ARTICLE TEMPLATE

VentroAR: An Augmented reality platform for ventriculostomy using the Microsoft HoloLens

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ABSTRACT
Freehand ventriculostomy is one of the most common neurosurgical procedures performed when cerebrospinal fluid increases in the ventricular system causing an increase in intracranial pressure. In freehand ventriculostomy, surgeons use anatomical landmarks to locate the burr hole on the skull and insert a catheter inside the brain to drain the cerebrospinal fluid. Often, several insertion attempts are required to successfully reach the ventricular target. Misplacement of catheter in ventriculostomy can cause complications such as infection, hemorrhage and longer hospitalizations. In this paper, we introduce an augmented reality pipeline using an optical tracking device and HoloLens to help surgeons locate ventricles more easily and reduce the risk associated with this procedure. The proposed system, VentroAR, was evaluated in a user study with 15 subjects. We found that the gesture-based registration accuracy was on average 10.75 mm and targeting accuracy was 10.64 mm. Although the HoloLens shows promise in terms of workflow and ease of use, more work needs to be done to improve accuracy for clinical acceptance.

KEYWORDS
Ventriculostomy, Augmented Reality, Microsoft HoloLens, Neuronavigation

1. Introduction

Ventriculostomy, a neurosurgical procedure that accesses the cerebrospinal fluid (CSF) to reduce intracranial pressure (ICP), is used in cases of hemorrhage, severe head trauma, tumors, spina bifida, and hydrocephalus Shahlaie and Muizelaar (2012), among others. It is the most commonly performed neurosurgical procedures primarily done at a patient's bedside or in an emergency room setting. The procedure involves drilling a hole into the skull (i.e., a burr hole) and guiding a silicone catheter through the brain to the ventricles to drain the excess CSF. In most cases, surgeons have access to pre-operative computed tomography (CT) scans to understand a specific patient's ventricular anatomy better. Furthermore, when possible and most commonly in an elective setting, image-guided neurosurgical (IGNS) systems can be used to facilitate ventriculostomy. In emergent cases, however, guidance is not usually available. Surgeons thus rely on anatomical landmarks on the skull to locate the ventricles, determine the best location for the burr holes, and find the best angle and depth for

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catheter insertion. In these emergency cases, accurate targeting of the ventricles is associated with between 23% to 60% misplacement rate due to human error% Raabe et al. (2018). Such errors can lead to various complications including hemorrhage, infection, and meningitis which can lead to increased length of hospital stays, morbidity, and even mortality Foreman et al. (2015).

Augmented reality (AR), i.e., the merging of real and digital elements, is increasingly being studied for diverse image-guided surgery (IGS) procedures, including neurosurgery Cho et al. (2020). AR visualization merges pre-operative patient data (e.g., a segmented tumor, vessels, ventricles) with the patient on the operating room table to enable more intuitive guidance and improve surgical workflows. Augmented reality can decrease a surgeon's cognitive load by allowing them to focus on the surgical site and patient Yudkowsky (2013) rather than continually shift focus between the monitor with guidance images and the patient Léger et al. (2017). In neurosurgery, in particular, AR has been used to help tailor craniotomies Kersten-Oertel et al. (2016); Cabrilo et al. (2014), distinguish between veins and arteries in neurovascular cases Kersten-Oertel et al. (2015), and determine resection corridors to minimize invasiveness in brain tumour resections Gerard et al. (2017).

Different hardware devices and various AR visualization techniques have been tested and analyzed in IGNS, including microscope overlays, projectors, half-silvered mirrors, mobile devices, and more recently, head-mounted displays (HMDs). At the core of these solutions is the merging of virtual data (e.g., anatomical models, tool trajectories) with the surgical field to guide the surgeon throughout the operation. To increase the accuracy of HMDs researchers have explored combining HMDs with conventional IGS systemsMeulstee et al. (2019); Gibby et al. (2020), however, such pipelines have not been directly evaluated for ventriculostomy.

In the following paper, we propose a navigation pipeline for ventriculostomy using the Microsoft HoloLens I. We use an optical tracker for evaluating the system's precision and updating the visualization parameters of the virtual models. Specifically, a manual registration method using simple hand gestures is used to align the patient's segmented head model with the actual patient, and a color-based depth feedback algorithm is used to help the users understand the target's location and the depth of the catheter tool. We assessed the system in a user study with 15 participants on a 3D printed phantom and found that the proposed gesture-based registration has an accuracy of 10.75 ± 4.01 millimeters and target hitting accuracy calculated of 10.64 ± 5.09 millimeters. In terms of usability of our developed system "VentroAR" received a score of 80.6 on the System Usability Scale (SUS) Sauro and Lewis (2016), indicating that the system usability is "good".

2. Related Work

The Microsoft Hololens is a head mounted display (HMD) with features such as spatial mapping technology, head localization, voice commands, gaze control and gesture-based interactions, making it a promising device for clinical applications. Zuo et al. (2020) evaluated the efficiency of the Microsoft HoloLens for the operating room and found that all of the surgeons involved in their study (n = 74) believed that it has sufficient features to be used for clinical applications and they were willing to use it. Despite the willingness to use HMDs in surgery, the accuracy of the SLAM localization of the HoloLens alone is not yet accurate enough for surgical applications, such as neurosurgery. Further limitations of Microsoft Hololens I include: head localization in high speed movements, real environment recognition limitations for uneven objects in dark surroundings, and a decrement in spatial mapping accuracy for distances under two meters Liu et al. (2018).

A number of groups have developed methods to improve the registration between the augmented elements and the real world for HMDs. Rae et al. (2018) implemented a manual landmark registration for burr hole placement using the HoloLens where the user aligns three landmarks on the hologram with their counterparts on a phantom using virtual buttons. They reported that 98% of experienced users successfully performed registration in a clinically acceptable range (less than 10mm). In similar research, Baum et al. (2019) used a wireless game controller for landmark registration of the virtual models to a patient. Although the registration accuracy was not reported in their work, they reported a lesion targeting accuracy of 10 mm for expert neurosurgeons and 21 mm for inexperienced trainees Baum et al. (2019).

Precise alignment of virtual data can also be done by taking advantage of the RGB camera of the HoloLens and computer vision algorithms to locate and track an image-based target or marker and align holograms with respect to this marker. The Vuforia engine is perhaps one of the more popular marker tracking SDKs that can be used with the Microsoft HoloLens. Azimi et al. (2020) used the Vuforia Engine to develop an automatic registration and trajectory planning system for ventriculostomy. Landmark-based registration is done using a pointer outfitted with a Vuforia marker. This type of registration was found to be 37% more accurate for tip placement compared to a manual registration method that they used as baseline, and tip distance to target was calculated to be 10.96 mm. In the work of Schneider et al. (2021), a Vuforia marker was attached to the patient's head in order to localize the projection of ventricle 3D models. Since automatic tracking of the surface of the skull is not feasible with current versions of Microsoft HoloLens, the authors used game controllers to more precisely align the holograms with the patient. This re-alignment is necessary for many applications that use the Vuforia SDK since the tracking does not offer sufficient accuracy. Li et al. (2018) developed a system using the HoloLens to display the segmented ventricles as well as the desired trajectory of the catheter. The results of their work showed 4.34 ± 1.63 millimeters error in target deviation and a decrease in number of passes of catheter from 2.33 ± 0.98 passes to 1.07 ± 0.258 times.

3. System Design

We developed an AR-based application, AR Ventro, for ventriculostomy using the Microsoft HoloLens I. The proposed system uses a manual registration step using simple hand gesture interaction to align the patient's head and ventricle models with the real patient. The surgical tool is tracked using an optical tracking device (Atracsys FusionTrack) and in order to improve the understanding of the distance of the catheter tip to the ventricles, a color-feedback method is used to guide the user. A custom API was developed for receiving OpenIGTLink packets and translating them to Unity coordinates. Details of the system are provided below.

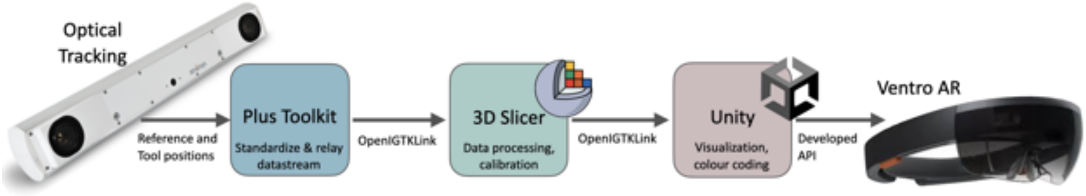


Figure 1. Tracking information from the Atracsys is received by the **PlusServer**. Calibration of the stylus, segmentation of all ventricles are performed using **3D Slicer**. A Unity application for the **HoloLens** was developed for visualizing ventricles, registration, and the depth visualization algorithm.

3.1. Hardware

The developed system uses a Microsoft HoloLens first generation[1] (4-core 1GHz processor, 2 GB memory, 1268×720 Resolution, ToF Depth sensor), an Atracsys FusionTrack 500 [2] and a workstation computer (i7-6850K 3.6 CPU, NVIDIA GTX 1080 GPU, Gigabyte GC WB867D-I wireless PCI card, running Windows 10).

3.2. Tracking

A pipeline to provide the HoloLens with tracking information (of the reference and tools) from the Atracsys FusionTrack was developed. First, the PlusServer receives transforms from the Atracsys tracking system and translates them into standard OpenIGTLink Tokuda et al. (2009) messages. An OpenIGTLinkIF client is created to receive the transform data from the PlusServer, and an OpenIGTLinkIF server is then used to send the transforms from 3D Slicer to the HoloLens. At the time of development there was no open-source OpenIGTLink supported API for the HoloLens, so a custom API (in C#) that receives OpenIGTLink messages through a TCP client-server connection was developed (see Figure 1).

3.3. VentroAR Application

The proposed application uses 3D Slicer, an open-source software library with various tools and plugins for clinical and biomedical image computing applications. 3D Slicer was used to segment the head and ventricles and for receiving and sending transforms through OpenIGTLinkIF, Tokuda et al. (2009), module of SlicerIGT, Ungi et al. (2016). The Slicer-Atracsys connection is made using the PLUS Toolkit, Lasso et al. (2014), which provides live streaming and recording of pose tracking data.

To display the virtual anatomy as holograms in the HoloLens, we developed Ventro AR using the Unity Engine (Version 2012.2.8f1) development environment (in C# using Visual Studio 2019). The default HoloLens setting profiles offered by Mixed Reality Toolkit (Version 2.5.0) were used to have the proper settings for HoloLens 1st generation in Unity. Mixed Reality Toolkit (MRTK) scripts (i.e., Object Manipulator and Interaction Gradable) were used to allow for manual registration of the virtual patient anatomy to the 3D printed phantom using the gesture features of the HoloLens.

In terms of visualizing the ventricle holograms, a color-coded depth visualization method was used. Specifically, the color of the ventricles changed based on the distance

[1] https://docs.microsoft.com/en-us/hololens/hololens1-hardware
[2] https://www.atracsys-measurement.com/products/fusiontrack-500/

Figure 2. Depth encoding of ventricles to tool tip: red represents far from target ($> 30mm$), yellow represents closer to target ($> 20mm$ & $< 30mm$) and green represents very close to target distance ($< 10mm$)

of the pointer tip to the target point on the ventricle. When the distance of the tip of a given tool is more than 30mm, the ventricles are red; when less than 20mm, they turn yellow, and then they turn green when the distance of stylus tip to target is less than 10mm. This color feedback aims to help participants better understand the depth of the tool with respect to the surgical target when it is inside the brain (see Figure 2).

4. User Study

To evaluate VentroAR, we conducted a user study where participants used the HoloLens VentroAR application to navigate to a target placed within the ventricle. The study used a 3D printed hollow head phantom (created from segmentation of an MRI) as described in Léger et al. (2020). Seven landmarks were added to the CAD model for registration purposes. Furthermore, there are two burr holes on the phantom: one to target the left lateral ventricle and one to target the right lateral ventricle. These hole's are placed in the vicinity of Keen's point one of 6 ventricular access points. The 3D printed model was attached to a rigid surface, and a 3D printed marker served as the world reference. A gelatin brain model was inserted into the head phantom to simulate brain tissue. The 3D printed pointer with a tracker was used to simulate the catheter.

4.1. Experiment Procedure

Prior to the study, each participant filled a pre-test questionnaire to gather basic information about their level of experience with the involved technologies. Next, each participant was trained with the system and the experimental task was explained in detail. Participants had a training session to get acquainted with the HoloLens, air tap gestures, and the overall flow of the experiment. When they were comfortable they performed the experimental task, after which all participants filled out a post-test questionnaire that included the System Usability Scale (SUS) and NASA Task Load Index (TLX).

4.2. Task Description

The task of the participants was to navigate a pointer to a specific target on the ventricle. Prior to navigation, participants performed a manual registration using gestures

Figure 3. Left: Participants used the Microsoft HoloLens air tap gesture to drag and move the hologram and align it with the phantom. **Right:** The hologram (blue) that the users aligned to the 3D printed head. The notches are the seven landmarks which were used to determine registration accuracy which were indicated by the participant with the tracked surgical pointer.

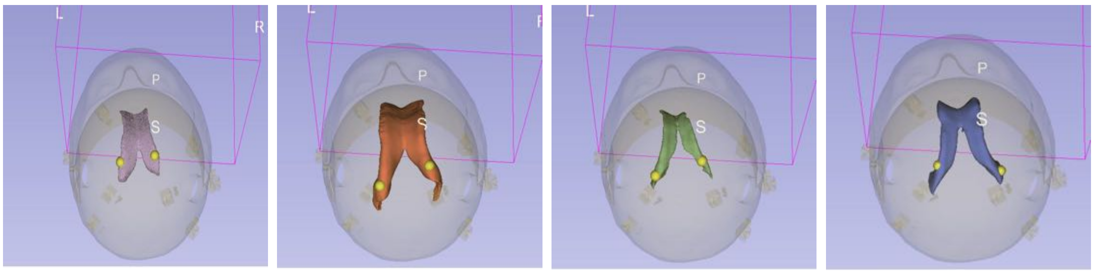


Table 1. Four different patient ventricles used in the user study. Each ventricle was segmented from CT images of different individuals using OASIS brain database using 3D Slicer LaMontagne et al. (2019).

to align the 3D hologram with the 3D printed head phantom. This step is facilitated by allowing the user to align the 7 landmarks of the phantom to the hologram (see Figure 3). However, in a real case the user could simply use landmarks like ear, nose, eyes, etc. for registration. Once the user was satisfied with the registration, after looking at it from various view angles, to evaluate registration accuracy, we asked participants to perform a landmark based registration with the tracked pointer using the seven landmarks on 3D model. Root mean square error (RMSE) was calculated using the Fiducial Registration wizard module of 3D Slicer.

Participants did registration once and then targeted four ventricles (see Table 1) with target points on both the left and right ventricle for a total of 8 targeting trials. A trajectory between the hole in the phantom and the point was visualized and participants were asked to follow this trajectory. Each trial ended when the participant announced they were at the target to the test administrator. The position of the tip of the pointer tip was then captured in 3D Slicer. Captured positions were used to calculate the accuracy of targeting.

5. Results

A total of 15 participants (7 female and 8 males) participated in the study. The participants were graduate students, seven users reported previous experience with HMDs, almost half of the participants had previous knowledge and experience with image-guided surgery systems (47%) and over half had experience with medical imaging (60%). Two-thirds of our participants did not wear glasses, and only one wore contact lenses. There were no color blind participants.

5.1. Registration Accuracy

We evaluated the manual tap gesture registration (using data from the tracked pointer) and found an RMSE of 10.76 ± 7.3 millimeters for all trials. After analysing our data with the GraphPad (www.graphpad.com) outlier calculator tool we were able to find two outliers (three standard deviations more than average). We believe these outliers occurred due to difficulties of user in depth perception that sometimes caused very high error rate in registration. After removing outliers registration accuracy is 8.27 ± 4.0 millimeters. This registration accuracy is inline with previous works that used gesture-based manual registration and were also on the order of 10 millimeters (Rae et al. (2018); Baum et al. (2019)).

5.2. Targeting Accuracy

Based on the 15 users targeting four ventricles with a left and right targets (120 trials), we calculated the targeting accuracy based on the distance of user's landing point and the target (DHtT). We found an overall target accuracy of 12.5 ± 8.5 millimeters. Removing outliers (using the method as described above), seven records with a distance to target more than 25mm (almost three times more than deviation) were eliminated. After omitting these outliers, the overall targeting accuracy was calculated to be 10.64 ± 5.0 millimeters. We further looked at each trial separately, for the left and right ventricle as shown in Table 2. The higher error for the right ventricles may be a result of the fact that users performed a better registration with the left landmarks, which most started with, and then adjusted to the landmarks on the right.

	Ventricle1	Ventricle2	Ventricle3	Ventricle4
Left	7.86 ± 5.79 mm	9.95 ± 5.32 mm	9.81 ± 4.58 mm	9.06 ± 4.54 mm
Right	14.23 ± 7.44 mm	10.68 ± 5.95 mm	10.98 ± 4.21 mm	13.24 ± 5.31 mm

Table 2. Root mean square error (RMSE) for left and right targets of all four ventricles

We also calculated the distance error for each dimension separately, and found a mean error of -8.58 ± 10.52 in the $x - axis$ (positive X represents right direction relative to user's view), 1.25 ± 7.51 in the $y - axis$ (positive Y represents up relative to user's view) and 11.67 ± 9.34 in the $z - axis$ (positive Z runs toward the user). The higher error in the z dimension points to the known limitation of the HoloLens to provide effective depth perception. Figure 4 shows the deviation of each measured target point in 3D.

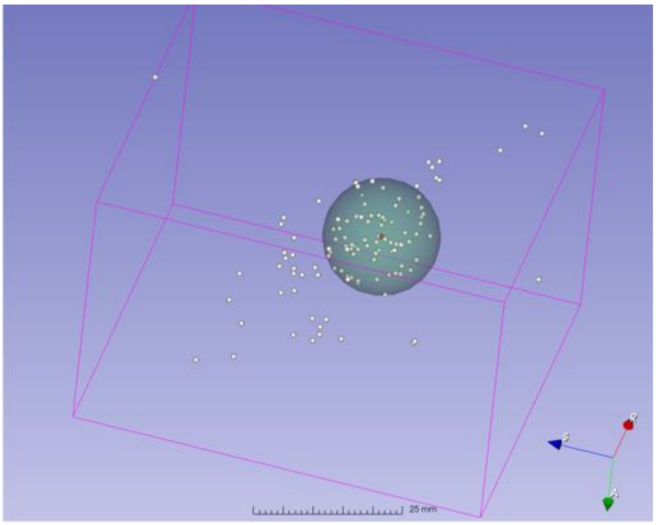


Figure 4. Distribution of hitting points relative to the target. The red point represents the target and white the individual points within a bounding box of all hitting points. A 10mm radius sphere is centered on the target point.

5.3. Depth Error Analysis

To further understand the targeting error, we calculated the depth error as illustrated in Figure 5. We projected each subject's hitting point on the trajectory line shown to the user during the study. Two distances were calculated to quantify errors. First, we calculate the distance between the subject's hitting point (shown in blue in Figure 5) and the projected point (in purple) on the trajectory line, or radial error (RE). Second, we compute the distance between the projected point on the trajectory and the target (in yellow) or depth error (DE). Based on these two distances, we can determine the user's deviation from the trajectory and a target undershoot or overshoot.

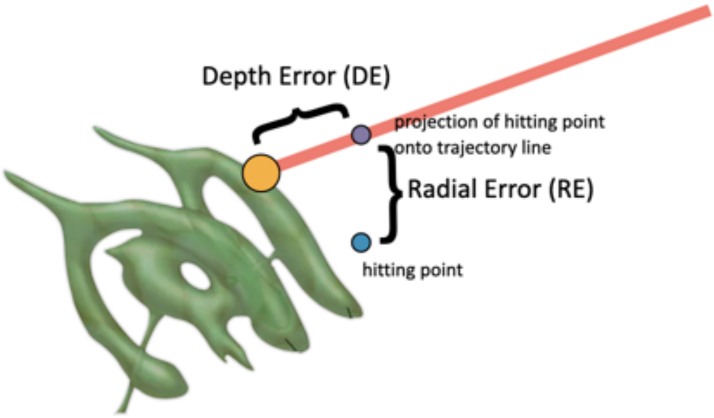


Figure 5. Illustration of error calculations. We calculate the distance between the subject's hitting point (blue point) and the projected point (purple point) on the trajectory line, or radial error (RE). We also compute the distance between the projected point on the trajectory (purple point) and the target (yellow point) or depth error (DE).

Table 3 gives the average of three distances calculated based on the subject's hitting point, total error (TE) which is the distance of user's hitting point to the target on the ventricle (i.e. target accuracy), depth error (DE), and radial error (RE). Outliers, defined as a data point three times greater than the standard deviation, were removed. Seven outliers for total error, eight for depth error and eight for radial error were removed. Total Error was calculated 10.64 ± 5.0 mm, depth error 4.98 ± 4.06 mm and radial error was 9.41 ± 5.23 mm. In order to determine if participants undershot or overshot the target, we signed distances of projected points that were before the target on the trajectory line as negative and distances of projection points after the target point as positive. For instance, in Figure 5 the distance of the green point to the target point (shown in yellow) would be negative. The distribution of target points across all participants is visualized in Table 4.

Total Error (TE)	**Depth Error (DE)**	**Radial Error (RE)**
10.64 ± 5.0 mm	4.98 ± 4.06 mm	9.41 ± 5.23 mm

Table 3. **TE** = total error or target accuracy, **DE**= Distance of projected point of user's hitting point on trajectory line to target and **RE** = Distance between user's hitting point and the projected point on the trajectory line.

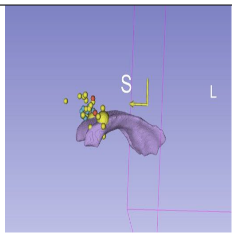
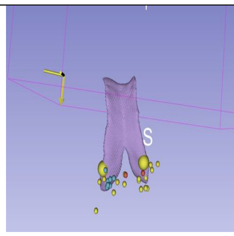
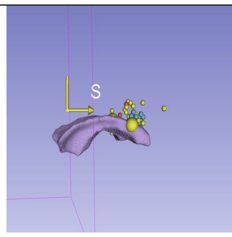
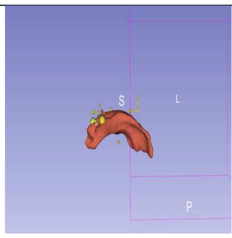
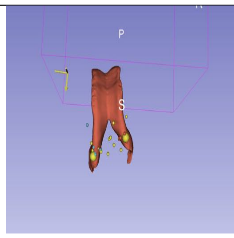
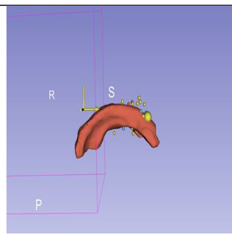
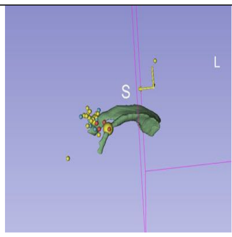
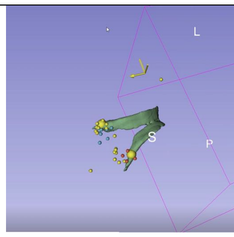
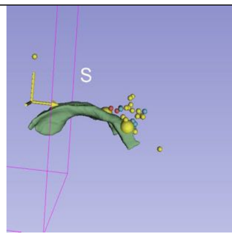
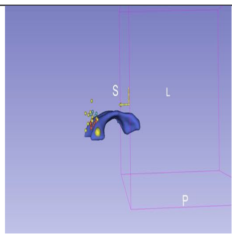
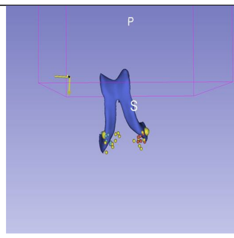
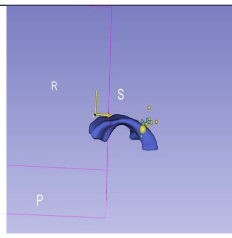
Ventricle 1			
Ventricle 2			
Ventricle 3			
Ventricle 4			

Table 4. Target points of all participants for each ventricle from three different views. Blue points in left target and red point for right target present data records closer than 10mm to the target.

5.4. Qualitative feedback

The System Usability Scale (SUS) was used to evaluate the ease of use of the system. The SUS consists of 10 questions scaling from 1 (strongly disagree) to 5 (strongly agree) with a full score of 100 and any system with a score under 50 is unacceptable, higher than 68 indicates a good system and 85.5 is considered excellent in terms of ease of usability for users Sauro and Lewis (2016).The overall SUS score calculated by (1) adding up the total score for all odd-numbered questions and subtracting 5 from the total to get X; (2) adding up the total score for all even-numbered questions and subtracting that total from 25 to get Y; (3) X + Y * 2.5. We removed the first question "I think that I would like to use this system frequently" as we did not target domain experts and thus our score is scaled to be out of 80. Table 5 gives the detailed results of the SUS. The total score for the SUS is 64.5/80 or 80.6/100 suggesting a good usability. The overall results of the questionnaire suggest that the participants thought the system was fairly easy to use, thought it could be picked up fairly quickly and were confident using it.

System Usability Scale Questions	**Average**
I think that I would like to use this system frequently	N/A
I found the system unnecessarily complex	1.73
I thought the system was easy to use	3.66
I think that I would need the support of a technical person to be able to use this system	2.53
I found the various functions in this system were well integrated	3.93
I thought there was too much inconsistency in this system	2.0
I would imagine that most people would learn to use this system very quickly	3.93
I found the system very cumbersome to use	2.0
I felt very confident using the system	3.46
I needed to learn a lot of things before I could get going with this system	1.93

Table 5. The 10 questions of the System Usability Scale (SUS) with the average score from 1 (strongly disagree) to 5 (strongly agree).

The NASA Task load index (TLX) was used to assess the perceived cognitive load and effort of using the system to target the ventricles. The NASA TLX calculates a subjective workload in six categories, mental demand, physical demand, temporal demand, performance, effort and frustration. We used scaling from 1 to 10 for each individual question. As we can see from Figure 6 (right) most participants found the mental and physical demand as well as the frustration and time pressure very low and felt fairly confident in their performance. The effort to achieve their performance was moderate. This suggests that although the task is challenging the system is able to help with the task in terms of cognitive and physical demand.

Additionally, the post-test questionnaires had questions aimed to determine the users physical comfort wearing the HoloLens, ease of registration, ability to target ventricles accurately, and impression of the correct depth of the ventricles (Figure 6). Participants answered on a Likert scale from 1 (low) to 5 (high). We found that 50% of users thought the registration task easy to perform, 29% found it hard and 21% were neutral. For the targeting task, 64% of users found the accurately hitting the target easy, 22 % the task hard and 14% were neutral. Only 21% of users felt confident to determine the depth of ventricles using the HoloLens, 43% were neutral and 36% of them struggled with depth perception of ventricles. One of users reported

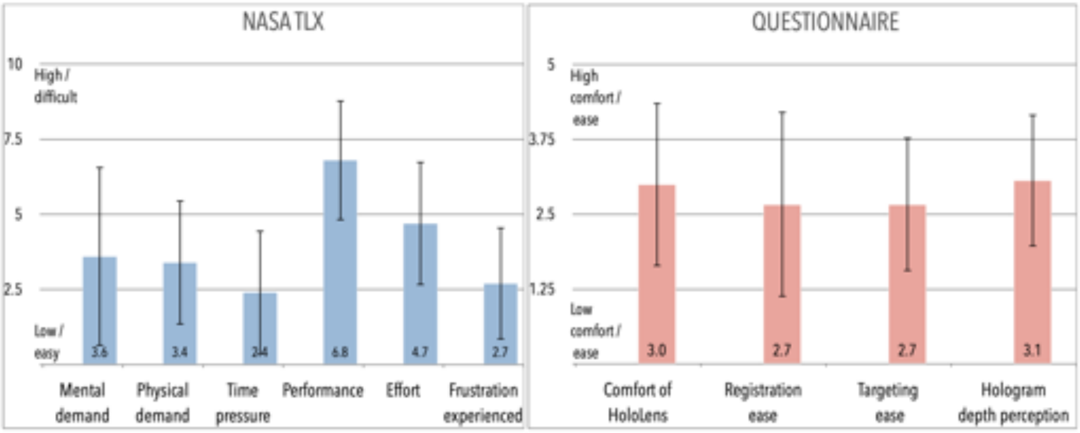


Figure 6. NASA TLX and questionnaire results. **Left:** Most participants found the mental and physical demand as well as the frustration and time pressure very low and felt fairly confident in their performance. The effort to achieve their performance was moderate. **Right:** Most participants found the HoloLens fairly comfortable, and found the task of registration and targeting moderate but had hard time judging the distance of the hologram.

eye discomfort after the study and two participants found the HoloLens very heavy to use.

6. Discussion

The results of our work suggest that gesture-based registration with the HoloLens may not be sufficiently accurate for clinical practice. This may be due to the fact that it is challenging for the user to accomplish accurately particularly for landmarks that need to be viewed from various angles. Despite the simplicity of such gesture-based manual registration methods, they are combined with limitations like frustration, a learning curve, and the fact that the system's accuracy is up to the user's judgment. Indeed, some of our subjects commented that an automated registration would make the system easier, and another noted that the alignment between real and virtual elements was challenging. These limitations may be alleviated with training or combining the manual alignment with automated methods (e.g. to improve an automated registration as in Léger et al. (2018)). This is something we will explore in future work.

Another limitation of our system and to augmented reality systems in general was related to the user's depth perception of the target with respect to the surgical tool. Although, we found that users could get fairly close to hitting the target in depth (DE = 4.98 mm), there was a fairly high radial error (RE = 9.41 mm) and total error (TE = 10.64 mm). The small depth error in comparison to other systems may suggest that the colour-coding depth visualization was effective. However, considering that the majority of users undershot the insertion target, in future revisions of our system, the colour-coding scheme could be revised to have a more gradual scale. In general, we believe our results suggest that using additional cues (e.g. visualization methods or even sound) can help in precise target hitting.

The qualitative evaluations of the system (SUS and NASA TLX) showed that the proposed system in general is usable and limits the cognitive load on users in targeting tasks. There are still some limitations however, with some subjects feeling discomfort in their eyes and the bulkiness and heaviness of the HoloLens. Although the HoloLens

II has mitigated some of the issues we encountered, it is not as widely available and we believe it is still valuable to evaluate older hardware which may be used in places with fewer resources.

7. Conclusion

In this paper, we proposed an AR-based application using the Microsoft HoloLens I for ventriculostomy. Specifically, we implemented a real-time pose tracking pipeline using an optical tracking camera and the HoloLens. We evaluated a gesture-based registration method and evaluated our proposed system with a study with 15 participants, finding a registration accuracy of 8.27 ± 4.0 millimeters and targeting accuracy of 10.64 ± 5.0 millimeters. Furthermore, an in-depth analysis of the targeting error showed that the color-based depth feedback visualization method may be effective in improving depth perception in AR visualization. More research is required to look at the radial and total errors to see how these can be reduced. Although the results of our proposed system fall in-line with pervious works in terms of accuracy and may be acceptable for training or surgical planning purposes, it is not currently precise enough for neurosurgical practice. This will be addressed in future work, with an automatic registration method. Finally, a comparative study to assess the usability and accuracy of the HoloLens and other displays (e.g., tablets) for ventriculostomy will also be explored in the future.

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