Enhancing Medical Education on the Diagnoses of Neuro-Ophthalmologic Diseases Through Gamification and Virtual Reality

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Abstract

Due to the complex and diverse symptoms of neuro-ophthalmologic diseases, medical training in diagnosing such eye diseases is very challenging and crucial for medical students in ophthalmology. Conventionally, medical students can only learn by rote memorisation through textbooks and then performing case studies for practice/examination under their instructors' guidance, for which learning effectiveness may be hindered. Accordingly, adopting the fundamental design principles of human-computer interaction (HCI) and virtual reality (VR) technologies, our team designed and implemented a VR-based simulation system, the Smart Neuro-Ophthalmologic Disease Educational Research Simulator (SNODERS), to effectively train medical students on the diagnoses of various neuro-ophthalmologic diseases and the effect of extraocular muscles on eye movements in a VR training game environment with different practising sessions and challenging missions.

The SNODERS system enables medical students to practise the examination of neuro-ophthalmologic diseases on a virtual patient by combining gesture recognition and gamification techniques using the latest MediaPipe Framework and the Unity Game Engine. Essentially, the MediaPipe is a machine-learning framework developed by Google to support real-time gesture recognition using simple web cameras. More importantly, with input from our medical experts, new visualisation techniques were developed to quickly convert the captured gesture information into the corresponding eye movements of the virtual patients through the Unity Game Engine. Other than a diversity of scenarios for medical students to practise diagnoses, many challenging game missions were implemented to evaluate and consolidate students' knowledge inside our VR game that can be used as a part of the examination/quiz or informal assessment for medical education.

To evaluate the effectiveness of the proposed SNODERS system for medical education, a set of questionnaires was carefully developed for a group of engineering and medical students to experiment with a prototype of the SNODERS system and then provide some initial feedback. The results of the preliminary system evaluation reveal the effectiveness of the proposed SNODERS system in stimulating students' learning interests and facilitating their learning progress in comprehending the symptoms of neuro-ophthalmologic diseases.

To our understanding, this work represents the first attempt to combine VR-based gesture recognition techniques with gamification to train medical students to diagnose neuro-ophthalmologic diseases effectively. The work reveals the potential applications of gamification and VR technology in various fields of medical education.

Keywords: medical education, ophthalmology, gesture recognition, virtual reality

1 Introduction

Neuro-ophthalmologic diseases refer to ocular disorders involving the neurological functioning of the eye movements and visual system (Lee et al., 2019; Somlai & Kovács, 2016). As a severely ageing urban society, Hong Kong has witnessed a rapid increase in the incidence of neuro-ophthalmologic diseases in the past decade (You et al., 2020). Cultivating qualified ophthalmologists with in-depth theoretical comprehension and extensive clinical diagnostic experience in neuro-ophthalmology is an urgent task for medical school. Nevertheless, medical pedagogy in ophthalmology has been challenging, especially for neuro-ophthalmologic diseases. Their complex physiological principles and diverse clinical manifestations greatly complicate the teaching process.

The ocular motility examination is an essential diagnostic method for neuro-ophthalmologic diseases that a medical student should proficiently acquire. During the ocular motility examination, an ophthalmologist should instruct the patients to gaze in different directions and observe the symptoms, including eye movement limitation, ptosis (eyelid droopiness), and pupil dilation, to determine the disease (Ansons, 2014). Fig.1 demonstrates the symptoms of a patient with sixth nerve palsy, a typical neuro-ophthalmologic disease, when looking at nine cardinal positions of gaze in an ocular motility examination. Regarding conventional teaching approaches to the ocular motility examination, like textbooks, slideshows, and video-based didactics, medical students are generally treated as audiences who should receive and memorise knowledge passively. Yet, they may often find it challenging to recall and understand all the corresponding symptoms by themselves without reference. Moreover, the tedious learning process could dampen their passion and interest.

Guided by the principle of facilitating medical pedagogy with specific HCI technology [?], our team develops the SNODERS system, a VR-based simulator, to engage medical students in actively learning neuro-ophthalmologic diseases. Through gesture recognition and real-time 3D animation techniques realised by the MediaPipe Framework and Unity Game Engine, the SNODERS system creates an immersive environment for medical students to interact with the virtual patient to practice a complete diagnostic procedure. The system also assists medical students in gaining insight into the anatomical and neurological causes of different neuro-ophthalmologic diseases. Moreover, a challenge mode scenario is implemented to add a gamification feature and motivate students' engagement. The SNODERS system intends to explore the potential of introducing HCI technology as a powerful complement to ophthalmology teaching. Its superior pedagogical engagement experience, low additional hardware requirements, and excellent compatibility make it a transferable model for intelligent medical training in ophthalmology.

Fig. 1. Patient suffering the sixth cranial palsy

2 Background and Related work

Due to the inherent complexity of eye-related neurology and extraocular muscle coordination, training medical students to correctly judge neuro-ophthalmologic diseases and thoroughly understand the underlying principles is regarded as a challenging task (Succar et al., 2016). To address this issue, HCI technologies have gained considerable attention in medical training simulations for their high interactivity and efficiency (Sadeghi Milani et al., 2022). Among the HCI technologies, virtual patient simulation is an effective interaction solution widely adopted by many intelligent medical training systems (Daher et al., 2020; Plackett et al., 2022; Tran et al., 2020). Efforts have also been undertaken to incorporate virtual patient simulation in the teaching process of diagnosing and managing neuro-ophthalmologic diseases from an academic perspective. Tom Lewis devised iRis, an interactive iOS application that enables an avatar to perform different symptom-related behaviours in response to the user's fingertip trajectory on the screen. The American Academy of Ophthalmology proposed the Strabismus Simulator, an educational tool designed to assist students in comprehending the examination process involving occluders and prism bars (*Strabismus Simulator*, 2015). The emergence of computer-aided animation and game engines has introduced a novel 3D approach for simulating ocular motility disorders and symptoms in the context of neuro-ophthalmologic diseases. Teresa and her team created a Neurological Examination Rehearsal Virtual Environment (NERVE) to focus on the clinical diagnosis training of common cranial nerve palsy disorders. The further investigation of their project suggests that the fusion of virtual patient simulation and social learning context could further enhance medical students' neuro-ophthalmology studies (T. R. Johnson et al., 2013). Using the Unity Game Engine, Tim Wood from Western University of Health Sciences developed the Eye Movement Simulator (EMS), a 3D web application capable of reproducing realistic pathologies of several cranial nerve diseases and different extraocular muscle weakness by dragging the computer mouse as the focal point for the eyes (*Eye Movement Simulator | CETL*, 2018).

Despite the outstanding contribution of HCI technology to medical education, there is still room for improvement. The homogenous and flat interaction method is the first shortcoming that needs to be tackled. The work mentioned above mainly employed mouse, keyboard and touchscreen interaction as their primary approaches. These traditional interaction methods could hardly give the students an immersive user experience. Thus, poor student engagement decreases teaching efficiency (Doherty & Doherty, 2019). The second area for improvement in the prior approaches is that they only considered a simple teaching scenario with demonstration, ignoring the gamification feature to motivate medical students in self-directed diagnosis practice (Plackett et al., 2022). The third issue is the need for neuro-ophthalmologic disease coverage and details of symptoms. In previous solutions, diseases with random symptom patterns, like myasthenia gravis and thyroid eye disease, were usually excluded (Douglas et al., 2015; Gilhus et al., 2019). Moreover, some solutions have omitted symptom details like pupil dilation, eyelid droopiness, and other facial and postural expressions.

By addressing these issues, the SNODERS system aims to enhance the interactivity and realism of the simulation. It innovatively integrates gesture recognition techniques, gamified learning scenarios and precise 3D animation control of virtual patients' symptoms.

3 System Design and Implementation

3.1 The System Architecture

The webcam image is used as the input resource for interaction instead of pricy VR motion sensors to reduce the entry barrier for ophthalmic educators. The SNODERS system is composed of two major components. The task of inferring the user's hand landmark information from a real-time captured image falls to the MediaPipe runtime framework for gesture recognition (F. Zhang et al., 2020). At the same time, the Unity Game Engine takes responsibility for real-time 3D animation control of the virtual patient avatar, user interface components management, and the execution of the visualisation algorithm. The MediaPipe Framework dynamically transfers the inferred user's gesture data to the Unity Game Engine in serialised JSON format (Jackson, 2016). The virtual patient avatar displays matching ocular motion and disease symptom responses based on the user interface input and gesture information.

The Unity Game Engine system furnishes fully featured interactive components and programmable animation scripts, providing an extensible platform for diverse teaching scenarios. Three featured scenarios in the Unity game scene are implemented to enhance students' comprehension of the symptomatology associated with various neuro-ophthalmologic diseases. The Disease Symptom Scenario is designed to demonstrate the symptoms of different neuro-ophthalmologic diseases. The Mission Challenge Scenario is a gamified platform that could be utilised for both practice and assessment purposes. The Muscle Weakness Scenario provides an insight into the influence of extraocular muscle dysfunction on ocular motility. The first two scenarios return the discrete disease types. Contrarily, the last scenario returns the continuously weakened extraocular muscle contractility on a per cent scale (N. Zhang & He, 2010). Two different sets of visualisation algorithms are employed correspondingly. An overview of the SNODERS system's components and associated information flow is given in Fig.2.

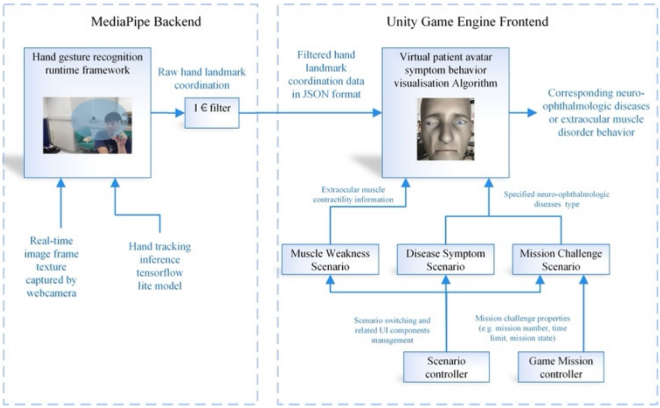

Fig. 2. An Overview of the SNODERS System Architecture

3.2 The Hand Gesture Recognition and Interpretation

The SNODERS system is intended to be an approachable solution for all ophthalmology educators with a low need for costly hardware accessories and additional software programming experience. Thus, our team created a workflow to use a webcam on a standard personal computer (PC) without a powerful graphic processing unit (GPU) to identify the user's hand gestures based on the MediaPipe Framework. Leveraging the pre-trained hand tracking Tensorflow lite model, the MediaPipe Backend infers the coordinates of the user's right index fingertip as the raw input for guiding the virtual patient avatar's gaze to different directions (Sánchez-Brizuela et al., 2023). The jitter of the hand landmark coordinate data may significantly hamper the accuracy and consistency of the virtual patient's gaze. To effectively address the jittering issue while maintaining acceptable latency, the one-euro filter is employed to process the raw inferred fingertip coordinate data (Casiez et al., 2012).

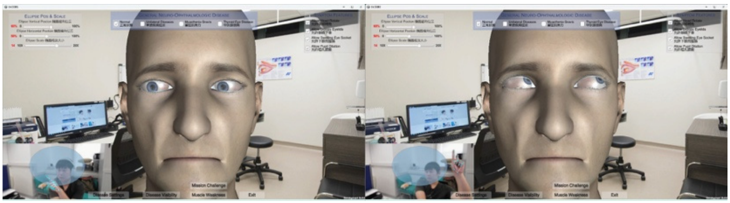

Fig. 3. Elliptical interactive shader: shader coverage

Based on reliable measurements of normal human ocular movement angles, our team fit an ellipse to represent the set of virtual patient's gaze projections on the vertical surface facing the user (Lim et al., 2014). The ellipse, a scalable shader over the webcam image, indicates the user the virtual patient's normal field of view. Suppose the user's right index fingertip is inside the ellipse area. In that case, the original Euler angles of the virtual patient's eye movement are proportionately transformed from the vertical and horizontal space distance between the user's right index fingertip and ellipse centre. Otherwise, the linear equation of the connection line between the user's right index fingertip and the ellipse centre is formulated to obtain the intersection coordinate of the ellipse and the connection line. Thus, the original distances are replaced with calculated values between the intersection and the ellipse centre. Fig.3 demonstrates the two situations in a virtual patient's normal-looking state. The user can freely regulate the position and scale of the interactive elliptical shader through the sliders at the upper left corner.

Algorithm 1 Elliptical interactive shader: transformation from user's fingertip coordinates to eye movement Euler angles

```
Input:
The pixel resolution width of user's WebCam, W;
The pixel resolution height of user's WebCam, H;
The normalized coordinate of user's right index fingertip, (x_tip, y_tip);
The center coordinate of ellipse, (X_center, Y_center);
The basis length of ellipse semi-major axis a
The basis length of ellipse semi-minor axis b
The scaling factor of ellipse, C;
Output:
The horizontal eye movement Euler angle in normal condition, φ;
The vertical eye movement Euler angle in normal condition, θ;
initialize camera, Mediapip process and shader. Retrieve W, H, C and (X_center, Y_center);
while camera image resource is available and MediaPipe process is running do
    if the elliptical interactive shader is modified by sliders in 'Ellipse Pos and Scale' panel or shader initialisation then
        Update new (X_center, Y_center);                    ▷ Move or resize the shader
        Update new C;
        A ← a * C;
        B ← b * C;
        F_shader(x, y) ← x^2/A^2 + y^2/B^2 = 1               ▷ Function of shader boundary
    end if
    if user's right hand detected then
        X_tip ← x_tip * W;
        Y_tip ← y_tip * H;
        if (X_tip − X_center)^2/A^2 + (Y_tip − Y_center)^2/B^2 ≤ 1 then   ▷ Shader coverage detection
            D_x ← X_tip − X_center;
            D_y ← Y_tip − Y_center;
        else
            P ← Y_tip − Y_center
            Q ← X_center − X_tip
            R ← X_tip * Y_center − X_center * Y_tip
            F_con(x, y) ← Px + Qy + R = 0                    ▷ Function of fingertip and shader center connection line
            (X_inter, Y_inter) ← F_con ∩ F_shader, X_inter * X_tip ≥ 0   ▷ Intersection of connection line and shader boundary
            D_x ← X_inter − X_center;
            D_y ← Y_inter − Y_center;
        end if
        φ_Raw ← D_x/C;
        θ_Raw ← D_y/C;
        φ ← OneEuroFilter(φ_Raw);                            ▷ Filter raw Euler angles to avoid jitter
        θ ← OneEuroFilter(θ_Raw);
    end if
end while
```

Fig. 4. Our Proposed Algorithm to Convert from the Users' Fingertip Coordinates to the Angles of Patients' Eye Movement

3.4 The Scene and Avatar Design

During VR engagement, the design of scenes and avatars can significantly influence the immersive experience (Cheymol et al., 2023; W. Zhang et al., 2017). A photograph of an actual ophthalmology clinic is employed as the background in the Unity Game Engine to create a more realistic teaching environment. Precise eye movement, facial expressions, and body posture control are required to execute the correct symptoms. Consequently, the virtual patient avatar possesses fine modelling, higher freedom of movement, and adjustable polymorphs. Moreover, medical ethics demand that the avatar be neutral and devoid of animated traits for the homogeneous affinity to different user groups.

3.3 The Disease Symptom Scenario

The Disease Symptom Scenario is the default scenario of the SNODERS system that allows users to observe the intuitive ocular motion limitation and symptom behaviours of mainstream neuro-ophthalmologic diseases. The user can select unilateral eye disease for each individual eye or bilateral eye disease for both eyes through the easy-to-use toggles. Relying on ophthalmology experts' professional opinions, our team simulates the diseases with fixed patterns, including eye-related cranial nerve palsies, orbital floor fracture, and internuclear ophthalmoplegia (Damodaran et al., 2014; Koenen & Waseem, 2023; Virgo & Plant, 2017). Diseases with unfixed patterns, including myasthenia gravis and thyroid eye disease, are also implemented with randomised disease behaviour (Douglas et al., 2015; Gilhus et al., 2019). The visualisation algorithms of different diseases are dynamically summoned to deploy corresponding eye rotation angle limitation and deviation parameters according to the user's selection in three panels. Dedicated randomisers are employed for diseases with unfixed patterns to generate new parameters in each trial to prevent duplication. The Disease Symptom Scenario reproduces the actual patient's symptoms with sophisticated visualisation algorithms to ensure authenticity. Fig.5 illustrates a comparative example between the SNODERS virtual patient and the actual patient, both suffering from partial third cranial nerve palsy (Tian et al., 2022).

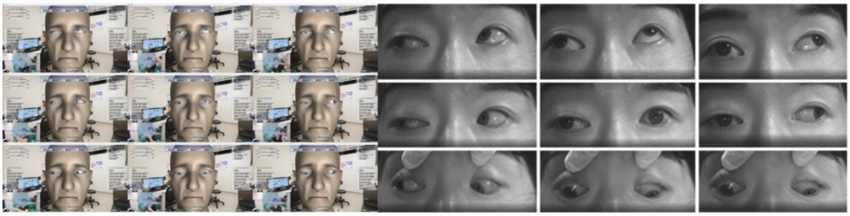

Fig. 5. Disease Symptom Scenario: SNODERS virtual patient versus actual patient

Moreover, the disease symptom features are highly customisable through the dedicated disease setting panels according to the user's demand. The ophthalmology educator can fine-tune the ocular motility behaviours through the sliders of the quantified disease parameters on a percentage scale. It is also possible to enable or inhibit specific behaviour traits associated with disease symptoms (e.g. pupil dilation, droopy eyelids). The ophthalmology educator can conceal the disease toggle panels for a brief quiz during class. These features add more flexibility and freedom to the teaching process.

3.4 The Muscle Weakness Scenario

Extraocular muscles are a group of six muscles that regulate the movement and positioning of the eyes, as shown in Fig.6 (Mudassar, 2022). They are crucial for maintaining the eye's proper alignment and enabling the eyes to gaze in different directions, which permits binocular vision and visual tracking (Jampel, 2009; Robinson, 1975). Nerve lesions brought by neuro-ophthalmologic diseases are directly reflected in a weakened ability of corresponding extraocular muscles. The eye movement is determined by a sophisticated combination of synergistic and antagonistic intermuscular actions (Guo et al., 2016). Due to the variation of mechanical advantage, the dominance of extraocular muscles in eye movement control changes with different eyeball rotation angles. For instance, the superior rectus and inferior oblique muscles contribute to the eyeball elevation (looking up). Nevertheless, in an adduction position (looking inward), the inferior oblique becomes the primary elevation source, negating the superior rectus's mechanical advantage.

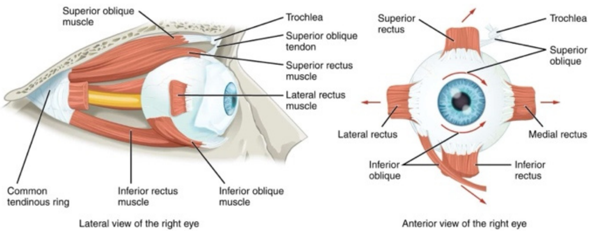

Fig. 6. Anatomical structure of extraocular muscles

Therefore, the Muscle Weakness Scenario is designed to elaborate on the underlying physiological principles of neuro-ophthalmologic diseases that have related influences on the extraocular muscles. Based on qualitative clinical, anatomical, and biomechanical analysis of extraocular muscle (Heidary & Phillips, 2022; Jain, 2019), our team propose a quantitative mathematical algorithm to visualise the relationship between ocular motility limitation and extraocular muscle contractility weakness. As shown in Fig.7, the sliders allow the user to modify the degree of extraocular muscle weakness. The algorithm dynamically defines the new boundary function of ocular motility limitation according to the degree of weakness. To more intuitively depict the contraction and stretching state of the extraocular muscles in different gazes, two models that rotate in synchronisation with the virtual patient's eyeballs are applied. This scenario aims to assist medical students in comprehending the mechanisms that shape disease symptoms instead of rote memorisation.

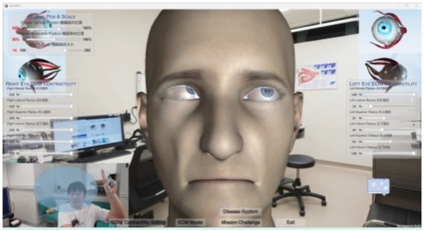

Fig. 7. Muscle Weakness Scenario

3.5 The Mission Challenge Scenario

Gamified learning has been proven to be an effective catalyst in boosting student's engagement and performance at undergraduate-level medical training (Do et al., 2023; Subhash & Cudney, 2018). Gamification of medical training is an essential feature of the SNODERS system. To the best of our knowledge, the Mission Challenge Scenario of the SNODERS system is the first practice to integrate gamified interaction patterns into the medical training of neuro-ophthalmologic diseases. The Mission Challenge Scenario is designed as a powerful tool that reinforces and tests medical students' knowledge of neuro-ophthalmologic disease symptoms. During the challenge game, tested students must accurately diagnose the type of neuro-ophthalmologic disease by conducting an ocular motility examination within a given time limit. They must determine diseases with either unilateral or bilateral conditions by ticking the corresponding toggles and pressing the submit button. For unilateral conditions, separate answers for each eye should be given. The correct answer appears in the mission interval to notify students whether they answered correctly. At the end of the game, a detailed report is generated to help ophthalmology educators evaluate students' performance. Medical students and ophthalmology educators can regulate the time limit, mission numbers and disease symptoms through the setting panels. For test purposes, ophthalmology educators can choose whether to have randomised or specified test sequences.

The visualisation algorithm and symptom control of the Misson Challenge Scenario are identical to that of the Disease Symptom Scenario. The difference is that the neuro-ophthalmologic disease types are predetermined in the setting process. The mission controller handles the mission process and pertinent parameters with an integrated finite state machine (FSM), as illustrated in Fig.8 (Adegun et al., 2020; Jagdale, 2021). The user has two options in the Setting State: either utilise the drag-and-drop list user interface to determine the disease-type sequence or let the program create even combinations of diseases at random (Adegun et al., 2020; C. H. Johnson et al., 2021). The validated disease-type sequence is stored in a queue data structure. For each new mission in the workflow, the disease-type information element at the front of the queue is retrieved and ejected until the queue is empty. The Answer State and Interval State time counts are managed by a timer whose corresponding time limit is defined in the Setting State. After a timeout or button call, the two states advance to the next appropriate state. The result of the test is announced in the Result State whenever the queue is empty. The Idle State is resumed when the new trial button is clicked.

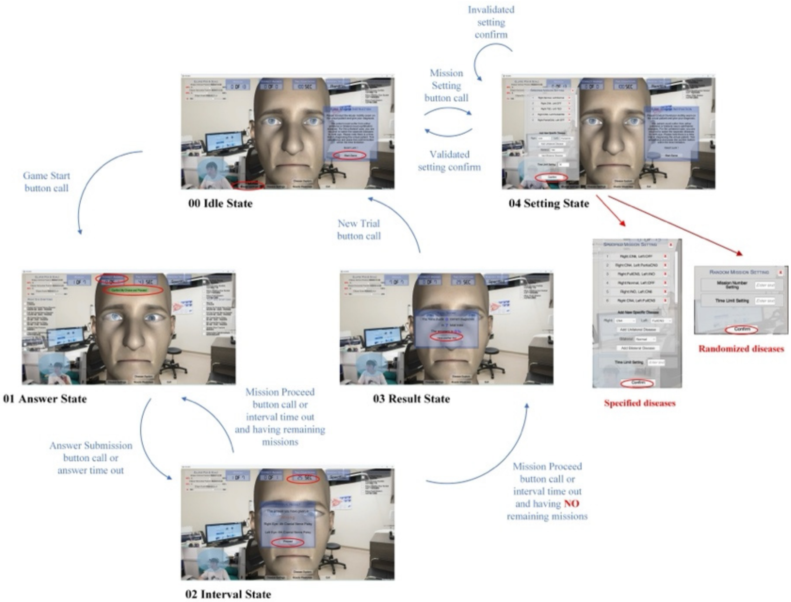

Fig. 8. Mission Challenge Scenario: finite state machine workflow

4 The Evaluation Results

To assess the teaching performance of the SNODERS system, a survey based on a questionnaire format was administered to 20 invited students who had used it. The user experience was assessed using a point system on a 1-5 scale. The overall average score of user experience satisfaction was 4.65/5.00, at a relatively high satisfaction level. Most subjects considered employing the SNODERS system in ophthalmology education an acceptable approach. In other feedback, some subjects mentioned that the system gave them an interactive experience while avoiding the VR sickness of head-mounted VR devices. All subjects held positive opinions regarding introducing the same learning pattern to other ophthalmology education.

The statistical results of each specific assessment metric are presented in Table. 2. The majority of the metric's assessment results were positive. With a 75% excellence rate, the assessment metrics that perform the best include correctness, clarity of the symptomatic expressions, and engagement enhancement. The outcome showed that the SNODERS system's disease reproduction closely resembles the symptoms of actual patients. Additionally, the SNODERS system significantly facilitated students' engagement in the learning process through the self-directed active learning pattern.

Table 1. User experience result.

User Experience Satisfaction Score (1 = Poor, 2 = Fair, 3 = Satisfactory, 4 = Good, 5 = Excellent, WAP stands for weighted average points)					
Poor (%)	**Fair (%)**	**Satisfactory (%)**	**Good (%)**	**Excellent (%)**	**WAP**
0	0	5%	25%	70%	4.65

Table 2. Specific assessment metric result.

Specific Assessment Metric Score (1 = Poor, 2 = Fair, 3 = Satisfactory, 4 = Good, 5 = Excellent, WAP stands for weighted average points)							
		Poor (%)	**Fair (%)**	**Satisfactory (%)**	**Good (%)**	**Excellent (%)**	**WAP**
1	**The realism of virtual patient's faces and eyes**	0	0	5%	30%	65%	4.60
2	**immersiveness of the clinical scenario**	0	0	10%	35%	55%	4.45
3	**Realism of finger-based interaction**	0	0	5%	25%	70%	4.65
4	**UI ease of operation**	0	0	10%	45%	45%	4.35
5	**Accuracy, clarity of symptomatic expressions**	0	0	0	25%	75%	4.75
6	**Facilitation in symptom memorisation**	0	0	0	30%	70%	4.70
7	**Facilitation in underlying principles comprehension**	0	0	5%	30%	65%	4.60
8	**Strong complementarity to book knowledge**	0	0	0	30%	70%	4.70
9	**Facilitation in discussions with teachers or students**	0	0	5%	40%	55%	4.50
10	**Engagement enhancement**	0	0	0	25%	75%	4.75
11	**Suitability for test, examination purpose**	0	0	25%	30%	45%	4.20

Evidently, the UI ease of operation and suitability for test and examination purposes performed less well than other metrics. Examining the subjects' narrative comments suggested that the new user may struggle to comprehend different UI components properly. However, all subjects could operate the SNODERS system independently after receiving guidance and a brief demonstration. Regarding the suitability for tests and examinations, some subjects mentioned that the SNODERS system had increased the difficulty compared to traditional writing forms. They were worried about how this testing strategy would impact their test results.

5 Concluding Remarks

This article presents an attempt to use HCI and VR technology to make a paradigm shift in ophthalmology education for neuro-ophthalmologic diseases. The proposed SNODERS system is intended to engage students in active learning through realistic clinical diagnosis simulations. The preliminary results show that the SNODERS system dramatically enhances teaching efficiency and attractiveness. Medical students can better memorise the disease symptoms and comprehend the underlying principles.

Moreover, this study explores the potential of fusion between engineering innovation and medical pedagogy. This work sheds light on many potential directions for interdisciplinary training and game-based learning for further investigation.

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