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Original Research

An Evaluation of the Microsoft HoloLens2 in the Clinical Teaching of Pain Pathways for Undergraduate Medical Students

Kevin J. Murphy, MB BCh BAO, FANZCA
Niall O'Brien
Murray Connolly, MB BCh BAO, FCAI
Gabriella Iohom, FCARCSI
James Gibson
George Shorten, DSc

Introduction

In medical education, vertical integration (VI) generally refers to the organization of teaching such that the relationship between material from basic and clinical sciences is aligned in order to enhance understanding. This integration can stimulate the building of relevant knowledge frameworks and enhance recall of learned material.[1-3] Different approaches to the achievement of vertical integration include small group teaching, data interpretation, and problem-based learning. Although attractive from an educational point of view, the interweaving of basic and clinical sciences can pose practical challenges for teachers and schools of medicine. The COVID-19 pandemic has magnified these challenges.[4,5]

These factors have created a strained learning environment with increasing student numbers, limited in-person interactions, and pressure to reduce costs and environmental impacts of "face-to-face" teaching.[6-9] Remote and distributed delivery of clinical education may be seen as potential solutions to these issues.

Although no universally accepted definition of mixed reality (MR) exists,[10] it is widely perceived to mean a distinct part of the reality-virtuality continuum described by Milgram and Kishino.[11] Even this widely cited concept is limited in that the continuum refers only to visual elements, and MR also enables manipulation of both real and virtual elements within an environment.[11] For the purposes of this study, we use MR to refer to the achievement of a blended experience within which learners and teacher(s) perceive and interact with virtual and real elements simultaneously.

Educational and training applications of MR are being implemented across various industries, including manufacturing, engineering, health care, and education. Head-mounted displays (HMDs) are used in diverse medical education settings including the teaching of anatomy, procedural training, and more recently live-streaming clinical ward rounds for students.[12,13]

The Microsoft HoloLens 2 headset offers one means of rendering an MR environment for educational purposes. In considering the use of the Microsoft HoloLens 2 for delivering virtual, in-person clinical tutorials, we considered that its functionality had the potential to:

- enhance learning by providing a form of instructional scaffolding. Specifically, this relates to the rendering of cell, organ, or system pathways proximate to a patient, as basic science and clinical concepts are integrated at relevant points during a clinical encounter.
- enable students at remote and different locations to participate in a meaningful way in clinical encounters. This could decrease student travel requirements by enabling the delivery of tutorials to students in multiple different locations simultaneously.
- significantly decrease the risk of transmission of infection with only the tutor entering the patient's environment, especially in the context of a future pandemic.

Building on previous work of ours and others,[14,15] we set out to further assess the feasibility, usability, and learning efficacy of MR using a Microsoft HoloLens 2 in the clinical teaching of medical students about pain pathways, anatomy, and physiology, with clinically elicited symptoms. Specific aims were:

- to establish 3-way live dynamic audio and visual communication among patient, student, and teacher, with active participation from each party.
- to develop a custom-built application with 3-dimensional (3-D) holographic images tailored to the existing medical school (University College Cork [UCC]) curriculum.
- to juxtapose relevant holographic images with a patient to augment vertical integration of concepts being learned by the student.
- to develop and refine a script and "running order" to ensure delivery of a consistent tutorial to different groups of students.
- to enable the tutor to demonstrate and practice interaction with artifacts such as pointing, drawing, expanding, and rotating.

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Methods and Materials

Human Subject Ethical Approval and Context

With institutional ethical approval by the Clinical Research Ethics Committee of the Cork Teaching Hospitals, and having obtained written informed consent from each participant (including students, patients, the tutor, and the technical facilitator, the latter two also being investigators), this prospective observational study was conducted at various clinical and educational sites of the Cork University Hospital (CUH), a busy teaching and tertiary referral center in Ireland. A mixed-methods approach was used, similar in design to that used in previously published work of ours,[14,15] and applied to examine novel MR functions and different subjects relative to that work.

Study Participants

UCC students from 2 cohorts participated in the study: third-year Graduate-Entry medical students and fourth-year Direct-Entry medical students. Each student was invited to participate while on a clinical rotation in the Department of Anaesthesia and Intensive Care Medicine at a busy, acute tertiary referral teaching hospital (CUH).

Patients scheduled to undergo elective surgery at the hospital were also recruited. Inclusion criteria were > 18 years old, English spoken fluently, and a postoperative course deemed by the tutor (K.J.M.) likely to provide a suitable basis for discussion of pain assessment, and of central and peripheral pain pathways.

Tutorial Structure

Tutorials were delivered on a weekly basis across the 2023/2024 academic year. The tutorials included a focused pain history and assessment of a patient, followed by an interactive, structured discussion of pain pathway anatomy and pain mechanisms using holographic artifacts, which followed a prepared sequence (Figure 1). Design of the tutorial was informed by specific topics and learning outcomes from the medical school curriculum (Module CP 4004: Clinical Practice and the Fundamentals of Adult Disease).

All tutorials were conducted by a single tutor (K.J.M.). A technical facilitator (N.O.) provided support in managing the information technology connectivity between the clinical setting and a nearby lecture theater. The tutor had no prior experience using the HoloLens 2 device or with similar augmented reality (AR) HMDs; the technical facilitator had significant experience in their use, including in clinical settings. The tutor underwent a familiarization period with the device with the assistance of the facilitator, which included using the Microsoft "HoloLens Tips" app, which offers a guided tutorial for new users. The tutor and technical facilitator participated in practice calls to confirm the functionality of the network in the clinical sites and audio-visual equipment within the lecture room.

An initial pilot "dry-run" tutorial was carried out before commencing the study proper. This comprised testing of connectivity and tutorial script with 5 medical students, and an additional medical student acting as a proxy patient. This session was intended to identify and address potential technical and logistical issues.

During the tutorials, the tutor (K.J.M.) interacted with a patient (face-to-face) in the pre- or postoperative units of CUH and remotely with a small group of (4-6) students in a nearby lecture theater (approximately 500 m distant). This interaction occurred via the HoloLens 2 worn by the tutor, institutional Wi-Fi (Eduroam), and Microsoft Teams. Once visual and audio connections were established and tested for clarity, the tutor introduced the patient to the students and then took a history and undertook an assessment of the patient's pain, before demonstrating and explaining the anatomy and physiology of pain pathways.

Throughout the patient assessment and explanation of pain pathways, the tutor interacted both with the patient and with the students as if conducting an in-person bedside tutorial. This included providing additional information, asking the students pertinent questions and giving feedback on answers, and expanding on the findings of the patient's assessment. Students only communicated with the patient by asking questions via the tutor. At set points during the tutorial, the tutor used text holograms each depicting a "pop quiz" relevant to the topic under discussion. Individual students were invited to provide answers to the questions posed.

Software

The Dynamics 365 Remote Assist application was used, in tandem with Microsoft Teams, to host each video call. This connection allowed the students to see the tutor's field of vision and hear both the tutor and patient. Hand gestures including the "hand-ray," "air-tap," "air-tap and hold," and "start-gesture" were used to control the HMD and manipulate the holographic artifacts.

A commercial company Holospatial (https://holospatial.co.uk/) was engaged to develop an application depicting interactive pain pathways suitable for use with the HoloLens 2 in the setting of the study tutorial. The application underwent 8 months of iterative development, with 4 user needs analysis sessions showcasing protoype updates (3 virtual, 1 in-person). These sessions lasted 1 hour each, and comprised detailed examination of the educational objectives of the tutorial, in particular focusing on incoporating additional MR functionality in a manner that was pedagogically sound. Feedback from investigators informed ongoing modifications until a consensus on the application's completion was achieved. Each demonstration was followed by a 30-minute feedback session. Written feedback was also collected and provided.

Based on these sessions, holographic 3-D models were selected and purchased from online libraries[16] based on anatomical accuracy and relevance for the learning outcomes of the tutorial. These included nerve synapse, spinal cord, thalamus, and brain holograms. These were labeled with a question and "drop-down" answer feature (designed by the tutor) and incorporated into the tutorial (Figure 2a-d).

The tutorial was designed such that specific holographic artifacts were juxtaposed to or superimposed onto the patient at preselected points. For instance, when a patient described the experience of pain or discomfort, a nerve synapse hologram was introduced to demonstrate nociceptive transduction, a cross section of a spinal cord was used to demonstrate pain signal

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transmission and modulation, and a brain hologram with alterable transparency was used to facilitate explanation of pain perception at the thalamus and cortex (Figure 3a-d).

The holographic pointer and "drawing" functions were used by the tutor to interact with the artifacts, identifying relevant anatomy and reinforcing specific points of discussion (Figure 3a and d).

Additional resources, including internet connectivity and hardware, were also taken into consideration (Supplemental Online Material, Appendix 1).

Assessment of Tutor Perceptions

Immediately after completion of the first tutorial, the tutor completed a System Usability Scale (SUS) assessment. The SUS is the most widely used standardized questionnaire for the assessment of perceived usability. Although the interpretation of SUS scores can be nuanced, the Lewis and Sauro[17] framework, based on a large dataset, indicates that a mean score of 79.4 correlates with an A-grade, placing it in the 80th-85th percentile.

Assessment of Student Perceptions

Immediately after completion of the tutorial, students completed a modified Evaluation of Technology-Enhanced Learning Materials: Learner Perceptions (ETELM-LP) questionnaire to assess their perceptions of the tutorial, which incorporated a series of 7-point Likert scale and open questions. They also completed an SUS assessment.

Assessment of Patient Perceptions

On completion of each tutorial, the patient was also asked to complete a mixed quantitative and qualitative questionnaire to assess their perceptions of the tutorial, which incorporated a 7-point Likert scale and open questions.

Results

Seven tutorials were completed involving 7 separate patients and 35 students. The study component of 1 tutorial (involving 1 patient and 5 students) was abandoned due to poor internet connection, and the data elicited from these students and during this tutorial were excluded from the final report. All 7 patients, 5 male and 2 female, underwent elective ambulatory surgery. All participated in the study postoperatively on the day of surgery admission unit once fully awake and alert. Four patients had orthopedic surgery, with 3 of these receiving a peripheral nerve block. The remaining patients underwent colorectal or general surgery.

Baseline characteristics of the student participants are summarized in Table 1.

Feasibility

Within the setting described, it was feasible to use the HoloLens 2 in delivering weekly bedside tutorials on pain assessment and management with patients in a busy teaching hospital. It was possible to create a live, interactive platform allowing simultaneous audio and video communication between patient, students, and teacher. Of note, audio enhancement was needed, and patient audio quality improved with an additional USB microphone (which is not included with the HoloLens2). Technical requirements included secure Wi-Fi access for both tutors and students, a technical facilitator to manage equipment at the student location, and a quiet space for patient examination. One tutorial out of 7 was abandoned because of technology-related issues, which appeared to be a transient unexplained hospital-wide loss of or inadequate Wi-Fi access.

Tutor Feedback

The tutor (K.J.M.) completed the SUS score immediately after his initial use of the HoloLens2 for a tutorial, which was 70.5 (a score > 68 is deemed above average[18]). He reported that that the HoloLens 2 was comfortable to wear, the visor was unobtrusive, and that the headset allowed for clear patient interaction and unimpeded observation of clinical signs. Following the initial familiarization period, hand gesture controls proved to be intuitive, facilitating smooth interaction with the device, which continued to improve over the course of the tutorials. The inclusion of MR features was useful, allowing for the integration of holographic diagrams, pointing, drawing, and highlighting. Dynamic manipulation of holograms, including expansion and rotation, facilitated uninterrupted exploration of different parts of the pain pathway during the tutorial. Although the tutor found that it was easy to superimpose artifacts accurately onto a patient from both a seated and standing position, he used a seated position for most of the tutorials based on student feedback on improved visual stream quality with this position. When juxtaposing images with a patient, the tutor had to be careful not to accidentally touch the patient, in particular when expanding the brain hologram adjacent to the patient's face. The tutor felt that the tutorial script, informed by student feedback, enhanced the overall consistency and flow of the sessions. Evaluations conducted after each session by the tutor and facilitator suggested that remote student engagement could be increased by the tutor addressing students by name when asking pop-quiz questions, rather than relying on volunteers to answer.

Student Feedback

Students completed the SUS and the median score was 72.5 (interquartile range [IQR] 62.5-80.0).

Quantitative student feedback via the modified ETELM-LP questionnaire is summarized in Table 2. Results are presented as (median [IQR]) and refer to a 7-point Likert scale.

Student Qualitative Feedback Results

Analysis of written feedback from 30 students identified 43 specific positive excerpts and 26 negatives (Table 3).

Patient Feedback

Quantitative feedback data from patient questionnaires are summarized in Table 4.

Three patients provided qualitative feedback. Positive comments included that "I felt safe and more comfortable than having loads of students poking at me" and "once you explained it before, I really didn't take much notice of the headset." One patient commented that "it would be nice to see the students, even for a bit at the start, just to see who I was talking to." Four patients declined to provide qualitative feedback.

Discussion

This study investigated the feasibility of using Microsoft HoloLens 2 with its MR capabilities to deliver live bedside tutorials

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on pain pathways to remote learners. In particular, it investigated the feasibility of superimposing holographic images onto a patient in real time in order to augment vertical integration of learned concepts. We selected postoperative pain assessment as a suitable topic to examine the application of basic neuroanatomy and physiology in a common clinical condition (postoperative pain). Feedback from students, patients, and the tutor indicated a generally positive experience.

This study used a mixed-methods approach, gathering both quantitative and qualitative feedback from students, patients, the tutor, and the tutorial facilitator. This approach provides a robust examination of stakeholder perceptions regarding the use of HoloLens 2 for delivering clinical tutorials to medical students.

Quantitative student feedback regarding audio-visual quality was predominantly positive. However, a minority of students reported technical difficulties and expressed a preference for traditional in-person tutorials. Patients' qualitative feedback indicated they felt safe, comfortable, and preferred the HMD-delivered tutorial over in-person group sessions. Although most agreed communication was clear, both patients and the tutor acknowledged occasional ambiguity in discerning who the instructor was addressing.

Moro et al[19] previously examined the effectiveness of learning when an identical lesson was delivered through AR using either the Microsoft HoloLens or a mobile hand-held tablet device, and more recently Minty et al[20] explored the use of MR technology for the objective assessment of clinical skills. Although papers such as these demonstrate the feasibility of using the HoloLens 2 in tertiary education, they did not simulate bedside tutorials and assess the ability of the device to facilitate vertical integration of basic and clinical sciences using a real patient.

Our findings regarding the feasibility, patient and student acceptance, and occasional audio-visual issues align with those of Mill et al[21] who examined the feasibility of the HoloLens 2 in broadcasting medical ward rounds. These findings are consistent with those previously reported by our group.[14,15] The current study extends this ongoing research by demonstrating the perceived usefulness of juxtaposing holographic elements with a patient during the tutorials, as reported by both the tutor and students, as well as using the 3-way live dynamic audio and visual communication among patient, student, and teacher, with active participation from each party. This study also expands the feasibility evidence to include topics integrating basic science and clinical concepts to support vertical integration.

We anticipate that the results we report in this article will justify a further line of investigation of the means by which MR and AR may enhance specific areas of instructional design in the setting of undergraduate and postgraduate medical education. In particular, the prompt juxtaposition of specific virtual artifacts could be used to enrich the learning experience by enabling students to participate in the "live" development of shared mental models, such as of the pathogenesis of disease (vertical integration) or of pattern recognition leading to differential diagnosis (horizontal integration). We believe a skilled teacher might use either AR or MR to "scaffold" individual progress in learning by choosing if and when to introduce the artifacts. The extent to which such educational advantages could be retained if the application of the MR format were extended to greater numbers of students simultaneously is unclear and will also require further study. Although the results of this preliminary study appear to identify a potential role for MR/AR technologies in future medical education, we do not believe that our findings in any way obviate the need for medical practitioners to develop clinical and communication skills through face-to-face interaction with "real" patients.

Our tutorial format aimed to reproduce some of the logistically relevant components of an in-person tutorial. The use of a pre-rehearsed script that was centered around relevant 3-D holograms and tailored to the curriculum of the students allowed for a reproducible learning experience of a specific length. In our study, both students and patients reported positive experiences regarding the structure of the tutorial.

To draw parallels with their experience of standard teaching modalities, the tutorial was simultaneously broadcast within the lecture theater on a large display monitor, a familiar environment for students accustomed to attending curriculum-based teaching sessions in this location. This approach allowed students to evaluate the HoloLens tutorial against their established frame of reference for traditional PowerPoint-based tutorials; it is possible that this (implicit) comparison contributed to the positive feedback we report regarding the increased educational benefit of the HoloLens session.

Maintaining patient confidentiality is paramount in medical education. Our study prioritized this by ensuring secure connections and controlled access throughout the learning process. Both the HMDs and student devices were connected to a secure institutional Wi-Fi network and accessed through university accounts. In addition, a technical facilitator controlled access to the audio-visual stream, and students participated from a supervised lecture hall. These measures ensured that only authorized personnel accessed the educational content, and the broadcast environment was secure, thus safeguarding patient privacy.

Although our SUS score exceeds those reported in previous studies of HoloLens 2 in clinical education settings,[15,19,22] our qualitative and quantitative findings highlight usability and technological issues. This underscores the importance of a comprehensive mixed-methods approach when evaluating new technologies in complex contexts like medical education.

The primary limitation of this study is related to the generalization of these results due to the small sample size, where the participants came from one university hospital in Ireland. Other limiting factors include the need for educators to undergo training to become proficient in using the technology effectively. Therefore, an individual who was thoroughly familiar with the HoloLens 2 was required to be present at all times during the tutorial for technical support. The fact that 1 clinician was tutor for each session ensured consistency and refinement over the course of the study; however, it also means that

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we cannot draw a conclusion on inter-clinician variation in acceptability or need for training. Furthermore, in our study, a researcher with considerable experience in the use of the Hololens 2 device was available throughout each teaching session to ensure that technical problems were minimized; the need for the availability of such technical expertise could serve as a limitation to applying the format we describe in other settings. Financial investment associated with acquiring and maintaining HoloLens 2 devices necessitates careful consideration, and external factors such as ambient noise and unreliable Wi-Fi connectivity can compromise the technology's functionality. It is important to note that the very limited information we provide in this article regarding learning efficacy is preliminary and certainly insufficient to enable comparison with other instructional approaches.

We believe that the next research priority in this area is to examine the learning efficacy associated with MR teaching (in comparison with traditional methods). This might be of greatest value in learning application of fundamental scientific information or principles (rendered using selected artifacts) in the setting of clinical assessment or diagnosis.

Conclusion

Our study results indicate that the incorporation of MR into clinical teaching is feasible and usable with moderate investment and preparation. It appears to offer important potential in supporting vertical integration of learning, at least in the setting described. This study's collaborative approach to application development, involving the tutor, technical facilitator, and other curriculum experts, appears to be a useful model for evaluation of novel educational technology development within health care education. Based on the findings reported here, we believe that MR/AR technologies may offer potential benefits in terms of student access to clinical encounters, providing support for certain forms of instructional design (such as vertical integration) and generation of valuable digital resources relating to rare events or diseases. The realization of any such benefits will require further investigation using novel technologies (both hardware and software) in diverse educational settings.

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*The following authors are at Cork University Hospital: **Kevin J. Murphy** is a Fellow in Regional Anaesthesia; **Murray Connolly** is a Consultant Anaesthesiologist. The following authors are at University College Cork: **Niall O'Brien** is a Biotechnician; **James Gibson** is a Medical Student. **Gabriella Iohom** is a Consultant Anaesthesiologist at Cork University Hospital and a Senior Lecturer in University College Cork. **George Shorten** is a Consultant Anaesthesiologist at Cork University Hospital and Professor Emeritus at University College Cork and Insight Research Centre for Data Analytics.*

Corresponding author: *Kevin J. Murphy, Department of Anaesthsesia and Intensive Care Medicine, Cork University Hospital, Wilton, Cork, Ireland T12DC4A. Telephone: +353874769730, Fax: 021 4546434*

Email address: *Kevin J. Murphy: kevinjmurphy9@gmail.com*

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Abstract

Background: In medical education, vertical integration (VI) refers to integration between the clinical and basic sciences. Mixed reality (MR) refers to a rendered experience in which virtual and "real" elements are perceived simultaneously by a learner. The Microsoft HoloLens2 is a novel headset that allows the rendering of an MR environment and facilitates a live 2-way broadcast to (a) remote environment(s). We present here a mixed-methods study that extends previous work of ours examining the feasibility, usability, and efficacy of MR in the clinical education of medical students, specifically teaching pain pathways in a clinical context.

Methods: A series of 7 interactive bedside tutorials on pain pathways and their relevance to postoperative pain management was delivered by a single teacher (K.J.M.) using the HoloLens2. Each tutorial included interaction with a patient during the postoperative period and a group of 5 medical students who were situated in a remote lecture theater within the hospital complex. The tutorial used insertion of virtual artifacts, including diagrammatic examples of pain pathways often superimposed on or positioned adjacent to the patient. Student feedback was elicited using a modified Evaluation of Technology-Enhanced Learning Materials: Learner Perceptions (ETELM-LP) tool.

Results: This was a prospective, observational study that used both qualitative and quantitative methods. Seven patients and 35 students participated across 7 separate tutorials. The mean System Usability Scale score for medical students was 72.5 (interquartile range 62.5–80.0) and for the clinician was 70.5, indicating favorable usability. The modified ETELM Questionnaire using a 7-point Likert scale demonstrated MR contributed to achieving the learning objectives of the tutorial (median = 6, range 5–7), and was superior to a lecture supported by computer-projected slides. There was disagreement among students regarding the value of the MR tutorial in comparison with a live patient encounter (median = 4, range 3–5). Patients consistently rated communication with the clinician highly (median = 7, range 6–7) and favored the MR tutorial over small group bedside teaching (median = 7, range 6–7).

Conclusions: We demonstrated within our institution that bedside clinical teaching of pain pathways using the Microsoft HoloLens2 and MR is both feasible and effective, and could enhance vertical integration of basic and clinical material within a medical undergraduate curriculum. This study's collaborative application development model, involving tutors, facilitators, and curriculum experts, sets a precedent for future educational technology in health care. Further evaluation of the usability of the device in this context is planned, and future research may evaluate the generalizability of our findings to other elements of medical education.

Keywords: Medical education, augmented reality, HoloLens, mixed reality, pain pathways

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Figures

Figure 1. *Tutorial structure. Abbreviation: IASP, International Association for the Study of Pain.*

Pain History and Assessment:

- Patient demographics
- Relevant past medical history
- Relevant past surgical and anaesthetic history
- Type and location of surgery
- Site, onset, and description of character of pain
- Radiation of pain
- Associated features (ie nausea, diaphoresis)
- Exacerbating and relieving factors
- Pain severity using verbal rating scale

Structure of discussion of pain anatomy and physiology:

- Definition of pain (as per IASP)
- Nociceptive transduction
- Transmission of pain signals
- Pain modulation
- Cognitive perception of pain
- Mechanism of action of analgesic medications
- Questions from students to patient

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Figures *continued*

Figure 2. *(a) Spinal cord hologram with associated "pop-quiz" question. (b) Thalamus hologram with associated question. (c) Nerve synapse hologram with associated question. (d) Brain hologram displaying user interaction with question/answer drop-down menu.*

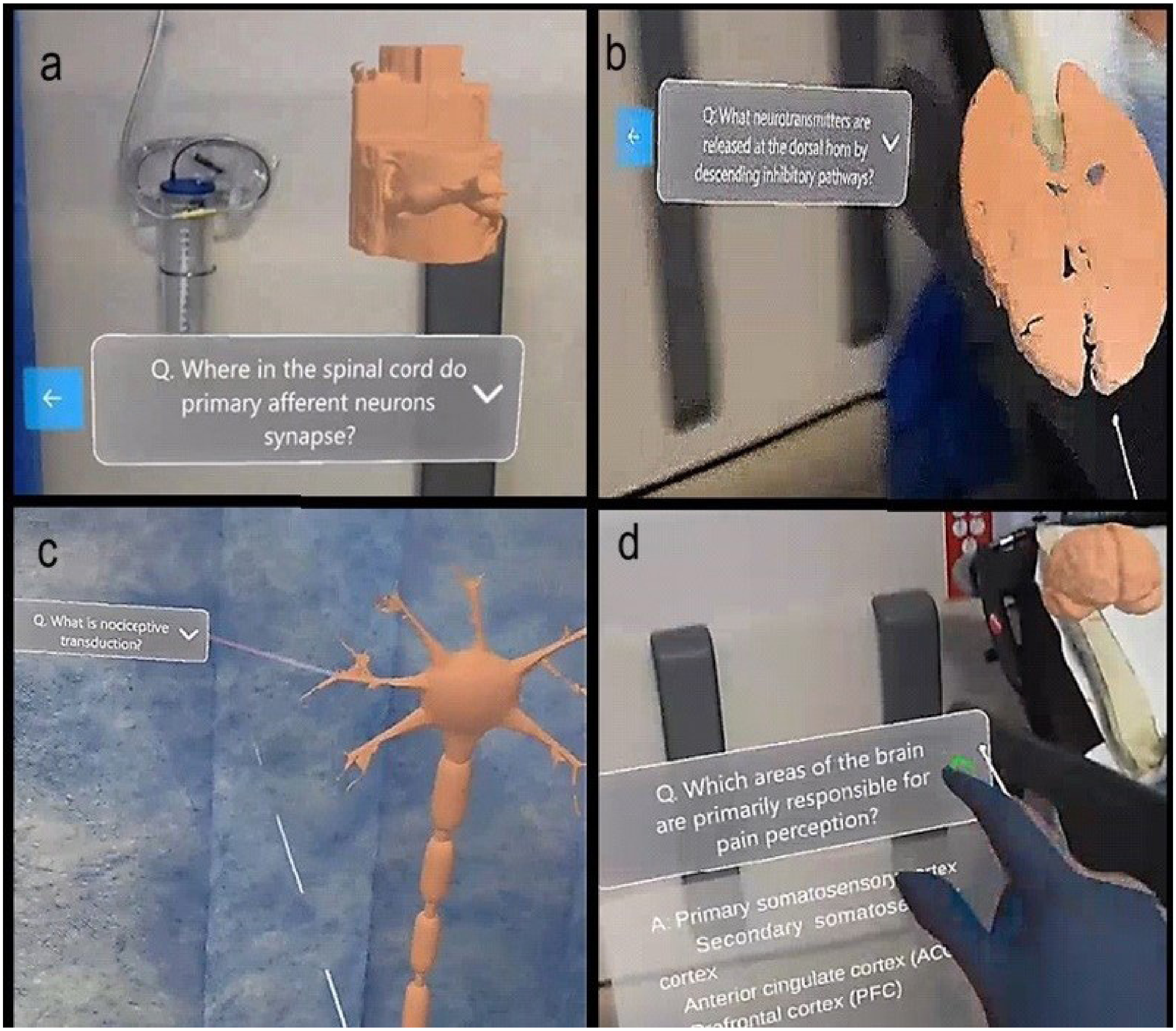

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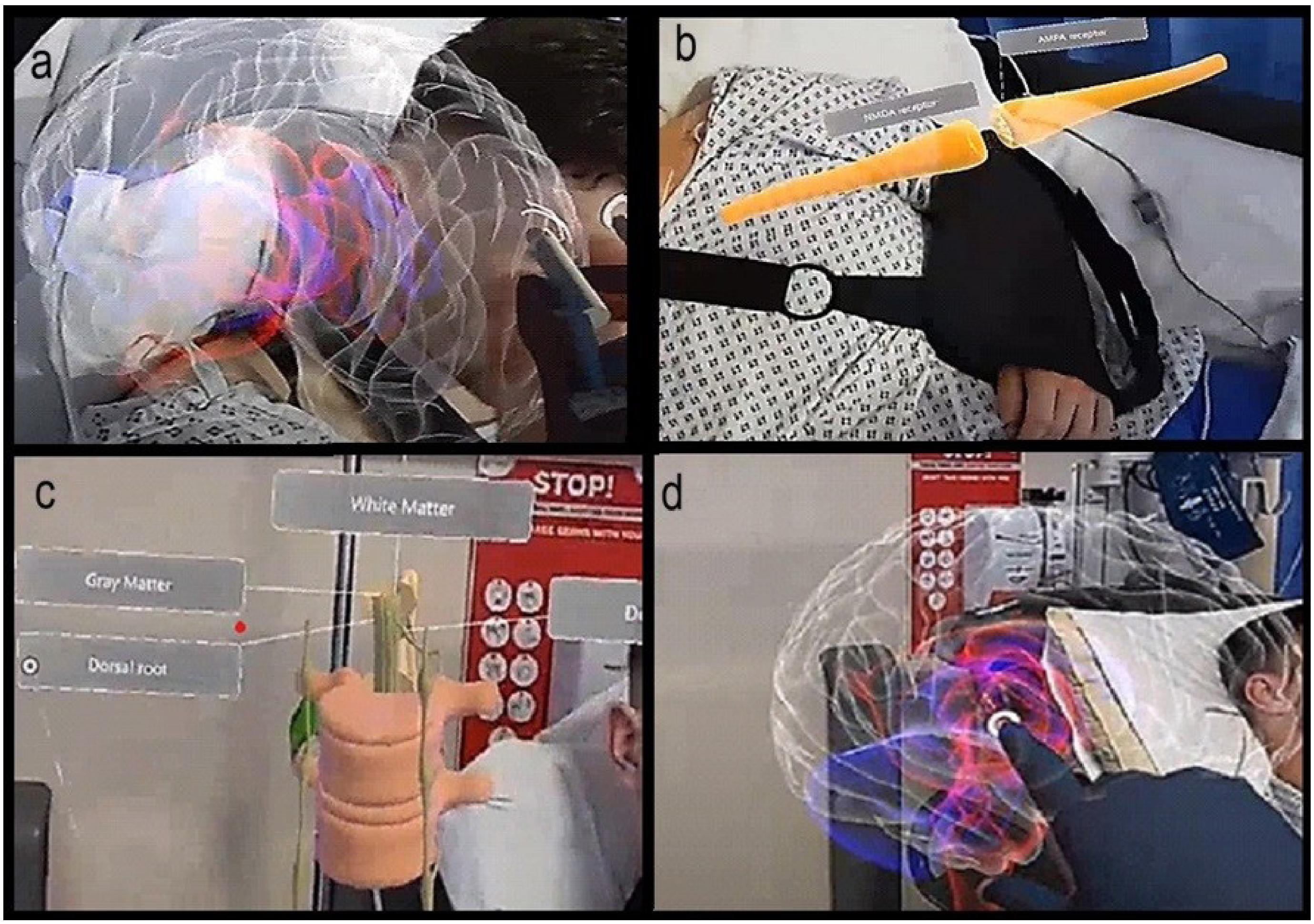
Figure 3. *Holograms adjacent to a patient used to support learner integration of clinical and basic science concepts. (a) Brain hologram displaying "drawing" function. (b) Nerve synapse hologram with labels. (c) Spinal cord hologram with labels. (d) Brain hologram showing "pointer" function.*



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Tables

Table 1. Baseline Characteristics of Student Participants

	Direct-Entry Medical Students	Graduate-Entry Medical Students	Total Students
No. of students, n (%)	16 (53.3)	14 (46.6)	30
Male, n (%)	7 (43.7)	4 (28.5)	11 (43.3)
Age, median (IQR [range])	23 (22-23 [21-24])	27 (25-28 [24-33])	23 (22-26 [20-35])

Abbreviation: IQR, interquartile range.

Table 2. *Student Experience: Modified ETELM-LP Results: 7-Point Likert Scale with 7 as Strongly Agree and 1 as Strongly Disagree*

	Statement	Median	IQR
1	I have experience with Mixed Reality in the past	2	1-3
2	The audio was clear	5	4-6
3	The video was clear	6	5-7
4	The Mixed Reality segment was useful	6	5-7
5	The artifacts (diagrams) were useful	6	5-7
6	It contributed to achieving the learning objectives of the tutorial	6	5-7
7	It replicated the experience of a live patient encounter	4	3-5
8	It was as beneficial as a live patient encounter	4	3-5
9	It was more beneficial than a traditional PowerPoint-based tutorial	6	5-7
10	The technologies and media supported the learning objectives	6	5-7
11	The course effectively blended online and face-to-face elements	5	4-7
12	Educational activities encouraged interaction and collaboration with other participants	6	5-7
13	This course required inappropriately high technology skills	2	1-3
14	Assessments (eg, tests and self-assessments) were appropriate for the course objectives, content, and activities	6	5-7
15	Mixed Reality served as a distraction from the overall value of the tutorial	3	2-4
16	I would like Mixed Reality to be incorporated in future tutorials	6	5-7

Abbreviation: IQR, interquartile range.

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Tables *continued*

Table 3. *Student Qualitative Feedback*

	Number of Statements Identified, n	Illustrative Quotes
Positive Themes		
Favorable outlook for the technology	19	"Very useful visualizing the pain pathway in 3-D next to a real patient, makes learning and understanding much more efficient" "I really liked how the holograms could be placed on a person and expanded. The drawing function was pretty cool too"
The utility of the device as a supplemental educational tool	15	"Interaction between the patient, instructor, and holograms helps tie concepts together" "A great example of how to help with visual learning, I found it very beneficial for tricky neuroanatomy"
Praise for the session design	9	"Having the holograms at the bedside as you're talking really helped with my understanding, and it felt like it had a clinical slant to it" "The tutorial seemed very structured and didn't take an excessive amount of time" "I thought it was pitched at the right level for what we're expected to know in the curriculum"
Negative Themes		
Comments on the design of the session	12	"It would have been better if we could have interacted with the patient more than we did. It happens with bedside tutorials too, but I think we didn't utilize the patient enough"
Technical problems encountered	8	"The video was shaky at times and this could be quite distracting" "There was occasionally a lag between the audio and video although both were clear"
Potential barriers to student learning	6	"Not as useful as bedside teaching" "It should not substitute tutorials where we physically interact with a patient"

Table 4. *Patient Questionnaire Results: 7-Point Likert Scale With 7 as Strongly Agree and 1 as Strongly Disagree*

	Question	Median	IQR
Q1	I have experience with Mixed Reality in the past	3	2-4
Q2	Communication with the doctor was clear	7	6-7
Q3	The HoloLens served as a distraction	2	1-2
Q4	The HoloLens made me uncomfortable	1	1-2
Q5	It was preferable to a large student group around my bedside (>5 students)	7	6-7
Q6	It was preferable to multiple small student groups at my bedside (5 or fewer students)	7	6-7
Q7	I felt safe during the session	7	7-7
Q8	It was an enjoyable experience	6	6-7
Q9	I would participate in a similar session again	7	7-7

Abbreviation: IQR, interquartile range.

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Supplemental Online Material

Appendix 1. *Resources Employed*

Resources necessary to provide the tutorials via the HoloLens included capital costs of the HoloLens device (€3,500), Bluetooth microphone and speaker (€88), multiport adapter (€119) as well as a licencing fee for use of 3D artefacts (€50), and annual licence costs of €275 per user (n=4). Human resources employed in design/development of the tutorials (6 person hours), tutor training 5 person hours (including use of Microsoft Remote Assist) and trialling equipment (4 person hours) totalled approximately 15 person hours. Those who invested time in preparation were the tutor (KM) and facilitator (NOB), and senior clinicians (GS, GI). Participating students did not undergo any specific training or preparation.

An internet connection of at least 1.5 mpbs of bandwidth is recommended by Microsoft for best audio, visual and content sharing experience. Secure, password protected wireless internet access via the UCC institutional network (Eduroam) was utilised by both tutor and students.

Broadcasts were hosted by an MSI running the Windows 10 operating system; audio was amplified using a Bluetooth portable speaker (Ultimate Ears Megaboom 3), and video was screened via a HDMI cable to a 36'' monitor, which was then projected onto a large lecture hall screen (approx. 338''). In order to bypass the noise cancellation technology within the HoloLens, an external microphone (Saramonic SmartMic+UC L/weight Smartphone Mic USB-C) and 3.5mm earphone were used.