Use of functional near-infrared spectroscopy to evaluate cognitive change when using healthcare simulation tools

Taylor, N., Wyres, M., Bollard, M. & Kneafsey, R.

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Title: The Use Of Functional Near-Infrared Spectroscopy To Evaluate Cognitive Change When Using Healthcare Simulation Tools.

Authors:

Dr Natasha Taylor, Faculty of Health and Life Sciences, Coventry University, United Kingdom
https://orcid.org/0000-0001-8274-6487

Martyn Wyres, Faculty of Health and Life Sciences, Coventry University, United Kingdom
https://orcid.org/ 0000-0002-6727-5995

Dr Martin Bollard, Faculty of Health and Life Sciences, Coventry University, United Kingdom
https://orcid.org/0000-0001-8188-0510

Dr Rosie Kneafsey, Faculty of Health and Life Sciences, Coventry University, United Kingdom
https://orcid.org/0000-0002-6613-5296

Corresponding author:

Dr Natasha Taylor.
Faculty of Health and Life Sciences, Coventry University, Richard Crossman Building, Jordan Well, Coventry CV1 5RW, United Kingdom Natasha.Taylor@coventry.ac.uk +44 (0)24 7688 7688

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Abstract

Background
The use of brain imaging techniques in healthcare simulation is relatively rare. However, the use of mobile, wireless technique, such as functional near-infrared spectroscopy (fNIRS) is becoming a useful tool for assessing the unique demands of simulation learning. For this study, this imaging technique was used to evaluate cognitive load during simulation learning events.

Methods
This study took place in relation to six simulation activities, paired for similarity, and evaluated comparative cognitive change between the three task pairs. The three paired tasks were: receiving a i) face-to-face and ii) video patient handover, observing a simulated scene in i) 2D and ii) 360-degree field-of-vision, and on a simulated patient i) taking a pulse and ii) taking a pulse and respiratory rate simultaneously. The total number of participants was *n*=12.

Results
In this study, fNIRS was sensitive to variations in task difficulty in common simulation tools and scenarios, showing an increase in oxygenated haemoglobin concentration and a decrease in deoxygenated haemoglobin concentration, as tasks increased in cognitive load.

Conclusion
Overall, findings confirmed the usefulness of neuro-haemoglobin concentration markers as an evaluation tool of cognitive change in healthcare simulation. Study findings suggested that cognitive load increases in more complex cognitive tasks in simulation learning events. Task performance that increased in complexity therefore affected cognitive markers, with increase in mental effort required.

What this paper adds.

Section 1: What is already known on this subject?

Numerous studies exist to support the use of the brain imaging technique of functional near-infrared spectroscopy. However, limited evidence has studied the outcomes of this brain-imaging tool in healthcare simulation.

Section 2: What this study adds.

This study finds that there is a significant change in cognitive load, as correlated to cortical oxygenation and deoxygenation changes, particularly in the standard healthcare simulation tools of: i) reviewing a simulated scene in 2-dimensions and as a 360-degree field-of-view scene, and ii) taking baseline observations as a single task and as multiple tasks carried out concurrently. The most significant addition of this study is that functional near-infrared spectroscopy is a useful tool to evaluate cognitive change in healthcare simulation.

INTRODUCTION

The preponderance of literature supports simulation as a healthcare learning technique and tool.[1] However, it is the theories of cognitive load that have the potential to either enhance or diminish the effectiveness of that simulation. The principles of cognitive load are embedded within healthcare simulation, as all learners have a finite working memory capacity. It follows then, that to ameliorate these cognitive strains has the potential to improve learning.[2] Therefore, this paper will address how some common simulation tools and techniques affect cognitive load. In the case of this study, cognitive load is evaluated via functional near-infrared spectroscopy.

By using a protocol for evaluating simulation tools or techniques that could be easily delivered in two different ways, one variation against the other could be objectively collected. These tools were patient handover (face-to-face handover compared with video handover), processing of clinical information in the same simulated setting (presented two-dimensionally compared with 360-degree field-of-vision) and simple psychomotor clinical assessment (obtaining one baseline observation compared with obtaining two baseline observations simultaneously). These were chosen to evaluate whether cognitive load of the student in common simulation settings were greater or lower in each of the paired comparisons. Why cognitive load, and its application to healthcare simulation, is so integral to student development is explored further in this section. However, to do this, a basic overview of the neuroimaging technique used is necessary.

Functional near-infrared spectroscopy

Brain imaging (or neuroimaging) refers to the use of imaging techniques to improve human understanding of brain functions. This is done by generating images of the structures and functions of the nervous system. This method is extensively used to support the diagnosis, monitoring and treatment of a range of brain diseases.[3,4] One of these brain imaging techniques is functional near-infrared spectroscopy. Functional near-infrared spectroscopy (fNIRS) is the use of near-infrared spectroscopy (NIRS) for the purpose of functional neuroimaging. It uses specific wavelengths of light, between 650 and 1000 nm, introduced at the scalp. This is used to gain non-invasive measurement of changes in the relative ratios of oxy-Hb and deoxy-Hb in the capillary beds during brain activity. This is shown as a finite increment in the variable, or Δ.

This fNIRS technology works based on the principle of relative transparency to near-infrared light of brain tissues and bone, and the light absorption characteristics of haemoglobin. The amount of haemoglobin in the tissue affects the amount of absorbed light and the relative changes of haemoglobin can be measured through the changes of attenuation, or reduced signal, of light.[5,6,7] During a measurement, a subject wears a cap or headband, usually in direct contact with the skin. Each probe in the cap or band has a source or detector optode inside, the source optode emits light and detector optode quantifies the received light. Each pair of a source and detector optode defines a measured channel. In the case of this study, a 16-channel set was used. However, these optodes have considerable overlap and are unable to pinpoint cortical locations with any reliable certainty and the overall problem of this study, that of changes in cognitive load in general in the paired comparisons, mean that each individual channel changes are not reported. Rather, it is the averaging of all of the channels, with peaked changes overall, that are presented in this study.

FNIRS can only measure activities at the surface of the brain and only at low spatial resolution (cm^2), in comparison with functional magnetic resonance imaging (fMRI). FMRIS can measure activities in any focal area of the whole brain at high spatial resolution (mm^3) but fNIRS has several potential advantages, particularly in healthcare simulation. FNIRS is less sensitive to motion, and therefore more suitable for long measurements and tasks which require movements, as seen in healthcare simulation activity. In addition, fNIRS system and operating costs are much cheaper than fMRI.[5] Nonetheless, despite the advantages and more than twenty years of development since the development of the first commercial fNIRS device, the application of fNIRS in simulation studies is still not widespread.[8,9]. However, it is hoped that this multiple phase study demonstrates the benefits of utilising fNIRS in healthcare simulation and provides the impetus for greater use of mobile brain imaging as an evaluation and research tool.

Cognition

Cognition and learning are considered analogous to healthcare simulation.[10] Therefore, the measurement(s) of cognition would appear to be correlated to the measurement(s) of learning. Where traditionally, assessment based on measures like the performance of actions in simulation occurs, brain imaging may be a useful adjunct to evaluate cognitive change. Cognition can be defined as the mental action or process of acquiring knowledge and understanding through thought, experience, and the senses,[11]. It is the mental processes involving the inputting and storing of information and how the information is then used, that is key here. In principle, cognition is the refining and condensing of the complex and often vast and overwhelming information of the world around us, to more manageable essentials. It is higher order cognition (HOC) that is central to learning and it is these sophisticated thinking skills that are the functions or domains explored in this study. These functions include decision-making, attention, working memory, reasoning and other cognitions [12] central to learning and therefore central to healthcare simulation. It is central also, that cognition is not seen as a single entity concept. There are no clear delineations within the cortex, which makes optical imaging of the brain reliant on macro-, general areas or regions, rather than microscopic identification of individual neuronal pathways for distinct cognitive functions.[8]

Cognitive load

Understanding the way the brain allocates mental resources according to the task demand is critically important for complex and high risk operational settings, such as healthcare simulation. The increase in cognitive workload when faced with a demanding task has been shown to lead to performance failure.[13,14] The cognitive workload construct assumes that task-related brain activity consumes an evident (and measurable) amount of mental resources.[15] One method of measuring cognitive resource engagement is to quantify the energy consumption across several cellular levels of the brain to meet demands of the task(s). The deployment of specialised neural pathways during cognitive activity, relies on a continuous supply of oxygen and glucose through cerebral blood flow, mediated specifically by astrocyte-neuron metabolic cooperation.[16] This change in blood flow due to neuronal activity is referred to as neurovascular coupling. Although this neurovascular coupling may not be directly comparable in all frontal cortex regions, this process is useful to ascertain changes in brain activity. This is done primarily by linking the measure of oxygenation and deoxygenation with the concept of cognitive workload, shown in previous studies showing that mentally demanding tasks require resources in prefrontal-cortex-dependent functions.[17] It is also generally accepted that the frontal lobes are involved when tasks are complex, have unique demands or require considerable attention.[18]

FNIRS as a measure of cognitive load

FNIRS technology has been used to estimate cognitive load in a range of cognition studies.[19] Consistent and reliable changes have been found in the standard n-back test, in oxygenation in the left dorsolateral prefrontal cortex as a function of memory load. In another n-back study,[18] linear increases in brain activation as a function of working memory load were found in both the right and the left prefrontal cortices. Variations in blood flow measured with fNIRS have also been related to the engagement of executive functions such as mental flexibility.[20] Therefore, when used in ecologically valid environments, fNIRS has shown changes in oxy-Hb and deoxy-Hb, when tasks have been increased in difficulty. However, it is important to note, for this study, that smaller differences in task difficulty could not be differentiated reliably.[21]

Research questions

As outlined, the use of fNIRS in healthcare simulation may be a useful adjunct to evaluate cognitive load during running of simulation events, using common simulation tools. Healthcare simulation has well established and evidenced [22] tools and the concept of the extent of cognitive load, as a comparison study, to evaluate the feasibility of fNIRS as a healthcare simulation evaluation is relevant here. The questions posed in this study are purposely comparative in nature, due to dearth of research in neuroimaging in simulation events. It is suitable to take a simulation tool, which may have two related, interchangeable learning outcomes and use fNIRS to evaluate cognitive load of these pairs.

Therefore, the research questions, in simple terms, are comparisons of three types of simulation tools namely: simulated patient handover, situational awareness of a simulated scene, and baseline observations of clinical parameters. These translate to three overarching research questions.

Question 1 What are the differences in cognitive load in participants processing information from video handover compared to face-to-face handover of the same simulated patient?

Question 2 What are the differences in cognitive load in participants processing information from two-dimensional compared to 360 degree field-of-view recording of the same simulated scene?

Question 3 What are the differences in cognitive load in participants taking a radial pulse measurement compared to taking a radial pulse measurement and breathing rate of the same simulated patient?

These comparisons are interlinked, in that they are all simulation tools but each question, and association analysis, is approached as a unique pair of tools, rather than all pairs analysed against all other pairs. This helps to clarify each simulation tool, of itself, rather than the cognitively, educationally, different tools of receiving a patient handover, in comparison with taking a baseline observation or viewing a simulated scene.

METHOD

The optical imaging technique used in this research works by emitting a near-infrared light source into the front part of the brain, where complex higher order thinking occurs. In this technique, a number of optical sensors measure the absorbed light, these sensors are called optodes, and relay the traces of this light absorption into graph or number format. There are multiple traces (or multiple lines presented graphically) because there are multiple channels, or views, of different parts of the frontal cortex. Some of these channels are very similar to others, in that there is limited delineation of views and therefore these channels cannot differentiate between activities in pinpoint areas, but they can measure haemodynamic activity in general areas of the front part of the brain. The general principle underpinning this study is that neural activity can be ascertained in general parts of the frontal cortex of the brain. This activity, in this type of optical imaging, is related to oxygenation. Increased oxygenation to the brain is needed when areas require an increase in metabolic activity (in very simplistic terms), and therefore this type of imaging measures increases (or decreases) in oxygenation and deoxygenation. This process, called neurovascular coupling, is the relationship between local neural activity and the subsequent changes in cerebral blood flow.

Participants

Participants were purposely sampled from academic employees of a nursing, midwifery and allied health school at a large higher education institution. All had at least one degree-level clinical health qualification. Twelve healthy subjects responded to the initial call for participants (age mean $\pm$ standard deviation=35$\pm$10.9 years). All participants were right handed and denied any uncorrected vision defects and denied any relevant drug use history. All participants gave their written informed consent after receiving both a detailed study letter and verbal explanation of the procedure. Organisational ethical approval was sought and gained, reference P78978.

Sample size

Compared to the development of statistical inference methods, relatively little literature has been focused on the development of power analysis methods in neuroimaging data. Theoretical work started as early as the application of RFT (random field theory) to neuroimaging data, with modelled signals in a statistic image as a Gaussian random process,[23] and produced a power surface by expressing power as a function of the threshold height and signal width. The power map [24] can be used to visualize local variability of power in different areas of the brain. In a mock pilot data analysis using two subjects, the T-statistic image from the mock pilot analysis generated a power map and this power map was used to show the estimated power if twelve subjects were included in this analysis to detect signals in the relevant cortices with 80% power. To confirm this finding, a randomly selected set of twelve contrast images from the remaining contrast images in the original data set were analysed. This analysis was performed to detect activations anticipated with the corrected threshold of $p<0.05$. This confirmed the statistically appropriate sample size and therefore, the total number of participants for this study was calculated as $n=12$.

Apparatus

The Biopac Systems UK 2000M imager was used, which provided a wireless, mobile device with data from eighteen optodes (two near) via full head forehead pad. Cognitive Optical Brain Imaging (COBI) Studio, was used, this is a hardware integrated software platform designed for fNIRS imaging systems on a standard laptop computer capture.

Procedure

All participants took part in all pairs of simulation tasks in the same order given below, these three simulation tasks were numbered sequentially throughout this study, as follows: Task 1=handover of a simulated patient tasks were 1i=video handover and 1ii=face-to-face handover of the same simulated patient. Task 2=observation of simulated scene task were 2i=two dimensional observation of a clinical scene and 2ii=360-degree field-of-vision observation of the same scene and Task 3=baseline observations were 3i=pulse rate measurement on simulated patient and 3ii=pulse and respiratory rate measurement on the same simulated patient.

Data filtering

The data were put through a low-pass filter to remove the additional meaningless information. These noisy data responded to a finite impulse response filter with an order of twenty. Motion artefacts and saturation were detected automatically by a Sliding-window Motion Artefact Rejection (SMAR) algorithm.

Data analysis

FnirSoft software was used to calculate oxygenation by applying the Modified Beer-Lambert Law. Once oxygenation data were calculated, all markers and exclude regions were transferred to graphical representations. These graphs displayed the markers: HbR (deoxyhaemoglobin), HbO (oxy-haemoglobin), HbT (total-haemoglobin) and Oxy (difference between oxy- and deoxyhaemoglobin). A block analysis was then carried out, the block was the total segment of data, defined by the start time and end time of each paired task; and contained all channels. All blocks were weighted equally.

This allowed paired event analysis within subjects. Then, to reliably compare these values statistically, the mean ΔHbO and ΔHbR signal intensities during the vascular response (i.e., the peak value reached during the temporal window from onset) were calculated for each participant for each task pair. Temporal variations (Δ) in the cerebral oxyhaemoglobin (ΔHbO) and deoxyhaemoglobin (ΔHbR) concentrations were calculated based on the values of $\Delta\mu\alpha$ at the two wavelengths.[25,26] Therefore, each pair of tasks was measured, each one of the pair of tasks measured relative to the other.

RESULTS

The results of this experiment were able to validate the reliability of the measurements of significant haemodynamic activity with respect to pairs of simulation tasks. To evaluate the scope of this activity, a series of paired sample t-tests were performed on the individual ΔHbO concentration change in the paired tasks.

In the first pair of tasks, video handover of a patient (M=1.99, SD=.09) compared with face-to-face handover of the same clinical patient (M=2.51, SD=0.24), significant difference in optode changes in oxyhaemoglobin was found $t(11)=-20.18$, $p<0.001$. As the t-distribution is symmetrical around zero, this negative statistic shows a 2-tailed significant difference in oxygenation change, acting as a marker of increase in cognitive load, during the face-to-face handover, in comparison with the cognitive load in the video handover condition.

In the second pair of simulation tasks, the changes in oxyhaemoglobin during observation of a simulated scene in two dimensions (M=2.09, SD=.03) compared with viewing the same scene in a 360-degree field-of-vision (M=2.60, SD=.02), significant difference in oxyhaemoglobin change was found $t(11)=-43.45$, $p<0.001$. This shows a significant increase in cognitive load, taken as an indicator of oxyhaemoglobin change, in watching the 360-degree simulated scene, in comparison with the cognitive load in viewing the same scene in the two-dimension condition.

In the third, and final pair of simulation tasks, the change in oxyhaemoglobin in taking a pulse rate on a simulated patient (M=.59, SD=.25) compared with taking a pulse rate and respiratory rate simultaneously on the same simulated patient (M=3.12, SD=.14), showed a significant difference in effect $t(11)=-27.77$, $p<0.001$. The shows a significant increase in cognitive load when carrying out simultaneous pulse and respiratory rate observations, when compared with just pulse rate observation.

DISCUSSION

This study addresses the question of whether fNIRS can evaluate cognitive change in healthcare simulation, specifically using the tools: i) handover of a simulated patient, ii) spatial awareness scene and iii) baseline observations on a simulated patient. Activation was found to increase in all of the task pairs where an increase in complexity occurred. Where working memory load was found to increase, an associated increase in oxygenation change was found. The task paired cognitive load changed despite the repeated measures of the conditions. In other words, in the first paired task, the video handover was presented first. The second paired task, where the face-to-face handover was presented, the clinical presentation of the patient, and their clinical condition and observations were identical in both presentations. Therefore, the increase in cognitive load in the face-to-face condition cannot be explained by a change or additional information given in the face-to-face condition as the information did not change between conditions. Although, it may be that the layering of two, albeit identical, packages of information increased the cognitive workload for the participants. This finding appears counterintuitive, that cognitive load should decrease when the same information is presented in multiple ways and on multiple occasions. It is the mainstay of simulation learning that several passes at the same event helps the learner to process and absorb the information; however, the findings of this study suggests that this may not be as simplistic as the generally accepted tenets of education appear.

For the second task pair, the same spatial awareness exercise of watching a simulated standard healthcare scene, watched on a two-dimensional screen and in a 360-degree field-of-view headset, a significant ΔHbO concentration change in conditions was found, with the 360-degree version showing a significantly increased change in concentration. Observed simulation is used frequently to prepare learners for clinical situations, low fidelity methods include the use of video footage to do this in the form of a lecture or seminar or watching a clinician-patient interaction on a 'flat' two dimensional screen with peers. However, this study appears to show a significant increase in activation of cortex and associated cognitive load increase when using a more immersive 360-degree field-of-view simulation tool. This may be due to the neural correlates found when stereoscopic vision is utilised, in that the depth perception required for watching a 360-degree field-of-view scene, by definition, causes visual fatigue and therefore, increases cognitive load.[27] The significance to healthcare simulation is noteworthy. These results would suggest that, by utilising more immersive, wider field-of-vision audio-visual footage via the use of a headset, learners can recruit brain activity to a significantly higher level than that of a standard two-dimensional audio-visual simulation resource. Whether this means that increased immersion increases cognitive load and therefore increasing difficulty for the learner requires more investigation to explore these questions further.

Finally, in the third pair of tasks, the focus was on taking a radial pulse on a simulated patient, and then taking a radial pulse and respiratory rate simultaneously on the same simulated patient, with the same physical parameters. The performing of a dual task such as recording pulse and respiratory rate simultaneously require an individual to rely on their working memory, leading to a subsequent increase in cognitive load. In this study, significantly more ΔHbO concentration change was recorded during this dual task. This suggests the added demands placed on an individual when they are multi-tasking. This idea of multi-tasking within a simulation may be a reflection of multi-tasking in an actual clinical environment and this finding could be extrapolated to any number of clinical contexts or environments. However, whether this cognitive load increase is mostly related to the multiple input of carrying out several tasks at once or increased cortical activation during more complex finger and hand placement,[28] has yet to be determined.

Limitations

This study has several acknowledged limitations, the first being the limited sample size. Although the number of channels used in an fNIRS study has some evidence to support the mathematical calculation of sample size, this emerging technology has limited mathematical models to support these figures. As fNIRS become more widely used, this should increase the amount of evidence to effectively calculate significant sample size. This lack of prior research provides another limitation of this study. There is little published research on the use of fNIRS in healthcare simulation, which means there is little prior evidence to draw on. In addition, perhaps the concept of task fatigue could be applied to this study. All participants took part in all six conditions, each pair of the three tasks, and therefore one might expect an increase in cognitive load as the experiment progressed. This could be ameliorated on further experiments by having different participants for each pair of simulation tasks. However, these limitations outlined can be seen as an opportunity for the healthcare simulation community to embrace the use of relatively mobile brain imaging techniques to evaluate the participants' experience. Therefore, it is hoped that this study inspires others use this exciting technology in healthcare simulation.

CONCLUSION

In conclusion, this study uses an emerging brain imaging technique, functional near-infrared spectroscopy, to evaluate cognitive load whilst using common simulation tools or events. This technique was found to be a good indicator of increased cognitive load in a set of paired tasks and these are discussed in the text. It is clear that further investigation, and use of fNIRS is needed to explore further these initial findings and provides a useful platform for further study.

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CONTRIBUTORSHIP STATEMENT Dr Natasha Taylor wrote ethical approval, study design and statistical analysis. Martyn Wyres, Dr Martin Bollard and Dr Rosie Kneafsey collaborated on the writing of the paper.

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