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Multi-sensory learning framework for visually impaired learners: Use of 3D, haptic, audio, olfactory media

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Abstract

Visually impaired (VI) people encounter difficulties in their regular activities including learning. Providing them equal opportunity is crucial, especially in virtual learning environment (VLE), as limited applications are available. A variety of technology-assisted and non-technology-assisted tools are available for the VI to assist in their daily activities. However, VI learners do not use virtual learning applications due to rich media involvement, which is unsuitable for them. Haptic or sense of touch is one of the technologies useful in VLE for VI learners. It can be used with audio sense and olfactory as additional senses to enhance the learning experience. This research aims to design a learning framework to develop a virtual learning environment for the VI learner. The study aims to design a framework to develop an application for the VI in a VLE, and validate the framework by conducting usability testing. The questionnaire for adult VI was adopted from the USE questionnaire, which tests the Usability, Satisfaction as well as Ease of Use, and Ease of Learning of the application. Questionnaire for children VI tested the application's effectiveness, operability, efficiency, and satisfaction. A total of 26 VI participated, and 21 of them are VI adults while 5 are VI children. Based on the usability with VI adults, average ratings are above 5 out of 7, and for the usability testing with VI children, average ratings are 3.7 and above out of 5. Hence, the rating obtained from usability tests were above average. The research was solely based on the Malaysian context and used only one haptic device. Thus, different haptic devices can be used to compare their effectiveness. The research can also be enhanced in other countries for learners with disabilities such as deaf, blind, and mute learners in learning calligraphy-based languages.

Keywords Haptic · Audio · Olfactory · Multi-sensory learning framework · Virtual learning for visually impaired

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1 Introduction

Visual impairment happens due to factors such as age, genetics, diabetes, corneal clouding, childhood blindness, and infections. As a result, visually impaired people usually encounter challenges in their daily activities, such as learning, walking, driving, reading, and socializing. The World Health Organization [1] states that at least 2.2 billion people worldwide are visually impaired or blind.

The visually impaired or the blind community has been side-lined by society in many ways. They usually require social and emotional support to ensure success both academically and socially [2]. According to research conducted at a higher secondary school for the blind, 22 out of 40 students were found depressed and experiencing difficulties in their daily lives [3]. These participants were in the range of 10 to 22 years old. Thus, paying more attention to providing better learning opportunities and environments for them is essential.

The visually impaired are always curious and eager to learn about the world. As they cannot rely on visual cues, it might be very complicated for them if there is no countermeasure for their educational needs [4, 5]. Unfortunately, there are limited e-learning frameworks or activities designed for visually impaired learners.

Learning theory describes how learners receive, process, and retain knowledge during the learning process. Research suggests that cognitive learning theory can assist visually impaired learners in developing their social skills [6]. This learning theory is used in many different areas of online learning [7]: learning using mobile games [8] as well as programming lessons through e-learning [9].

Theories of physiological characteristics in disability research can be divided into two categories [10]: defect theory and compensatory theory. In the defect theory, people with specific disabilities cannot live like ordinary people due to their defective organs, and their physiological development cannot reach the same level as that of ordinary people. In the compensatory theory, the defected organ(s) is/are compensated accordingly with the ability of other organs. For example, since the visually impaired' s sense of sight is defective, they perform better in other senses such as hearing, touch, olfaction, and taste.

Vision is the primary sense required for learning, and researchers estimate that 80% of the information we receive is through our vision [11]. As such, visually impaired learners must depend on their other available senses, such as hearing, smell, and taste. Hearing can provide information about the surroundings to the visually impaired. Senses like smell and taste can enhance the data perceived by the surroundings. Other sensory clues such as textures, air currents, and aromas, can also provide helpful information that aids the visually impaired in feeling confident and safe. These senses can assist them in learning by providing a more engaging and fun environment. Various technological and non-technological tools are available to help the visually impaired in learning [12].

According to previous research works [13] [14], visually impaired users use the sense of smell to differentiate fruits with similar shapes and textures. In addition, olfaction is attributed to the sense of smell in the human sensory system [15], enhancing human memory, which is important in learning.

Due to the significant impact on learners' performance who use olfactory devices in an e-learning environment compared to those who do not, olfactory tools have been used to improve user experience in the entertainment industry. The authors [16] have revealed that olfactory-enhanced multimedia applications affect users' perceptions and experiences toward multimedia applications. Therefore, this research aims to propose a learning framework for visually impaired learners in a virtual edutainment environment; and to develop a three-dimensional-3D- enabled and haptic audio and olfactory tool based on the application for the visually impaired to learn shapes in a virtual learning environment. The scenario used in this research deals with that learning the shapes of fruits.

2 Methodology

2.1 Study design

The study is based on the usability of the proposed framework and prototype.

2.2 Study location

The best way to communicate with visually impaired learners is through community or supporting organizations [17]. For this, the Malaysian Association for the Blind (MAB) and the National Council for the Blind (NCB) were contacted to get permission to conduct the research experiment with members of the society. Accordingly, with consent from NCB, research was conducted at the Malaysian Association for the Blind (MAB).

2.3 Sample size

According to [17] if the research focuses on users with visual impairments and they are required to take part in the study, it is generally acceptable to have 5–10 users. Thus, the Malaysian Association for the Blind (MAB) was contacted to provide at least 5 visually impaired students and teachers for preliminary testing. The total number of participants were 26 which comprised of 21 visually impaired adults and 5 visually impaired children.

2.4 Participants and sampling method

There are two main stakeholders in this research; visually impaired learners and teachers involved in teaching visually impaired learners. The participants were identified and briefed on the background of the study to obtain their consent. The location of the participants is Kuala Lumpur, Malaysia. Participant information sheets and consent forms were also prepared and submitted to MAB for approval. The visually impaired also fill up the forms with the assistance of a data collector. As suggested by various researchers [18], it is important not to collect names or other data that can be used to identify an individual to ensure the participants' privacy. Hence, the names of participants were not collected.

2.5 Measures

According to the study [13], the limitations and challenges faced by visually impaired users in using virtual edutainment applications are the rich media content involved, especially pictures and videos, and the lack of suitable applications available. Therefore, it is important to address these limitations when designing the framework. As mentioned in introduction, the visual impaired' s sensory skills in teaching and learning are essential aspects to consider while designing the framework. Hearing, touch, taste, and smell are important senses for the visually impaired in learning, thus, these senses were considered when designing the framework. Sensory skills are important for visually impaired learners to connect with the surrounding environment and gain knowledge. As they heavily rely on these senses, multimedia representations of the three senses (hearing, touch, and smell) were matched, as shown in the following Fig. 1, to be implemented in the prototype.

There are many learning theories which can be applied to learning process and among them, the cognitive learning theory was selected in this research. The learners were trained through the cognitive learning theory to provide them with the process of acquiring and storing information. In the cognitive learning theory, the learners either did not have any knowledge, or had limited knowledge on the learning process that they would be conducting. Thus, they were provided with detailed information on the learning process. The learners were allowed to go through the process as per the information provided. The leaners were then requested to answer the questionnaire in order to evaluate the output of the learning process. In this learning theory, the learners were also allowed to provide feedback on the learning process and on any steps which caused difficulties to them. Besides the learning theory, theories of physiological characteristics were also considered in designing the framework. There are two theories of psychological characteristics, namely the defect theory and the compensatory theory. For the visually impaired, the visual sense is the defect sense; and hearing, touch and olfactory senses fall under compensatory senses. Based on the above consideration, Fig. 2 proposed learning framework for visually impaired learners to learn in a virtual learning environment.

The proposed framework received validation from a panel of five experts, which include a visually impaired teacher with experience in teaching computer lessons to visually impaired students, an English teacher who specializes in teaching visually impaired students, a seasoned software developer, a software development engineer, and a skilled UX/UI designer. Three sections were included in the framework verification form: section A for the collection of demographic information, section B for the verification of components included in the framework, and section C for the collection of feedback for framework verification. In section B (components verification), the important senses used by visually impaired learners and how these senses could be represented in virtual learning environments were verified. The theory of e-learning and theories of physiological characteristics in disabled people were also verified. Based on the results, they provided unanimous support for the incorporation of the senses of touch,

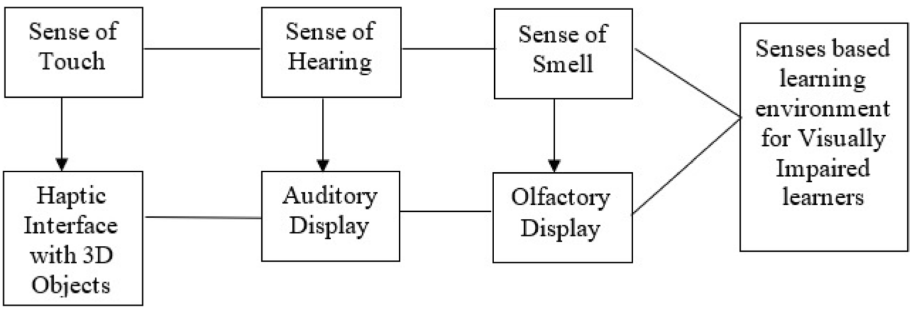

Fig. 1 Representation of multimedia elements corresponding to human senses

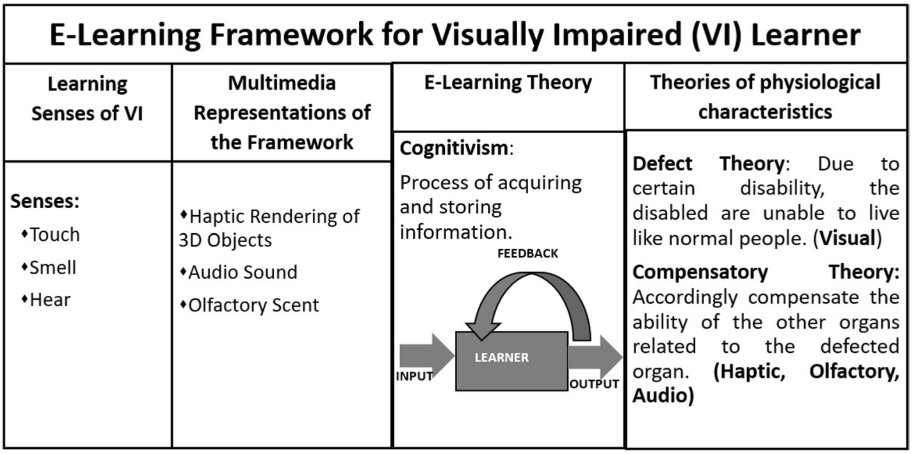

Fig. 2 E-learning framework for visually impaired learners in a virtual learning environment

smell, and hearing into virtual learning environments. Furthermore, they endorsed the inclusion of haptic rendering for 3D objects, olfactory elements, and audio cues as effective ways to represent these senses in the virtual learning space.

When it came to evaluating the alignment of the framework with e-learning theory and theories related to the physiological characteristics of disabled individuals, most of the experts (four out of five) expressed confidence in the framework's compliance with these concepts. However, one expert, a software engineer, had some reservations regarding the integration of learning theory and physiological characteristics. During an informal discussion, it was noted that some participants might not be well-versed in the intricacies of learning theory. Nevertheless, the consensus was that the framework's utilization of physiological characteristics and compensatory theories was deemed appropriate and beneficial for its intended application.

In this research, the USE questionnaire was adopted for the adults group [19]. Part A of the usability questionnaire is focused on the demographic information of the participants. Part B of the questionnaire focuses on the four elements of USE questionnaire: usefulness, ease of use, ease of learning and satisfaction. The questionnaire was designed using a seven-point Likert scale, and participants were asked to rate the statements, ranging from 1 for Strongly Disagree, to 7 for Strongly Agree. According to Lund [19], it was found that users evaluate the products primarily using three dimensions, i.e., Usefulness, Satisfaction, and Ease of use. While there were some evidences that other dimensions were used, the above three dimensions served most effectively between the interfaces. Similar to the questionnaire for the adult group, the questionnaire for the child group also consisted of two parts: objective questionnaire and subjective questionnaire. The objective questionnaire was given to investigate how often visually impaired users correctly identified the 3D haptic objects with auditory and olfactory senses, as well as without the sense of olfactory, in a virtual learning environment. The subjective questionnaire focused on the Effectiveness, Operability, Efficiency and Satisfaction of the proposed prototype. The questionnaire was developed based on the Framework for Evaluating the Usability of Mobile Educational Applications for Children [20]. The child group in this study were visually impaired learners aged between 9 to 14 years old, and the data for subjective measures was collected through 5-point Likert scale. This is because 7-point Likert scale is not suitable to be answered by children [21].

2.6 Procedures

All questionnaires were forward–backward translated into Malay independently and were printed out. It was read to the visually impaired learners during the experiment. Firstly, the Haptic device was introduced to the visually impaired learner, followed by the olfactory device. It took around 10 min and after that visually impaired learners start the experiment to touch the shapes of fruits by using the stylus based haptic device. The application provides smell of the fruits that visually impaired learner is touching, and the name of the fruit was played. After one round of the experiment, the sound and smell of the fruits were off alternative and asked the visually impaired user to identify the shapes by touching. According to the study [22], sound was the main influencing factor to identify the shapes of the fruits correctly, without sound, smell assists visually impaired users to identify the shapes correctly.

3 Results and discussion

The results obtained from usability study with both adults are child learners are analysed using the descriptive analysis in this study. Descriptive analysis is a type of data analysis that aids in accurately describing, displaying, or summarising data points so that patterns may appear that satisfy all the data's requirements. It answers the questions about who, what, where, when and to what extent. It does not matter whether the goal of the study is to identify and describe population trends and fluctuation or description of random samples in new countermeasures or intended studies of critical phenomena, description plays an important role in the scientific process. When descriptive analysis identifies previously unidentified socially significant occurrences, for example, it stands alone as a research output. Description frequently reveals causal understanding and the mechanisms underlying causal links. No matter how important a researcher's results may be, they only contribute to the knowledge and learning when others read and comprehend them. Utilizing proper analytical, communication, and data visualisation techniques to convert raw data into reported findings in a format that is helpful for each intended audience is an important step in research. While descriptive statistics is the use and analysis of such statistics, a descriptive statistic is a summary statistic that quantitatively describes or summaries aspects from a set of data.

3.1 Evaluation results by visually impaired adult group

The 21 participants who participated in this research were a mix of students, trainees, teachers, computer braillists, receptionists, and computer teachers. The majority of the participants aged above 25 years old, while 14.3% (3 out of 21) of the participants aged between 19 and 25 years old. The participants consisted of 11 males and 10 females. 66.7% (14 out of 21) of the participants were completely blind, and 33.3% (7 out of 21) were partially blind. The cause of blindness varied, as shown in the following Table 1.

It was found that 52.4% of the participants were blind since birth, and 42.9% of them lost their vision progressively. Only one individual lost his vision due to an accident. In terms of computer usage, 52.4% (11 out of 21) of the participants used the computer very frequently (every day), 4.8% (1 out of 21) used the computer frequently (few days in a week), 23% (5 out of 21) used the computer occasionally (few days in a month), and 14.3% (3 out of 21) used the computer very rarely. Amongst the 21 participants, one of them had never used a computer before. Table 2 shows the summary as below.

Table 1 Cause of blindness according to gender

Cause of Blindness	Male	Female
Since birth	4	6
Since young age (less than 5 years old)	1	0
Since teenage	1	0
Progressive loss	4	4
Due to accident	1	0

The participants used the computer for different purposes. Figure 3 depicts the purpose of computer usage by the participants.

The majority of the participants used the computer for learning and for job requirements, followed by for word processing and internet activities. Some of them used the computer for financial management, as well as leisure, and a small number of them used it for gaming. The following figure depicts the correct identification of 3D fruit shapes by the visually impaired participants using the proposed application. Based on the result obtained as shown in the Fig. 4, sound was the primary factor for the correct identification of the objects. However, without the audio media, the olfactory media was seen to be able to enhance the correct identification of the objects in a virtual environment.

Amongst the participants, three female participants correctly identified all the shapes. Two of them were 32 years old, and one of them was 20 years old. They were identified as a braillist, receptionist, and trainee, respectively, at the MAB. All of them used the computer on a daily basis. Their average rating was summarised as follows: Usefulness (4.24),

Table 2 Number of participants according to frequency of computer usage

Frequency of Computer Usage	No. of Participants
Very Frequently (Everyday)	11
Frequently (Few days in a week)	1
Occasionally (Few days in a month)	5
Rarely (Few times in a year)	3
Never use before	1

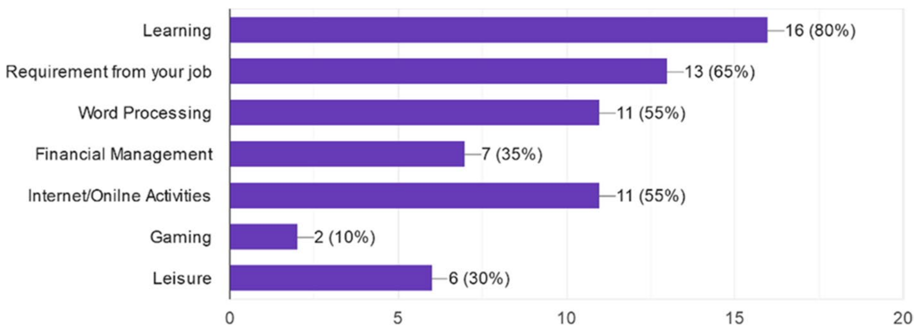

Fig. 3 Purpose of computer usage by participants

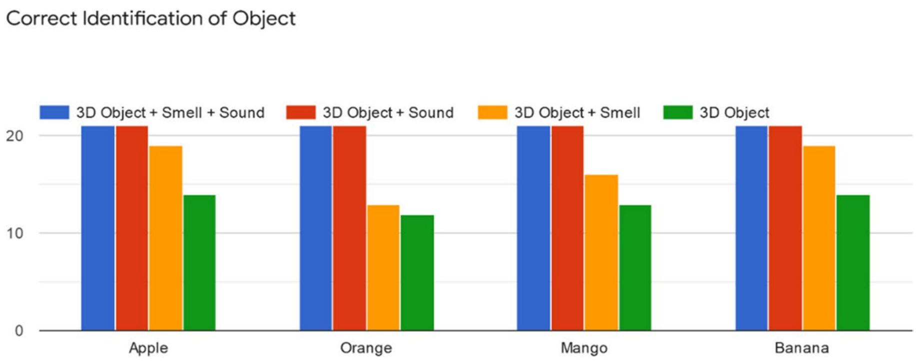

Fig. 4 Correct identification of objects by the adult group

Ease of Use (4.64), Ease of Learning (4.44), Satisfaction (4.5). Even though they were able to identify all the shapes correctly, their rating for the application was barely above average.

Among the participants, there were also two computer teachers who were visually impaired. Both of them were males, aged 31 and 43 years old. Even though they used the computer daily, one of them could not identify the mango (3D + smell, 3D only), and the other could not identify the orange, mango, and banana (3D + smell, 3D only). However, their average rating for the application was as follows: Usefulness (5.14), Ease of Use (4.77), Ease of Learning (4.9), Satisfaction (5.33). This could be because they, as teachers, thought that the application was useful, and gave it a better rating in terms of satisfaction. There were also four participants who incorrectly identified more than half of the shapes (3 shapes). They were identified as two computer teachers, a braillist, and a receptionist. The following Table 3 illustrates the average rating of individual participants according to the four constructs of USE: Usefulness, Ease of Use, Ease of Learning, and Satisfaction.

The frequency of computer usage did not affect the correct identification of shapes. Their average rating for the application was 4.64 (Usefulness), 4.52 (Ease of Use), 5.04 (Ease of Learning), and 4.42 (Satisfaction). For this group, the ratings for usefulness, ease of use, and satisfaction were barely above average, and only the ease of learning was rated 5 and above. There were 16 participants who could correctly identify half of the shapes, or more (2 or 3 shapes). This group consisted of seven trainees at MAB, namely three computer braillists, an audio technician, an instructor, a computer teacher, a Welfare officer, a Finance volunteer, as well as a job seeker with visual impairment. Among them, seven of them used the computer every day, five of them used the computer occasionally, three of them used the computer very rarely, and only one participant never used the computer. Their average rating for the application was as follows: Usefulness (5.47), Ease of Use (5.21), Ease of Learning (5.67), Satisfaction (5.50). The summary of the average, minimum, and maximum rating of all 21 participants toward the proposed application according to the four USE constructs are shown in Table 4.

3.2 Evaluation results by visually impaired child group

The usability questionnaire was intended to study the Effectiveness, Operability, Efficiency, and Satisfaction of 3D-based Olfactory-, Haptic-, and Audio-Enabled Application for Visually Impaired Users in Virtual Edutainment Environments. The questionnaire was

Table 3 Average rating of individual participants based on the four constructs

	Usefulness	Ease of Use	Ease of Learning	Satisfaction
Participant 1	6	4.64	6.33	6.16
Participant 2	5.57	5.55	5.83	6.5
Participant 3	4.14	3.64	4	3.67
Participant 4	5.7	4.55	4.33	4.83
Participant 5	4.86	4.55	5.33	5.17
Participant 6	5.86	5.9	6.83	4.83
Participant 7	3.43	3.73	4	3.83
Participant 8	6.14	5.9	6	6.33
Participant 9	5.14	4.82	5.5	4.67
Participant 10	5.29	5	5.83	4.67
Participant 11	6.29	6.18	6.83	6.67
Participant 12	4.14	3.64	3.83	4.33
Participant 13	4.86	4.64	5.17	5.17
Participant 14	7	6.73	6.5	6.5
Participant 15	6.86	6.64	6.67	6.67
Participant 16	4.71	4.82	5.83	5.33
Participant 17	5.86	5	6.67	6.67
Participant 18	4.29	5.18	5.33	4.5
Participant 19	4.57	4.27	4.33	4
Participant 20	5.86	5.64	5.5	5.5
Participant 21	3.71	5.73	4	4.67

Table 4 Average, maximum and minimum rating of the application

	Usefulness	Ease of Use	Ease of Learning	Satisfaction
Average	5.25	5.08	5.46	5.27
Maximum	7.00	6.73	6.83	6.67
Minimum	3.43	3.64	3.83	3.67

filled at the end of test session. Part A of the usability questionnaire mainly focused on the demographic information of the participants. There were a total of five participants, two of them were 14 years old, while the other three were 9 years old, 10 years old, and 12 years old. Among them, three of them were female and two were male. As for the vision level of participants, 80% (4 out of 5) of them were partially blind and 20% (1 out of 5) was completely blind. Among them, 40% (2 out of 5) of the participants were visually impaired since birth and 60% (3 out of 5) lost their vision progressively.

Two participants used the computer very frequently (everyday), one participant used the computer frequently (few days in a week), and two participants had never used a computer before. All the participants mentioned that they used the computer for learning purposes only. Similar to the results obtained from the adult group, all the shapes could be identified if participants were given 3D objects with sound and smell together, or without smell as shown in the following Fig. 5. In this case, sound was also a factor influencing the results. Once the sound media was removed and smell was introduced,

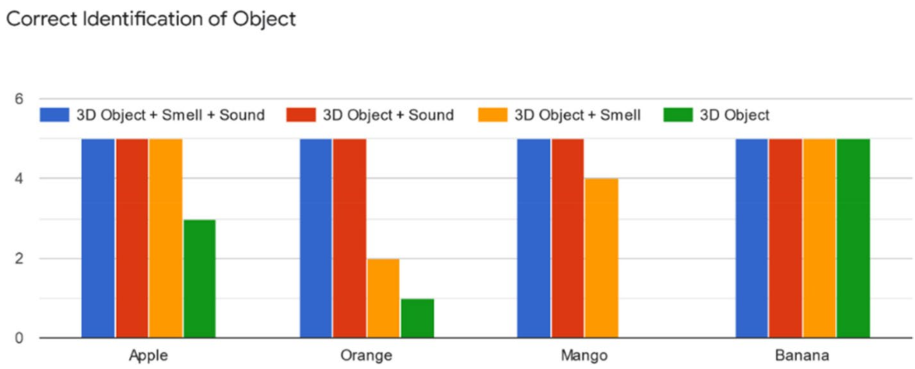

Fig. 5 Correct identification of objects by the child group

Table 5 Average rating of individual participants based on the four constructs

	Effectiveness	Operability	Efficiency	Satisfaction
Participant 1	4.4	4.43	4	4.5
Participant 2	4	4.29	4.5	4.5
Participant 3	2.6	2.85	2.75	2.5
Participant 4	3.8	4.7	5	4
Participant 5	4.6	4.7	4.5	4.75

100% (5 out of 5) of the participants identified the apple and banana correctly, 80% (4 out of 5) identified the mango and 40% (2 out of 5) identified the orange correctly. If only haptically enabled 3D object was given, 100% (5 out of 5) of the participants identified banana correctly and 60% (3 out of 5) identified apple correctly. However, only 20% of the participants could correctly identify the orange and none of the participants identified the mango correctly. Thus, compared to 3D objects with and without smell, 3D objects with smell could assist visually impaired users better in identifying shapes.

The following Table 5 illustrates the average rating of individual participants according to the four constructs of the questionnaire: Effectiveness, Operability, Efficiency and Satisfaction.

Based on the results, the frequency of computer usage did not affect the correct identification of the shapes for the focus group as well. Their average rating for the application was 3.70 out of 5 for effectiveness, 4.07 out of 5 for operability, 4.06 out of 5 for efficiency, and 3.88 out of 5 for satisfaction. For this group, all the ratings were above average. The summary of the average, minimum, and maximum rating of all five participants toward the proposed application according to the four constructs are shown in Table 6.

4 Conclusion

In this research, different elements were considered in developing a learning framework for visually impaired learners in a virtual learning environment. Various aspects were considered, such as sensory skills of the visually impaired in their learning process,

Table 6 Average, maximum and minimum rating of the application by child group

	Effectiveness	Operability	Efficiency	Satisfaction
Average	3.70	4.07	4.06	3.88
Maximum	4.4	4.7	5	4.5
Minimum	2.6	2.85	2.75	2.5

suitable learning theories, implementation of senses in virtual environments, as well as theories of physiological characteristics of the disabled in the field of disability research. The proposed framework was verified by experts and a 3D-Haptic-Audio-Olfactory-based prototype was developed based on the verified framework. The proposed application was evaluated by two groups of users, visually impaired adults and visually impaired children The results obtained from this research was positive and participants agreed that the application was easy to use.

They also agreed that the application give them sense of satisfaction and enhance their experience in learning. In conclusion, it was surprising to see that, even if the participants were able to identify all the shapes correctly, their rating for the application was not so high. This could be because some of them have never used a computer for learning. Participants who used computers for teaching gave above average ratings for the application. It could also be concluded that the frequency of computer usage did not affect the correct identification of shapes. Based on the result, sound is the most influencing factor to identify the shapes and without sound media, olfactory devices can also enhance the identification of objects in virtual environments and enhance their learning experience. The research supports the general opportunities identified for the visually impaired in learning and can be used for e-learning as an option in their learning journey.

As for the limitation, the research participants are from the Malaysia Association for the Blind (MAB) and more participants from different geographical area should be included in experimental testing. Besides, various type of haptic and olfactory devices can also be considered to include to compare the efficiency and performance of the proposed application. The research can also be further improved to use a combination of haptics and olfaction in many other learning areas as well as to target for other disabled learners such as deaf blind, mute, etc.

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Data availability The data that support the findings of this study are available from the corresponding author on reasonable request.

Declarations

Conflicts of interests/Competing interests There is no conflict of interests to disclose.

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