decrease in the secondary task over training demonstrated a shift of mental resources to the primary task: the surgical exercise. This indicates that, with more practice, mental resources are freed up for additional tasks.

Introduction

The rapid progress in surgery with increasing use of laparoscopic and robotic-based minimally invasive techniques presents new challenges for the acquisition of surgical skills. Simulation-based training is used widely to develop motor skill learning 1–3 needed for minimally invasive surgery (MIS) (similar to that when learning a musical instrument 4,5). The learner must cope with different haptics, two-dimensional image interpretation, and the fulcrum effect with paradoxical movement in many situations. Attentional resources available in novices are limited owing to the complexity of the task, especially at the beginning of the learning curve, interfering with ability to cope with disturbances or complications during the exercise or during an operation. A number of different simulation environments have been developed to study the learning trajectories for different skills required for MIS, and to assess the accuracy, speed, and efficiency of movements 1–5.

The neuroscience literature on the acquisition of motor skills is sparse regarding the neural underpinnings and prerequisites of skill learning 6–9, and this has been largely neglected in the development of simulator-based MIS training programmes. Instead, the number of repetitions has been used widely as a rough discriminator of motor skill competence.

Brain event-related brain potentials (ERPs) are small voltage fluctuations in the human electroencephalogram (EEG) that can be recorded non-invasively from the intact scalp of a volunteer, and are induced by external events, such as sensory stimuli 10. The ERPs are extracted from the EEG by averaging over a number of similar events.

ERPs have been used extensively 20–25 to assess mental resource allocation in dual-task situations. In particular, the P300 component of the ERP to stimuli in the secondary task has been used as a marker to track control dynamics in the primary task 23,26–28.
This experimental study involved a dual-task situation in which an additional auditory detection task was included during a laparoscopic surgical task. Mental resources at the beginning and end of a 5-week laparoscopic training programme were evaluated using ERPs. The hypothesis was that laparoscopic training and increasing familiarity in performing laparoscopic tasks should free up mental resources for additional (secondary) tasks.

**Methods**

**Lübeck Toolbox curriculum**

The Lübeck Toolbox (LTB) curriculum was used for MIS training. It consisted of six related exercises: pack your luggage, weaving, Chinese jump rope, triangle cut, hammer cut, and suturing (Fig. 1). The LTB exercises were performed as described previously.9

The LTB video box trainer (LTB Germany, Lübeck, Germany) and the following instruments were used for MIS training: atraumatic grasping forceps (Endopath V, 5-mm Overholt 5DCD; Ethicon Endo-Surgery, Cincinnati, Ohio, USA), laparoscopic scissors (Endopath V, laparoscopic scissors, curved, 5mm; Ethicon Endo-Surgery) and needle drivers (Endopath V, 5-mm needle holder E705R; Ethicon Endo-Surgery). VicrylTM SH PLUS 3-0 (Ethicon, Norderstedt, Germany) was used as suture.

**Lübeck Toolbox curriculum analysis**

The number of repetitions and duration of each repetition to reach a defined training criterion was used to operationalize the learning progress. These numbers were obtained from previous studies on the LTB curriculum.8,9 For each exercise and subject, quartiles of the numbers of repetitions were calculated and used to derive the mean duration per quartile. For each exercise, the Friedmann test was applied to test for significant learning progress (R version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria).

**Study design and event-related potential task**

This was an experimental study performed in the Departments of Surgery and Neurology, University of Lübeck, Germany. The study was approved by the Ethics Committee of the Universität zu Lübeck (ethics committee protocol 19-095). Informed consent was obtained from all participants at the beginning of the study. Medical students with no previous experience in laparoscopic surgery took part in a 5-week laparoscopic training programme according to the LTB curriculum. At the beginning and the end of the LTB curriculum, the study participants participated in a dual task with EEG recording. The primary task was the pack-your-luggage exercise from the LTB, and the secondary task comprised an auditory change detection task. A jingle at the beginning of each run indicated ‘begin with the pack-your-luggage exercise’. With an offset of 2 s, the auditory change detection task started. Two alternating tones (800 and 880 Hz, interstimulus interval (ISI) 1100 ms) were presented via headphones. With a probability of 0.1, a tone was repeated instead of presenting an alternative one. It was the subject’s task to indicate a sound repetition by pushing a foot switch with their dominant foot. Sound loudness was adjusted individually at the beginning of each session to a comfortable level. The change detection task was implemented in Psychtoolbox version 3.0.14 (http://psychtoolbox.org, running under Matlab® 2018b (https://mathworks.com), and Windows® 7 (Microsoft, Redmond, Washington, USA)). The tones were presented via Sennheiser headphones (Wedemark, Germany) connected to a Steinberg U12 USB audio interface (Hamburg,

![Fig. 1 Six training tasks of the Lübeck Toolbox and duration of exercises](#)

Tasks: a pack your luggage, b weaving, c Chinese jump rope, d triangle cut, e hammer cut, and f suturing. g Mean(s.d.) duration per quartile of performed runs per exercise.
Germany). Auditory stimulus presentation was stopped when participants finished the training task.

Electroencephalogram recording and analysis

EEGs were recorded using 16 gtec Sahara dry electrodes connected to a gtec USB amplifier system (Thanstetten, Austria). Electrodes (F3, Fz, F4, Fc5, Fcz, Fc6, C3, Cz, C4, Cp5, Cp6, P3, Pz, Oz) were mounted in an elastic cap and referenced to the right mastoid. To control for eye movement artefacts, bipolar standard electrodes were placed at the left and right outer canthus of the eyes (horizontal electro-oculographic (HEOG) artefacts), and below and above the right eye (vertical electro-oculographic (VEOG) artefacts). Data were recorded using a sampling rate of 250 Hz (bandpass filtered 0.1–30 Hz). EEGLAB and ERPLAB toolboxes were used for EEG data analysis. The EEG data processing pipeline comprised epoching to the stimulus presentation (−1500 to 1500 ms), and identification of EOG and other artefacts using independent component analysis implemented in EEGLAB. Subsequently, identified artefact components were subtracted from the EEG data, and individual ERPs for the conditions before/after training × standard/target were calculated by averaging per condition and subject using the mean activity between −100 and 0 ms as baseline. Finally, ERPs were individually standardized using z-transformation. Because of excessive movement artefacts, two subjects had to be excluded from the analysis, resulting in a final sample of 12 subjects. Parietal attention effects were parameterized by averaging potentials across the centroparietal/parietal electrode positions Cp5, Cp6, P3, Pz, and P4, and calculating the mean amplitude between 400 and 600 ms after stimulus presentation. For the statistical evaluation of the training effect, we first calculated the difference between standard and target tone per subject and condition (before/after training). The resulting difference scores were subjected to a Wilcoxon matched pairs test comparing the before with the after training condition. The use of the non-parametric Wilcoxon matched-pairs test is determined by the group size.
Results

Lübeck Toolbox curriculum

All 14 participants (mean(s.d.) age 26.07(2.33) years; 10 women) successfully completed the LTB curriculum. The median number of repetitions participants needed to reach the criterion for the LTB exercises was 30 (range 24–70) for the luggage task, 40 (24–72) for weaving, 32 (12–71) for Chinese jump rope, 27 (11–76) for triangle cut, 23 (9–52) for hammer cut, and 17 (11–56) for suturing. The mean exercise times for the LTB tasks per quartile decreased significantly over time for each of the seven training sessions all \((P < 0.001)\) (Fig. 1).

Auditory task: event-related potentials and behaviour

ERP analysis revealed a large positivity at central–parietal electrode sites for the target tone before training (Figs 2 and 3). This effect was absent after training. Comparison of the difference target–standard tone between before and after training revealed a significant effect at the parietal electrode cluster \((W = 67, P = 0.026)\). This decrease in ERP amplitude was not accompanied by significant before–after differences in accuracy (percentage correct responses: \(W = 48, P = 0.518\)) and reaction times \((W = 42, P = 0.850)\) in the auditory change detection task.

Discussion

The LTB features several tasks that mimic surgical techniques used in minimally invasive laparoscopic surgery. The present study corroborated earlier results obtained with the LTB\(^8,9\), that naive trainees rapidly improved performance to criterion within several training sessions. The repeated (target) tones were associated with a P300 component in the ERP.

The amplitude of the P300 component has been interpreted as an index for mental resources that are available for processing of the task at hand, with reduced P300 indicating reduced mental resources\(^23,25–28\). The reduced P300 amplitude to auditory target stimuli at the end of the training period therefore indicates that fewer resources are allotted to the secondary auditory task and, by inference, more resources are available for the primary surgical motor task. The increasing speed and precision of the surgical task was thus achieved by recruitment of mental processing resources, shielding the important primary task from interference by the auditory task. It seems reasonable to conclude that, in this
early training stage, improvement is mainly due to reallocation of mental resources.

In both animals and humans, learning of a new skill entails an initial phase of rapid improvement in performance, and a subsequent phase of more gradual improvements as skills become more automatic. These stages are characterized by distinct neural mechanisms. In experimental studies, the early stages of visuomotor learning have been shown to involve the dorsomedial striatum, equivalent to the putamen in primates. Functional neuroimaging has been used to describe by the dorsolateral striatum, equivalent to the putamen in primates. Functional neuroimaging has been used to describe changes in piano players and non-musicians revealed by functional magnetic-resonance signals. 

The present study attests to the value of ERPs in tracking changes in mental resource allocation during acquisition of MIS skills. Neuroscientific measures can reveal different stages of skill learning, and have the potential for evaluation of MIS surgical skills acquisition independent of roughly defined numerical repetitions. Although the present research was restricted to novice learners and only tracked the first stages of skill learning, studies examining dual-task performance over a long period of time as well as those involving expert surgeons might point to greater applicability, such as the ability to differentiate between trained and untrained surgeons or indicators of progress during a learning curve.

**Funding**

DFG

**Acknowledgements**

M.T. and M.H. contributed equally to this work. T.F.M. is supported by the Deutsche Forschungsgemeinschaft (DFG) and the German Federal Ministry of Research and Technology. Analytical methods, study materials, and the data sets generated during the present study are available from the corresponding author on reasonable request.

**Disclosure** The authors declare no conflict of interest.

**References**

1. Buckley CE, Kavanagh DO, Traynor O, Neary PC. Is the skillset obtained in surgical simulation transferable to the operating theatre? Am J Surg 2014;207:146–157
2. Hund-Georgiadis M, von Cramon DY. Motor-learning-related changes in piano players and non-musicians revealed by functional magnetic-resonance signals. Exp Brain Res 1999;125: 417–425
3. Altenmüller E, Furuya S. Brain plasticity and the concept of metaplasticity in skilled musicians. Adv Exp Med Biol 2016;957: 197–208
4. Zendejas B, Brydges R, Hamstra SJ, Cook DA. State of the evidence on simulation-based training for laparoscopic surgery: a systematic review. Ann Surg 2013;257:586–593
5. Seymour NE, Gallagher AG, Roman SA, O’Brien MK, Bansal VK, Andersen DK et al. Virtual reality training improves operating room performance: results of a randomized, double blinded study. Ann Surg 2002;236:458–463
6. Fraser SA, Klassen DR, Feldman LS, Ghitulescu GA, Stanbridge D, Fried GM. Evaluating laparoscopic skills: setting the pass/fail score for the MISTELS system. Surg Endosc 2003;17:964–967
7. Ritter EM, Scott DJ. Design of a proficiency-based skills training curriculum for the fundamentals of laparoscopic surgery. Surg Innov 2007;14:107–112
8. Laubert TTM, Auerswald P, Zimmermann M, Brüheim L, Keck T, Benecke C. Implementation of a laparoscopic simulation training in undergraduate medical education—the Lübeck Toolbox-Curriculum. Zentralbl Chir 2017;142:1–7
9. Laubert T, Esnaashari H, Auerswald P, Hofer A, Thomaschewski M, Bruch HP et al. Conception of the Lübeck Toolbox curriculum for basic minimally invasive surgery skills. Langenbecks Arch Surg 2018;403:271–278
10. Molenberghs P, Cunningham R, Mattingley JB. Brain regions with mirror properties: a meta-analysis of 125 human fMRI studies. Neurosci Biobehav Rev 2012;36:341–349
11. Ossmy O, Mukamel R. Perception as a route for motor skill learning: perspectives from neuroscience. Neuroscience 2018;382: 144–153
12. Papale AE, Hooks BM. Circuit changes in motor cortex during motor skill learning. Neuroscience 2018;368:283–297
13. Makino H, Hwang EJ, Hedrick NG, Komiyama T. Circuit mechanisms of sensorimotor learning. Neuron 2016;92:705–721
14. Luck SJ. An Introduction to the Event-Related Potential Technique. Cambridge: MIT Press, 2014
15. Fernandes MS, Moscovitch M. Divided attention and memory: evidence of substantial interference effects at retrieval and encoding. J Exp Psychol Gen 2000;129:155–176
16. Naveh-Benjamin M, Craik FIM, Guez, J, Kreuger S. Divided attention in younger and older adults: effects of strategy and relatedness on memory performance and secondary costs. J Exp Psychol: Learn Mem Cogn 2005;31:520–537
17. Camiccioli R, Howieson D, Lehman S, Kaye J. Talking while walking: the effect of a dual task in aging and Alzheimer’s disease. Neurology 1997;48:955–958
18. Mathias AP, Vogel P, Knauff M. Different cognitive styles can affect performance in laparoscopic surgery skill training. Surg Endosc 2019;34:4866–4873
19. Taatgen NA, Huss D, Dickson D, Anderson JR. The acquisition of robust and flexible cognitive skills. J Exp Psychol 2008;137:548–565
20. Duncan SJ, Gosling A, Panchuk D, Polman RCJ. Validation of a multidirectional locomotive dual-task paradigm to evaluate task-related differences in event-related electro-cortical activity. Behav Brain Res 2019;361:122–130
21. Han M, Shi L, Jia S. Attentional resources modulate error processing-related brain electrical activity: evidence from a dual-task design. Brain Res 2017;1670:68–75
22. Zendel BR, de Boysson C, Mellah S, De Montel JF, Belleville S. The impact of attentional training on event-related potentials in older adults. Neurobiol Aging 2016;47:10–22
23. Scheer M, Bültthoff HH, Chuang LL. Steering demands diminish in undergraduate medical education—the Lu¨ beck Toolbox-Curriculum. Zentralbl Chir 2012;123:1123–1130
24. Kida T, Kaneda T, Nishihiira Y. Dual-task repetition alters event-related brain potentials and task performance. Clin Neurophysiol 2012;123:1123–1130
25. Schubert M, Johannes S, Koch M, Wieringa BM, Dengler R, Münte TF. Differential effects of two motor tasks on ERPs in an
auditory classification task: evidence of shared cognitive resources. Neurosci Res 1998;30:125–134

26. Isreal JB, Chesney GL, Wickens CD, Donchin E. P300 and tracking difficulty: evidence for multiple resources in dual-task performance. Psychophysiology 1980;17:259–273

27. Wickens CD, Kramer AF, Vanasse L, Donchin E. Performance of concurrent tasks: a psychophysiological analysis of the reciprocity of information-processing resources. Science 1983;221:1080–1082

28. Sirevaag EJ, Kramer AF, Coles MGH, Donchin E. Resource reciprocity: an event-related potentials analysis. Acta Psychol 1989;70:77–97

29. Yin HH, Mulcare SP, Hilário MR, Clouse E, Holloway T, Davis MI et al. Dynamic reorganization of striatal circuits during the acquisition and consolidation of a skill. Nat Neurosci 2009;12:333–341

30. Luft AR, Buitrago MM. Stages of motor skill learning. Mol Neurobiol 2005;32:205–216

31. Karni A, Meyer G, Jezzard P, Adams MM, Turner R, Ungerleider LG. Functional MRI evidence for adult motor cortex plasticity during motor skill learning. Nature 1995;377:155–158

32. Miyachi S, Hikosaka O, Lu X. Differential activation of monkey striatal neurons in the early and late stages of procedural learning. Exp Brain Res 2002;146:122–126

33. Miyachi S, Hikosaka O, Miyashita K, Karadi Z, Rand MK. Differential roles of monkey striatum in learning of sequential hand movement. Exp Brain Res 1997;115:1–5

34. Schneider W, Shiffrin RM. Controlled and automatic human information processing: 1. Detection, search, and attention. Psychol Rev 1977;84:1–66

35. Logan GD. Toward an instance theory of automatization. Psychol Rev 1988;95:492–527

36. Ahissar M, Laiwand R, Hochstein S. Attentional demands following perceptual skill training. Psychol Sci 2001;12:56–62

37. Maquestiaux F, Hartley AA, Bertsch J. Can practice overcome age-related differences in the psychological refractory period effect? Psychol Aging 2004;19:649–667

38. Strobach T, Schubert T. No evidence for task automatization after dual-task training in younger and older adults. Psychol Aging 2017;32:28–41

39. Delorme A, Makeig S. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J Neurosci Methods 2004;134:9–21

40. Lopez-Calderon J, Luck SJ. ERPLAB: an open-source toolbox for the analysis of event-related potentials. Front Hum Neurosci 2014;8:213