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PhD Thesis

Augmented and mixed reality for therapeutic education in diabetes

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June 2025

*To M.Carmen, my thesis director,
for her essential guidance and expertise, crucial to the rigor and development of this work.*

*To Marcela, my life partner,
for every gesture of support, for your endless love, and for believing in me and motivating
me throughout these years.*

*In loving memory of my beloved mother, Rina,
You were and always will be my greatest motivation and inspiration to achieve each of my
professional goals. Your love and your example live on in me every day. You are always
in my thoughts.*

Abstract

Therapeutic education is essential for patients with diabetes to effectively manage their disease, and technology can offer innovative tools to facilitate this process. This doctoral thesis is presented as a compendium of three articles. The main objective was to design, develop, and validate Augmented Reality (AR) and Mixed Reality (MR) applications for therapeutic education in diabetes, specifically focused on learning to count carbohydrate choices in food.

Three versions were developed. The first, an AR application for mobile devices, included foods relevant to Spanish patients. The second, also an AR application for mobiles, adapted the content for Ecuadorian patients. In the AR applications, a real dish is used with an image glued to its center, which simulates the design of a physical dish. The virtual content, such as food, is anchored to the center of the physical dish and displayed in real size according to the corresponding carbohydrate choices, allowing the physical dish to function as a tangible user interface. The third version, developed in MR, was designed for use with headsets, incorporating passthrough functionality in both grayscale and color. Although the core of the MR application remained unchanged, the passthrough experience varies by device: Meta Quest 2 only supports this feature in grayscale, while Meta Quest 3/3S allows for its visualization in color. The user interacts with the application using their hands, without the need for controllers. The applications are structured into three levels, each focused on a food category: dairy products, cereals, and fruits, which include 7, 8, and 10 foods respectively. Each level begins with a learning phase, where foods are presented in real size along with their weight, number of carbohydrate choices, and glycemic index. Afterward, patients access an evaluation phase, in which they must select the correct amount of carbohydrates for the different foods from three available options.

The design, development, and validation of the three applications have been published in the three articles that comprise this thesis. The validations presented in each of these articles are described below. The first study involved 70 Spanish children with Type 1 diabetes. The objective of this study was to determine the effectiveness of the AR application in terms of learning about carbohydrate choices in different foods, as well as to evaluate the satisfaction and perceived usability by children with diabetes. The results indicated a significant improvement in knowledge about carbohydrate choices. Learning was independent of gender and age. Likewise, the levels of satisfaction and usability perceived by the children were high.

The second study involved 27 Ecuadorian patients with Type 1 diabetes, both children and adults. All participants initially received a traditional educational session and, a week later, used the AR application. Two weeks later, an evaluation was conducted to

measure knowledge retention. Additionally, the data from the Ecuadorian participants were compared with those obtained in the previous study with Spanish children. The main objective of this study was to evaluate the effectiveness of the AR application in transferring knowledge about carbohydrate choices in food, analyzing short- and mid-term retention in children and adults. Secondary objectives included the evaluation of usability and satisfaction perceived by the patients, as well as the comparison of the results obtained in Ecuador and Spain. The application proved to be effective for short-term knowledge transfer in both children and adults, significantly surpassing the traditional teaching method. A 'suggestively' significant impact ($p = 0.044$) was observed on mid-term knowledge retention (two weeks), although with a decrease compared to the levels reached in the short-term. No significant differences were found in learning outcomes based on gender or age. The user experience was rated as excellent.

The third study involved 92 Ecuadorian patients with Type 1 diabetes (children and adults). Participants were assigned to one of four groups in a between-subjects design: Group 1 used a traditional learning method; Group 2 used the mobile AR application; Group 3 used the MR application with grayscale passthrough; and Group 4 used the same MR application but with color passthrough. The objective of this study was to quantify and compare the effectiveness in knowledge transfer about carbohydrate choices among the four learning methods. Both mobile AR and MR, in their grayscale and color passthrough modalities, proved to be effective methods for improving knowledge about carbohydrate choices. Mobile AR and color MR significantly outperformed the traditional teaching method. Likewise, grayscale MR obtained better learning outcomes compared to conventional teaching. Among all modalities, MR with color passthrough showed the highest results, surpassing both mobile AR and grayscale MR. In terms of user experience, all versions (AR and MR) were rated as excellent, with mobile AR and color MR offering a superior experience compared to grayscale MR.

The general conclusions derived from this thesis are as follows:

- Effectiveness of extended reality technologies: The results show that AR and MR applications significantly improve short-term learning about carbohydrate choices, surpassing the results obtained through traditional methods.
- High acceptance by patients: The developed applications, both AR and MR, were well-received by patients, who reported a satisfactory user experience and perceived the applications as easy to use. These results suggest a good willingness to adopt this type of technology as a support in therapeutic education and diabetes management.
- Positive impact regardless of age or gender: The effectiveness of AR and MR applications for learning is not significantly influenced by the age or gender of the patients, which positions them as potentially universal solutions within the diabetic population.
- Cross-cultural viability: The AR application proved to be effective in both Spain and Ecuador, which suggests that this type of application can be adapted and be useful in different cultural and geographical contexts.
- Superiority of the latest technology: The quality of the immersive experience, such as that offered by MR with color passthrough, improves both learning outcomes and the user experience compared to AR or grayscale MR. This demonstrates that

the exploitation of advanced technologies, such as color passthrough in MR, can contribute to optimizing the effectiveness of this type of educational tools.

- Confirmed need for therapeutic education: The studies show a knowledge gap in carbohydrate management among patients with diabetes, which reinforces the importance of designing and developing effective educational tools, such as those researched in this thesis.

Resumen

La educación terapéutica es fundamental para que los pacientes con diabetes gestionen eficazmente su enfermedad, y la tecnología puede ofrecer herramientas innovadoras para facilitar este proceso. Esta tesis doctoral se presenta como un compendio de tres artículos. El objetivo principal fue diseñar, desarrollar y validar aplicaciones de Realidad Aumentada (RA) y Realidad Mixta (RM) para la educación terapéutica en diabetes, centradas específicamente en el aprendizaje para contar raciones de hidratos de carbono en los alimentos.

Se desarrollaron tres versiones. La primera, una aplicación de RA para dispositivos móviles, incluyó alimentos relevantes para pacientes españoles. La segunda, también una aplicación de RA para móviles, que adaptó el contenido para pacientes ecuatorianos. En las aplicaciones de RA, se utiliza un plato real al que se ha pegado una imagen en el centro del mismo, que simula el diseño de un plato físico. El contenido virtual, como los alimentos, se ancla en el centro del plato físico y se muestra a tamaño real según las raciones de hidratos de carbono correspondientes, permitiendo que el plato físico funcione como una interfaz de usuario tangible. La tercera versión, desarrollada en RM, fue diseñada para su uso con visores, incorporando la funcionalidad passthrough tanto en escala de grises como en color. Aunque el núcleo de la aplicación de RM se mantuvo sin cambios, la experiencia de passthrough varía según el dispositivo: Meta Quest 2 solo admite esta función en escala de grises, mientras que Meta Quest 3/3S permite su visualización a color. El usuario interactúa con la aplicación utilizando sus manos, sin necesidad de controladores. Las aplicaciones se estructuran en tres niveles, cada uno centrado en una categoría de alimentos: productos lácteos, cereales y frutas, que incluyen 7, 8 y 10 alimentos respectivamente. Cada nivel comienza con una fase de aprendizaje, en la que se presentan los alimentos a tamaño real junto con su peso, número de raciones de hidratos de carbono e índice glucémico. A continuación, los pacientes acceden a una fase de evaluación, en la que deben seleccionar la cantidad correcta de hidratos de carbono para los distintos alimentos a partir de tres opciones disponibles.

El diseño, desarrollo y validación de las tres aplicaciones ha sido publicado en los tres artículos que conforman esta tesis. A continuación, se describen las validaciones presentadas en cada uno de dichos artículos. En el primer estudio participaron 70 niños españoles con diabetes de Tipo 1. El objetivo de este estudio fue determinar la eficacia de la aplicación de RA en términos de aprendizaje sobre las raciones de hidratos de carbono en distintos alimentos, así como evaluar la satisfacción y la usabilidad percibidas por los niños con diabetes. Los resultados indicaron una mejora significativa en el conocimiento sobre las raciones de hidratos de carbono. El aprendizaje fue independiente del género y la edad. Asimismo, los niveles de satisfacción y usabilidad percibidos por los niños fueron elevados.

En el segundo estudio participaron 27 pacientes ecuatorianos con diabetes de Tipo 1, tanto niños como adultos. Todos los participantes recibieron inicialmente una sesión educativa tradicional y, una semana después, utilizaron la aplicación de RA. Dos semanas más tarde, se llevó a cabo una evaluación para medir la retención de conocimientos. Además, los datos de los participantes ecuatorianos se compararon con los obtenidos en el estudio previo realizado con niños españoles. El objetivo principal de este estudio fue evaluar la eficacia de la aplicación de RA en la transferencia de conocimientos sobre las raciones de hidratos de carbono en los alimentos, analizando la retención a corto y medio plazo en niños y adultos. Como objetivos secundarios, se incluyó la evaluación de la usabilidad y satisfacción percibida por los pacientes, así como la comparación de los resultados obtenidos en Ecuador y en España. La aplicación demostró ser eficaz para la transferencia de conocimientos a corto plazo tanto en niños como en adultos, superando significativamente el método de enseñanza tradicional. Se observó un impacto ‘marginamente’ significativo ($p = 0.044$) en la retención de conocimientos a medio plazo (dos semanas), aunque con una disminución respecto a los niveles alcanzados a corto plazo. No se encontraron diferencias significativas en los resultados del aprendizaje en función del género o la edad. La experiencia de usuario fue valorada como excelente.

En el tercer estudio participaron 92 pacientes ecuatorianos con diabetes de Tipo 1 (niños y adultos). Los participantes fueron asignados a uno de cuatro grupos en un diseño entre sujetos: Grupo 1 utilizó un método de aprendizaje tradicional; Grupo 2 utilizó la aplicación móvil de RA; Grupo 3 utilizó la aplicación de RM con passthrough en escala de grises; y Grupo 4 utilizó la misma aplicación de RM pero con passthrough a color. El objetivo de este estudio fue cuantificar y comparar la eficacia en la transferencia de conocimientos sobre raciones de hidratos de carbono entre los cuatro métodos de aprendizaje. Tanto la RA móvil como la RM, en sus modalidades con passthrough en escala de grises y en color, demostraron ser métodos eficaces para mejorar el conocimiento sobre las raciones de hidratos de carbono. La RA móvil y la RM en color superaron significativamente al método de enseñanza tradicional. Asimismo, la RM en escala de grises obtuvo mejores resultados de aprendizaje respecto a la enseñanza convencional. Entre todas las modalidades, la RM con passthrough a color fue la que mostró los resultados más altos, superando tanto a la RA móvil como a la RM en escala de grises. En cuanto a la experiencia de usuario, todas las versiones (RA y RM) fueron valoradas como excelentes, siendo la RA móvil y la RM en color las que ofrecieron una experiencia superior en comparación con la RM en escala de grises.

Las conclusiones generales derivadas de esta tesis son las siguientes:

- Eficacia de las tecnologías de realidad extendida: Los resultados muestran que las aplicaciones de RA y RM mejoran significativamente el aprendizaje a corto plazo sobre las raciones de hidratos de carbono, superando los resultados obtenidos mediante métodos tradicionales.
- Alta aceptación por parte de los pacientes: Las aplicaciones desarrolladas, tanto de RA como de RM, fueron bien recibidas por los pacientes, quienes manifestaron una experiencia de usuario satisfactoria y percibieron las aplicaciones como fáciles de usar. Estos resultados sugieren una buena disposición para adoptar este tipo de tecnologías como apoyo en la educación terapéutica y el control de la diabetes.

- Impacto positivo independientemente de la edad o el género: La efectividad de las aplicaciones de RA y RM para el aprendizaje no se ve significativamente influenciada por la edad ni el género de los pacientes, lo que las posiciona como soluciones potencialmente universales dentro de la población diabética.
- Viabilidad transcultural: La aplicación de RA demostró ser efectiva tanto en España como en Ecuador, lo que sugiere que este tipo de aplicaciones pueden adaptarse y ser útiles en diferentes contextos culturales y geográficos.
- Superioridad de la tecnología más reciente: La calidad de la experiencia inmersiva, como la que ofrece la RM con passthrough a color, mejora tanto los resultados del aprendizaje como la experiencia del usuario en comparación con la RA o la RM en escala de grises. Esto evidencia que la explotación de tecnologías avanzadas, como el passthrough a color en RM, puede contribuir a optimizar la efectividad de este tipo de herramientas educativas.
- Necesidad confirmada de educación terapéutica: Los estudios evidencian una brecha en el conocimiento sobre la gestión de hidratos de carbono entre pacientes con diabetes, lo que refuerza la importancia de diseñar y desarrollar herramientas educativas efectivas, como las investigadas en esta tesis.

Resum

L'educació terapèutica és fonamental perquè els pacients amb diabetis gestionen eficaçment la seua malaltia, i la tecnologia pot oferir ferramentes innovadores per a facilitar este procés. Esta tesi doctoral es presenta com un compendi de tres articles. L'objectiu principal va ser dissenyar, desenvolupar i validar aplicacions de Realitat Augmentada (RA) i Realitat Mixta (RM) per a l'educació terapèutica en diabetis, centrades específicament en l'aprenentatge per a comptar racions d'hidrats de carboni en els aliments.

Es van desenvolupar tres versions. La primera, una aplicació de RA per a dispositius mòbils, va incloure aliments rellevants per a pacients espanyols. La segona, també una aplicació de RA per a mòbils, que va adaptar el contingut per a pacients equatorians. En les aplicacions de RA, s'utilitza un plat real al qual s'ha pegat una imatge al centre, que simula el disseny d'un plat físic. El contingut virtual, com els aliments, s'ancora al centre del plat físic i es mostra a grandària real segons les racions d'hidrats de carboni corresponents, permetent que el plat físic funcione com una interfície d'usuari tangible. La tercera versió, desenvolupada en RM, va ser dissenyada per al seu ús amb visors, incorporant la funcionalitat passthrough tant en escala de grisos com en color. Encara que el nucli de l'aplicació de RM es va mantindre sense canvis, l'experiència de passthrough varia segons el dispositiu: Meta Quest 2 només admet esta funció en escala de grisos, mentre que Meta Quest 3/3S permet la seua visualització en color. L'usuari interactua amb l'aplicació utilitzant les seues mans, sense necessitat de controladors. Les aplicacions s'estructuren en tres nivells, cadascun centrat en una categoria d'aliments: productes lactis, cereals i fruites, que inclouen 7, 8 i 10 aliments respectivament. Cada nivell comença amb una fase d'aprenentatge, en la qual es presenten els aliments a grandària real juntament amb el seu pes, nombre de racions d'hidrats de carboni i índex glucèmic. A continuació, els pacients accedixen a una fase d'avaluació, en la qual han de seleccionar la quantitat correcta d'hidrats de carboni per als distints aliments a partir de tres opcions disponibles.

El disseny, desenvolupament i validació de les tres aplicacions ha sigut publicat en els tres articles que conformen esta tesi. A continuació, es descriuen les validacions presentades en cada un d'estos articles. En el primer estudi van participar 70 xiquets espanyols amb diabetis de Tipus 1. L'objectiu d'este estudi va ser determinar l'eficàcia de l'aplicació de RA en termes d'aprenentatge sobre les racions d'hidrats de carboni en distints aliments, així com avaluar la satisfacció i la usabilitat percebudes pels xiquets amb diabetis. Els resultats van indicar una millora significativa en el coneixement sobre les racions d'hidrats de carboni. L'aprenentatge va ser independent del gènere i l'edat. Així mateix, els nivells de satisfacció i usabilitat percebuts pels xiquets van ser elevats.

En el segon estudi van participar 27 pacients equatorians amb diabetis de Tipus 1, tant xiquets com adults. Tots els participants van rebre inicialment una sessió educativa tradicional i, una setmana després, van utilitzar l'aplicació de RA. Dos setmanes més tard, es va dur a terme una avaluació per a mesurar la retenció de coneixements. A més, les dades dels participants equatorians es van comparar amb les obtingudes en l'estudi previ realitzat amb xiquets espanyols. L'objectiu principal d'este estudi va ser avaluar l'eficàcia de l'aplicació de RA en la transferència de coneixements sobre les racions d'hidrats de carboni en els aliments, analitzant la retenció a curt i mitjà termini en xiquets i adults. Com a objectius secundaris, es va incloure l'avaluació de la usabilitat i satisfacció percebuda pels pacients, així com la comparació dels resultats obtinguts a l'Equador i a Espanya. L'aplicació va demostrar ser eficaç per a la transferència de coneixements a curt termini tant en xiquets com en adults, superant significativament el mètode d'ensenyament tradicional. Es va observar un impacte 'marginalment' significatiu ($p = 0.044$) en la retenció de coneixements a mitjà termini (dos setmanes), encara que amb una disminució respecte als nivells aconseguits a curt termini. No es van trobar diferències significatives en els resultats de l'aprenentatge en funció del gènere o l'edat. L'experiència d'usuari va ser valorada com a excel·lent.

En el tercer estudi van participar 92 pacients equatorians amb diabetis de Tipus 1 (xiquets i adults). Els participants van ser assignats a un de quatre grups en un disseny entre subjectes: Grup 1 va utilitzar un mètode d'aprenentatge tradicional; Grup 2 va utilitzar l'aplicació mòbil de RA; Grup 3 va utilitzar l'aplicació de RM amb passthrough en escala de grisos; i Grup 4 va utilitzar la mateixa aplicació de RM però amb passthrough en color. L'objectiu d'este estudi va ser quantificar i comparar l'eficàcia en la transferència de coneixements sobre racions d'hidrats de carboni entre els quatre mètodes d'aprenentatge. Tant la RA mòbil com la RM, en les seues modalitats amb passthrough en escala de grisos i en color, van demostrar ser mètodes eficaços per a millorar el coneixement sobre les racions d'hidrats de carboni. La RA mòbil i la RM en color van superar significativament el mètode d'ensenyament tradicional. Així mateix, la RM en escala de grisos va obtenir millors resultats d'aprenentatge respecte a l'ensenyament convencional. Entre totes les modalitats, la RM amb passthrough en color va ser la que va mostrar els resultats més alts, superant tant la RA mòbil com la RM en escala de grisos. Pel que fa a l'experiència d'usuari, totes les versions (RA i RM) van ser valorades com a excel·lents, sent la RA mòbil i la RM en color les que van oferir una experiència superior en comparació amb la RM en escala de grisos.

Les conclusions generals derivades d'esta tesi són les següents:

- Eficàcia de les tecnologies de realitat estesa: Els resultats mostren que les aplicacions de RA i RM milloren significativament l'aprenentatge a curt termini sobre les racions d'hidrats de carboni, superant els resultats obtinguts per mètodes tradicionals.
- Alta acceptació per part dels pacients: Les aplicacions desenvolupades, tant de RA com de RM, van ser ben rebudes pels pacients, els quals van manifestar una experiència d'usuari satisfactòria i van percebre les aplicacions com a fàcils d'usar. Estos resultats suggerixen una bona disposició per a adoptar este tipus de tecnologies com a suport en l'educació terapèutica i el control de la diabetis.
- Impacte positiu independentment de l'edat o el gènere: L'efectivitat de les aplicacions de RA i RM per a l'aprenentatge no es veu significativament influenciada per l'edat

ni el gènere dels pacients, la qual cosa les posiciona com a solucions potencialment universals dins de la població diabètica.

- Viabilitat transcultural: L'aplicació de RA va demostrar ser efectiva tant a Espanya com a l'Equador, la qual cosa suggerix que este tipus d'aplicacions poden adaptar-se i ser útils en diferents contextos culturals i geogràfics.
- Superioritat de la tecnologia més recent: La qualitat de l'experiència immersiva, com la que oferix la RM amb passthrough en color, millora tant els resultats de l'aprenentatge com l'experiència de l'usuari en comparació amb la RA o la RM en escala de grisos. Açò evidencia que l'explotació de tecnologies avançades, com el passthrough en color en RM, pot contribuir a optimitzar l'efectivitat d'este tipus de ferramentes educatives.
- Necessitat confirmada d'educació terapèutica: Els estudis evidencien una bretxa en el coneixement sobre la gestió d'hidrats de carboni entre pacients amb diabetis, la qual cosa reforça la importància de dissenyar i desenvolupar ferramentes educatives efectives, com les investigades en esta tesi.

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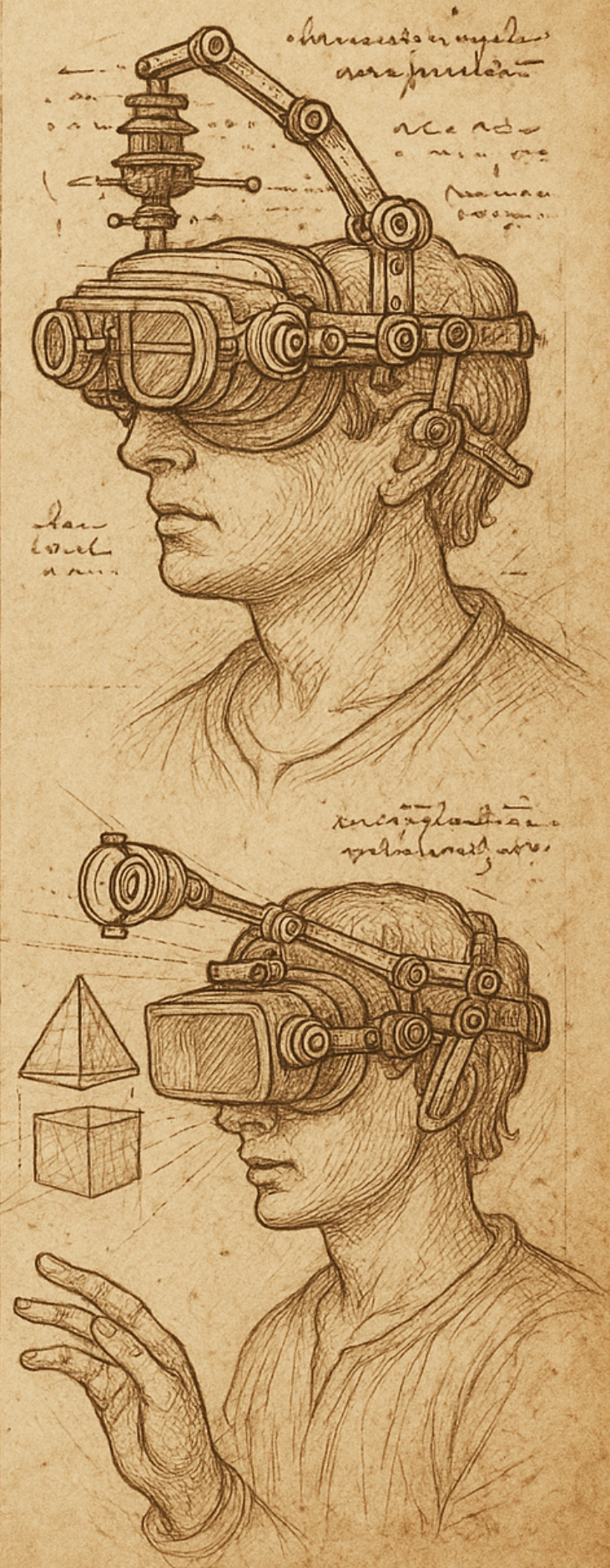
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AVMENTATA REALITAS

MIXTA REALITAS



Chapter 1

Introduction

1.1 Motivation

Diabetes mellitus is a global health crisis, affecting more than half a billion adults worldwide, and imposing severe personal and economic burdens [1]. Its management increasingly demands innovative approaches beyond conventional medical care, especially in patient education. Diabetes mellitus is characterized by a metabolic disorder in which the body is unable to produce enough insulin or to use it effectively, resulting in elevated blood glucose levels (hyperglycemia) [2]. This condition can lead to the development of severe long-term microvascular and macrovascular complications [2]. The main types of diabetes include Type 1 diabetes, Type 2 diabetes, and gestational diabetes mellitus. Type 1 diabetes is an autoimmune process in which insulin-producing pancreatic beta cells are destroyed, requiring exogenous insulin administration and primarily manifesting in childhood and adolescence. Type 2 diabetes is characterized by insulin resistance and/or insufficient insulin production, being more common in adults but with an increasing prevalence in adolescents, and its management includes diet, exercise, oral medication, and, in advanced stages, insulin. Gestational diabetes occurs during pregnancy due to the inability to produce or use enough insulin for the needs of gestation [2].

The global burden of diabetes is significant, with hundreds of millions of people affected worldwide. According to recent forecasts, approximately 589 million adults (aged 20 to 79 years) were living with diabetes in 2024, with a projected increase to 853 million by 2050 [1]. The rising prevalence is particularly pronounced in low- and middle-income countries [1], and it represents a considerable economic and social burden on health systems. For example, a study in the USA showed a 48% increase in the total costs of diabetes and prediabetes between 2007 (\$218 billion) and 2012 (\$322 billion), including medical expenses and reduced productivity [3]. More recent data indicate a continuous escalation of this economic burden [1], [4]–[7]. A study conducted in 2017 estimated that the combined cost of diagnosed diabetes, undiagnosed diabetes, prediabetes, and gestational diabetes reached nearly \$404 billion [4]. More recently, a report by the American Diabetes Association focusing exclusively on diagnosed diabetes estimated a total economic cost of \$412.9 billion in 2022, broken down into \$306.6 billion in direct medical costs and \$106.3 billion in indirect costs [5]. Globally, the estimated health expenditure attributed to diabetes was \$1.015 trillion in 2024, an amount that has increased 3.4-fold in the past 17 years. Diabetes accounted for roughly 12% of total global health spending in 2024 [1]. Regionally, Europe

accounted for approximately \$193 billion (about 19% of the global total) [6], while South and Central America spent around \$81 billion (8%) [7].

The World Health Organization (WHO) defines therapeutic education in diabetes (TED) as an educational process integrated into treatment that aims to provide people with diabetes and their families with the competencies (knowledge, skills, and attitudes) and support necessary for self-management of the disease [8]. TED is recognized as a fundamental pillar in disease management [9]. The minimum contents of adequate TED include dietary habits, physical activity, self-monitoring (glucose, blood pressure, weight, and foot self-examination), and knowledge about the disease and its treatment. Although most patients who have participated in education programs consider them useful (81% according to the DAWN2™ study), participation is limited (only 49% participated in any program), and the percentage is even lower for family members (23% participation, despite three-quarters finding it useful) [10]. Healthcare professionals also recognize the need to increase patient and family training (65%) and demand more diabetes educators (66%) [10]. A significant challenge is the limitation of available educational resources, with printed brochures being the most common resource (85% of healthcare professionals) [10]. This suggests a clear need to improve communication and educational resources.

Nutritional management is an essential component of TED to prevent insulin resistance, delay its development, and avoid vascular and neurological complications resulting from poor glycemic control. Nutritional recommendations focus on controlling daily caloric intake, meal distribution, and macronutrient balance, with knowledge about the carbohydrate content in foods being crucial for optimal glycemic control and maintaining near-normal glucose levels [11]. Educational interventions in childhood and adolescence (and their families) have proven particularly effective in improving glycemic control and psychosocial behavior, being even more effective in children than in adults. These interventions should be motivating, user-centered, usable, reliable, engaging, age-appropriate, and comprehensible. They should have smooth content transitions, be highly interactive, repetitive, and very practical. Objectives should be clear and solve real problems, with reviews and summaries available. The most effective interventions are those that are integrated into daily routines, personalized, and increasingly supported by new technologies as motivational tools [12].

Addressing the challenges of traditional educational methods and aiming to enhance patient engagement, the integration of assistive technology systems, especially extended reality (XR) technologies, which include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), opens up new opportunities. AR superimposes virtual elements onto the real world to enrich the learning experience and has been shown to improve learning outcomes [13]. VR creates fully immersive digital environments, isolating the users from their physical surroundings [14]. Although MR has various definitions, one of the most widely accepted describes it as an interactive and immersive blend of real and virtual elements that coexist and allow dynamic interaction [15]. XR technologies have been applied across a wide range of domains, including medicine [16], industry [17], and entertainment [18], with growing evidence supporting their potential in educational contexts through VR [19], AR [20]–[22], and MR [23], [24].

Building on these technological capabilities, research has increasingly focused on applying extended reality to diabetes education and management. Among these, VR has shown

significant promise as a tool to support individuals with diabetes, a fact that has drawn growing attention from the research community, as evidenced by recent reviews [25], [26]. Hao et al. [25], in a systematic review, reported that VR-based rehabilitation shows promising effects in enhancing balance in people with diabetes. Vaughan [26] emphasized that both VR and AR tools may enhance diabetes education and disease management in adults and children with Type 1 or Type 2 diabetes. For Type 1 diabetes, several VR tools have been developed to support self-care. One platform [26] offers training for safe exercise to prevent hypoglycemia, carbohydrate counting in a virtual kitchen, glucose monitoring in the workplace, and blood testing techniques. This system was tested using mobile VR (Google Cardboard). Serious games have also been created for children, incorporating reward mechanisms, engaging narratives, and a focus on the disease’s biochemical aspects [27]. In another study, Lanning et al. [28] developed a VR system to expose adults with Type 1 diabetes to typical challenges, concerns, and daily tasks associated with closed loop systems (automated insulin delivery). They demonstrated that VR interventions are feasible and can effectively familiarize individuals with common issues related to food and drug administration. For Type 2 diabetes, VR has been applied in both educational and therapeutic contexts. Diabetes Island, a virtual environment within Second Life, provided diabetes self-management education, real-time interaction with healthcare professionals, and gamified incentives. The intervention led to reduced distress, healthier behaviors, and increased engagement among African American women with low levels of physical activity and high-fat diets [29]. The Wii Fit Plus [30] has also been used to promote physical activity in adults with Type 2 diabetes, improving metabolic control and quality of life after 12 weeks of use. Stress management has been addressed through VR-based mindfulness interventions [31], while immersive exercise programs using VR and IoT technologies demonstrated improvements in blood glucose levels and muscle mass [32]. Feedback mechanisms in VR (auditory, tactile, and visual) have been shown to enhance balance, particularly for users with impairments due to diabetes [33]. Finally, cinematic VR has been explored as a training tool for care providers [34]. Their results suggest that this form of education can enhance cultural self-efficacy and improve attitudes toward diabetes among healthcare professionals and administrators.

In contrast to VR, the use of AR in TED remains an emerging field, with relatively few studies investigating its educational potential. One of the works most closely related to our AR application is by Domhardt et al. [35], who developed a mobile AR application to estimate the carbohydrate content of real food. Their application uses a virtual mesh overlay that users adjust to match real food items, enabling volume and weight estimations. Although aligned in purpose, this approach differs from the AR presented in this thesis in both design and conceptualization. Their approach involves real food that must be prepared for each session, whereas ours relies on virtual food elements. Our AR application showcases the full potential of AR by seamlessly integrating realistic 3D food models into real environments. This allows users to explore the items from multiple angles (360°), creating a convincing illusion of real food served on physical dishes. Conversely, the visualization of mesh wireframes on minimally detailed backgrounds lacks the immersive quality achieved through realistic environmental integration. Other relevant AR studies include an application designed to educate patients with Type 2 diabetes about antihypertensive medications by scanning predefined patterns, such as medication packages [36], and Jerry the Bear[®] [37], a toy with image targets that helps children simulate diabetes care tasks like glucose monitoring or insulin administration, though not focused on carbohydrate

counting. Another study presented an AR application that uses QR codes to visualize 3D models of diabetes medications [38], demonstrating that AR positively impacted learning outcomes among pharmacy students. Finally, AR based on barcode markers has also been used to improve the health locus of control in patients with Type 2 diabetes [39]. This application offered interactive educational modules on key diabetes topics and was used in a three-month intervention. Although the AR application enhanced patients' health control perception, no significant difference was found between intervention and control groups overall.

Compared to VR and AR, the application of MR, particularly those using passthrough technology, remains largely unexplored in the context of TED. To date, no MR applications using passthrough have been developed specifically for this purpose. In fact, only a limited number of passthrough-based MR tools have been presented and evaluated in other domains. One of the first MR applications of this kind focused on piano learning using Meta Quest 2 and grayscale passthrough [23]. Two visualization modes (wireframe and solid) were tested. Although grayscale passthrough had limitations, both modes offered users a satisfactory learning experience. A follow-up study leveraged Meta Quest 3's color passthrough capabilities for a similar piano learning application [24]. Compared to Synthesia, a conventional digital piano trainer, the MR tool provided better performance outcomes, higher user satisfaction, strong presence, and minimal adverse effects. The benefits were consistent regardless of age or gender. Users particularly valued the ability to view the real keyboard alongside integrated virtual aids. A third MR study explored its application in food and sensory behavior research [40]. It used passthrough technology to merge real-world elements with virtual scenes, such as projecting the real environment onto planes attached to a virtual table. This hybrid setup allowed real food to appear embedded in virtual environments. Researchers compared three different virtual dining scenarios (a lab booth, a basic restaurant, and a fully textured restaurant). They concluded that experts rated the virtual restaurant environment as more acceptable than eating in a sensory booth, but less acceptable than a real restaurant setting.

Despite the limited number of applications currently available for TED, ongoing advances in XR technology and hardware are rapidly expanding what is possible in this field. Research to support TED has evolved significantly in terms of the technology and devices used, beginning with VR, followed by AR, and advancing to MR, including passthrough capabilities in both grayscale and color as well as headsets like the HoloLens 2. This evolution has opened up new possibilities for presenting information and enhancing the patient learning experience. It is closely linked to the rapid growth of XR technologies and the increasing capabilities of the hardware and software that power immersive applications. The adoption of XR has accelerated across various fields, including simulation, design, entertainment, and education [41]. This progression has been driven by concurrent advancements in both software, such as ARKit, ARCore, and Vuforia, and headsets like the Meta Quest 2/Pro/3/3S and Microsoft HoloLens 2. In July 2021, Meta introduced an experimental API (Application Programming Interface) known as passthrough for the Oculus Quest 2. This feature leveraged the headsets forward-facing infrared cameras and positional sensors to reconstruct a three-dimensional representation of the users physical environment. Early MR applications emerged with the ability to merge real and virtual inputs, though first-generation passthrough presented notable technical limitations. The system utilized cameras originally optimized for motion tracking rather than visual

fidelity, resulting in low-resolution, grayscale imagery with limited depth accuracy and temporal stability, particularly at short viewing distances. Additionally, the passthrough feed functioned as a static visual layer, inaccessible to the application runtime, thereby constraining real-time interaction with the physical environment. In response to these constraints, Meta released the Meta Quest Pro in October 2022. This next-generation headset incorporates enhanced infrared sensing capabilities alongside a high-resolution, forward-facing RGB camera. These hardware improvements enabled color passthrough with increased spatial fidelity, dynamic range, and stability, constituting one of the primary technological advancements over its predecessor. The other significant upgrade was the inclusion of facial expression and eye-tracking technologies, allowing for more nuanced user interaction and avatar realism in social and collaborative XR applications. Subsequently, in October 2023, Meta launched the Meta Quest 3, further advancing the capabilities of its XR lineup. This headset features improved color passthrough with higher resolution and frame rate than the Quest Pro, providing users with a more immersive and responsive MR experience. Recently, on April 30, 2025, Meta announced the public availability of the Passthrough Camera API in version v76 of the Meta Horizon OS. This API grants access to the front-facing RGB cameras on the Meta Quest 3 and 3S headsets, enabling developers to build more advanced and realistic MR applications. This evolution reflects an ongoing commitment to advancing technology in ways that support application development across diverse fields, including the development of more effective, interactive, and engaging educational tools for individuals with diabetes. It allows a transition from simply overlaying information on mobile screens to a more seamless and enriched integration of virtual elements within the user’s real-world environment.

In light of these technological advancements, this thesis responds to the growing need for innovative tools to improve TED, overcome the limitations of conventional methods, and enhance patient engagement by leveraging the potential of XR technologies. It centers on the design, development, and evaluation of AR- and MR-based applications to support the education of patients with diabetes, targeting diverse user profiles, including different age groups (children and adults) and cultural contexts (Spain and Ecuador). The effectiveness of these applications is assessed in terms of short- and mid-term knowledge acquisition, user satisfaction, and usability, and is compared against conventional educational methods. Additionally, the feasibility and user perception of MR are explored, including the evaluation of different visualization modes (grayscale and color). The main contributions of this thesis include the development of novel mobile AR applications and the first MR application using passthrough technology (grayscale and color) specifically designed for TED in patients with diabetes. In the AR applications, a physical dish with a printed image at its center is used to replicate the appearance of a real dish. Virtual elements, such as food items, are precisely anchored to the center of this dish and rendered at true scale based on their carbohydrate content. This setup allows the dish to serve as a tangible user interface. The user interacts with the MR application using their hands, without the need for controllers. The applications are structured into three levels, each corresponding to a food group, dairy products, cereals, and fruits, comprising 7, 8, and 10 food items respectively. In each level, users begin with a learning phase where foods are displayed at real scale within the user’s environment, along with their associated weight, carbohydrate choices, and glycemic index. This is followed by an evaluation phase in which patients must identify the correct carbohydrate content from three given options. In summary, this thesis seeks to bridge the gap between emerging XR technologies and

the urgent educational needs of people with diabetes by offering engaging, interactive, accessible, and effective applications. The findings intend to inform future strategies for improving therapeutic education and, ultimately, contribute to better disease management and quality of life across diverse cultural and healthcare contexts.

1.2 Scientific goals and research hypotheses

The main objective of this thesis is to evaluate the effectiveness and potential of AR and MR technologies to improve TED, specifically in learning carbohydrate counting in patients with Type 1 diabetes.

The specific objectives are the following:

- Design and develop innovative mobile AR and MR applications to support TED, specifically in learning carbohydrate counting.
- Determine the effectiveness of these AR/MR applications for knowledge transfer about carbohydrate content/choices in patients (children and adults) with Type 1 diabetes.
- Evaluate the short- and medium-term retention of knowledge acquired through AR/MR applications.
- Measure and evaluate the usability and user satisfaction/experience perceived by patients when using these AR/MR applications.
- Compare the effectiveness (learning, usability, satisfaction) of AR/MR applications against traditional learning methods in TED.
- Compare the effectiveness of different extended reality technology implementations in TED: mobile AR vs. MR with grayscale passthrough (using devices like Meta Quest 2) vs. MR with color passthrough (using devices like Meta Quest 3).
- Determine if user factors such as participants' age and gender influence learning outcomes or user experience with AR/MR applications for TED.
- Evaluate the applicability and effectiveness of AR applications in different cultural and demographic contexts, comparing results obtained in studies conducted in Ecuador and Spain.
- Determine the potential of AR/MR applications as valuable, motivating, accessible, and patient-centered educational tools for TED and diabetes self-management.

The general hypotheses are the following:

- **GH1.** TED supported by AR and MR technologies will lead to greater acquisition of knowledge about carbohydrate counting in patients with Type 1 diabetes (children and adults), compared to traditional educational methods.
- **GH2.** Patients will positively value the different applications of extended reality (mobile AR, MR with grayscale passthrough, and MR with color passthrough) with respect to user experience.

- **GH3.** Factors such as age and gender will not significantly influence learning effectiveness when using AR/MR applications for TED across different cultural contexts.

To achieve the proposed research objectives, a research plan was designed that included the design and development of two specific applications for learning carbohydrate counting: an AR-based solution for mobile devices and an MR-based solution for Meta Quest headsets. The feasibility and effectiveness of both applications were subsequently subjected to rigorous empirical validation through the following experimental studies.

Study 1 – Augmented reality application for therapeutic education in children with diabetes.

The study involved 70 children with diabetes (5-14 years, mean age 9.19 ± 2.38), 41 girls and 29 boys. Participants were randomly divided into two groups (Group A, N=42; Group B, N=28). Both groups completed a prior knowledge questionnaire (A) and used the AR application designed to learn about carbohydrate choices or servings (showing virtual food on a real dish). After the learning session, Group A completed a post-knowledge questionnaire (B) with the same foods as questionnaire A, while Group B completed a post-knowledge questionnaire (C) with different foods than questionnaire A. All children also completed a satisfaction and usability questionnaire (D).

The objective of this study was to determine the effectiveness of the AR application in terms of learning about carbohydrate choices, as well as the satisfaction and usability perceived by children with diabetes. The performance (knowledge) of the participants was evaluated and compared before and after learning with the AR application, and the results were compared between the two types of post-questionnaires. Results were also analyzed based on subjective variables (satisfaction, usability) and considering age and gender.

The first hypothesis (H1) was that children would increase their knowledge about the carbohydrate choices of foods by using the AR application. The second hypothesis (H2) was that the learning outcomes would not be influenced by age or gender.

Study 2 – Augmented reality for therapeutic education in patients with diabetes: short- and mid-term learning benefits.

The main study involved 27 Ecuadorian patients with Type 1 diabetes (14 males, 13 females; age 5-28 years, mean 15.85 ± 5.92). An intra-subject design was used where participants first received a traditional educational session (Session 1: pre-test -> traditional class -> post-test) and, one week later, used an AR application designed to teach the carbohydrate content of different foods (Session 2: pre-test -> AR app use -> post-test). A mid-term retention assessment was performed two weeks after Session 2 (Session 3: post-test). Additionally, data from Ecuadorian participants were compared with data from our study with 42 Spanish children.

The main objective of this study was to evaluate the effectiveness of the AR application for knowledge transfer about carbohydrate content in foods, assessing short- and mid-term retention in children and adults. Secondary objectives included evaluating the usability and satisfaction perceived by patients and comparing the results obtained in Ecuador with those of the previous study.

Participants' performance (scores on knowledge questionnaires) was evaluated and compared before and after each intervention (traditional and AR) and at mid-term follow-up.

Results were also compared between the Ecuadorian and Spanish groups, and subjective variables (usability with Short-UEQ and satisfaction with a specific questionnaire) were analyzed, also considering age and gender.

The hypotheses were that (H3) the AR application would significantly improve short-term knowledge compared to the traditional method, (H4) the AR application would show significant knowledge retention in the medium term, (H5) learning outcomes would not be influenced by age or gender, and (H6) the AR application would have high levels of usability and satisfaction.

Study 3 – Mixed reality in therapeutic education for diabetes: Comparison of grayscale and color passthrough with augmented reality and traditional methods.

The study involved 92 Ecuadorian patients with Type 1 diabetes (51 males, 41 females; age 5-36 years, mean 15.78 ± 6.142). Participants were assigned to one of four groups in an between-subjects design: Group 1 (N=25) used a traditional learning method; Group 2 (N=27) used a mobile AR application; Group 3 (N=20) used a new MR application with grayscale passthrough (using Meta Quest 2); and Group 4 (N=20) used the same MR application but with color passthrough (using Meta Quest 3). Each participant completed a prior knowledge questionnaire, participated in their assigned group's learning session (teaching carbohydrate content), and then completed a post-knowledge questionnaire. The groups using AR and MR applications also completed usability and satisfaction questionnaires (Short-UEQ and specific questionnaire).

The objective of this study was to quantify and compare the effectiveness in knowledge transfer about carbohydrate content of an MR application in color and grayscale passthrough modes, versus an AR application and a traditional educational method. Simultaneously, a comparative evaluation of usability and user satisfaction with the AR applications and MR applications on Quest 2 and Quest 3 headsets was carried out.

Performance (knowledge) was evaluated by comparing pre- and post-intervention scores within each group and among the four groups. Subjective variables (usability, satisfaction) were compared among the three groups that used AR/MR applications. Data were also analyzed considering age and gender.

The hypotheses were that (H7) all methods would improve knowledge; (H8) technology-based methods (AR, MR) would outperform the traditional method; (H9) MR with color passthrough (Quest 3) would outperform MR with grayscale (Quest 2) and AR in learning.

1.3 Structure of the thesis

The thesis document is structured as follows:

- The first section of this document (Part I), serves as an introduction to the doctoral thesis, detailing the motivation of the thesis, the key scientific objectives, the proposed research hypotheses, the studies carried out, and the general organization of the subsequent sections.
- The second section of this document (Part II), presents a selection of the most representative publications that support this thesis, which were published in JCR-indexed journals. Specifically, this part includes three publications that substantiate the doctoral work.

Publication 1. Calle-Bustos, A.-M.; Juan, M.-C.; García-García, I.; Abad, F. (2017) An augmented reality game to support therapeutic education for children with diabetes. PLoS ONE, 12(9), e0184645, <https://doi.org/10.1371/journal.pone.0184645>

It describes the design and implementation of the first AR application to support therapeutic education. The AR application was validated with Spanish children diagnosed with diabetes, evaluating its effectiveness in teaching carbohydrate choices, along with user satisfaction and usability.

Publication 2. Calle, M.; Abad, F.; Juan, M.-C. (2025) Augmented Reality for therapeutic education in patients with diabetes: short- and mid-term learning benefits. Sensors, 25(4), 1017. <https://doi.org/10.3390/s25041017>

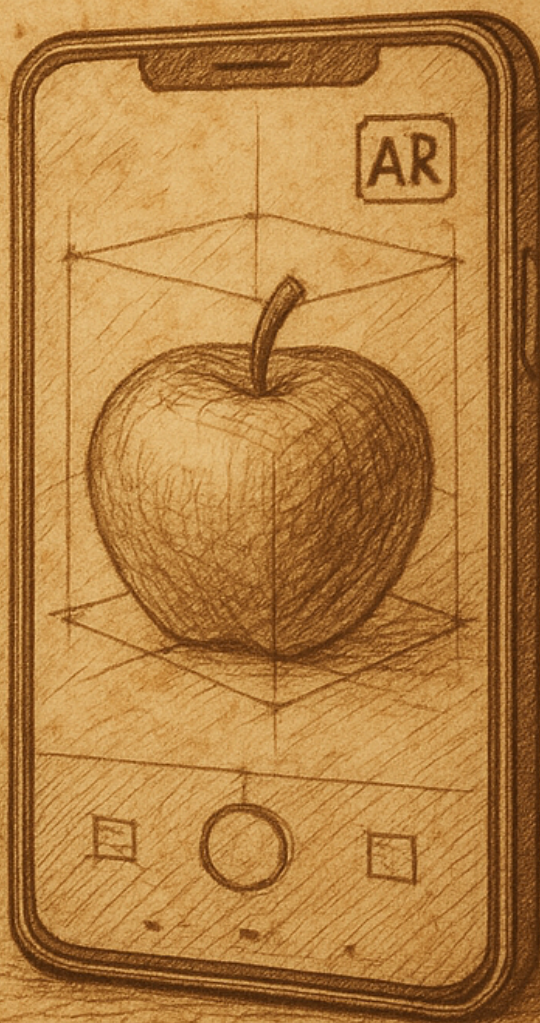
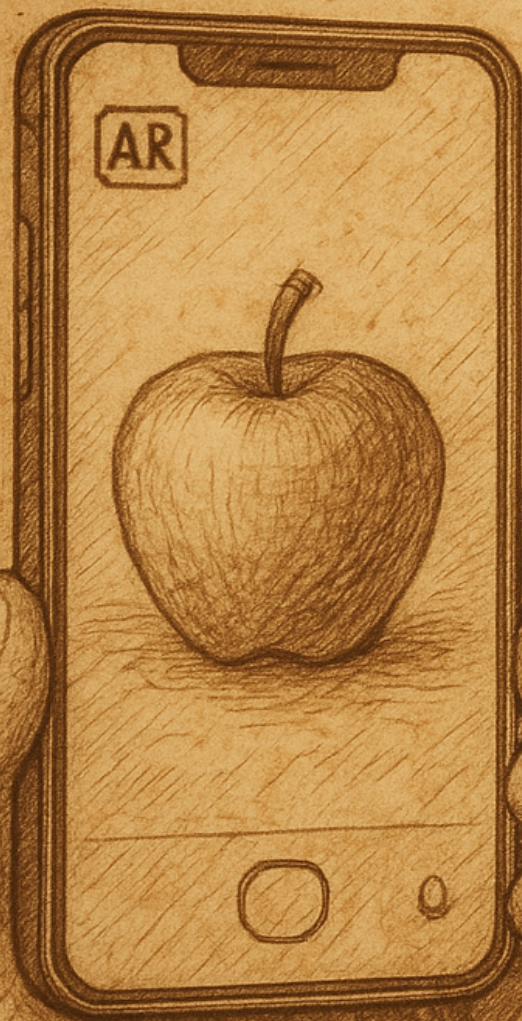
It details the adaptation of the previous AR application for Ecuadorian patients (children and adults), evaluates its effectiveness in short- and mid-term learning compared to traditional methods, and compares the results with those of the previous Spanish study.

Publication 3. Calle, M.; Abad, F.; Juan, M.-C. (2025) Mixed reality in therapeutic education for diabetes: grayscale and color passthrough compared with augmented reality and traditional Methods. Applied Sciences, 15(7), 4021 <https://doi.org/10.3390/app15074021>

It presents the design, development and comparative evaluation of a new MR application using passthrough technology (in grayscale with Quest 2 and in color with Quest 3) against the previous AR application (from publication 2) and traditional methods, analyzing learning outcomes and user experience in Ecuadorian patients.

- The third section of this document (Part III), is dedicated to the discussion of the results obtained in the thesis, presents a summary of the work carried out along with the general conclusions and future lines of research, and lists the publications that have derived from this doctoral thesis.

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Chapter 2

An augmented reality game to support therapeutic education for children with diabetes

Calle-Bustos, A. M., Juan, M.-C., García-García, I., & Abad, F. (2017). An augmented reality game to support therapeutic education for children with diabetes. *PLOS ONE*, 12(9), e0184645. <https://doi.org/10.1371/journal.pone.0184645>

2.1 Abstract

Therapeutic education in diabetes helps patients take responsibility for self-control of their disease, and providing technological support systems facilitates this education. In this paper, we present an augmented reality game to support therapeutic education for patients with diabetes. Our game helps children (aged 5-14 years) to learn carbohydrate (carb) content of different foods. The game shows virtual foods on a real dish. The number of carb choices corresponding to the visualized food is also shown (1 carb choice = 10 grams of carbs). A study to determine the effectiveness of the game in terms of learning and perceived satisfaction and usability was carried out. A total of seventy children with diabetes participated in the study. From the results, we observed that the initial knowledge about carb choices of the children who participated in the study was low (a mean of 2 on a scale from 0 to 9). This indicates that therapeutic education for patients with diabetes is needed. When the results for the pre-knowledge questionnaire and the post-knowledge questionnaire were compared, it was shown that the children learned about carb choices by playing our game. We used two post-knowledge questionnaires (one post-knowledge questionnaire that contained the same foods as the pre-knowledge questionnaire and a

second post-knowledge questionnaire that contained foods that were different from the ones on the pre-knowledge questionnaire). There were no statistically significant differences between these two different post-knowledge questionnaires. Moreover, the knowledge acquired was independent of gender and age. We also evaluated usability and perceived satisfaction. The children were satisfied with the game and considered that the game offers a high degree of usability. This game could be a valuable therapeutic education tool for patients with diabetes.

2.2 Introduction

Diabetes mellitus, also known as diabetes, is a chronic disease that is triggered when the body loses its ability to produce enough insulin or use it effectively. Insulin is a hormone that is secreted in the pancreas that allows the glucose of the food to pass to the body's cells, where it is stored or converted into energy. A deficiency in insulin causes excessively high levels of blood glucose (hyperglycemia), leading to the development of serious, long-term microvascular and macrovascular complications. There are three main types of diabetes: Type 1 diabetes, Type 2 diabetes and gestational diabetes mellitus. In type 1 diabetes, pancreatic cells produce insulin (beta cells). These cells destroy themselves by an autoimmune mechanism, and the body stops producing the insulin needed. Type 1 diabetes mainly develops during childhood and requires exogenous administration of insulin. In type 2 diabetes, the body can produce insulin, but either not enough is produced or the body does not respond to its effects (insulin resistance). It develops mainly in adulthood, although its prevalence during adolescence has been increasing. It requires strict control of food and exercise as well as oral anti-diabetic medication. Advanced stages may require insulin therapy. Gestational diabetes mellitus occurs when the body cannot produce or use enough of the insulin required for gestation.

According to the DAWN2[™] study [42], the number of people with diabetes worldwide is estimated to be 382 million, which could increase to 592 million in 2035. In the DAWN2[™] study, the opinions of more than 15,000 patients or their relatives were collected in 17 countries on four continents. Diabetes is a highly prevalent disease that is responsible for a significant economic burden on society in most countries. For example, a study carried out by Cefalu et al. [43] found that, in the US, the total cost of diabetes and prediabetes rose 48% over the 5-year period from 2007-2012, growing from \$218 to \$322 billion for both medical expenditures and reduced productivity [3], [44]. Cefalu et al.'s study [43] estimated that the average annual economic cost of diabetes for each American is approximately \$1,000 [44]. When expressed as the average annual burden for each person diagnosed with diabetes, the costs have increased by 10%, rising from \$9,975 in 2007 to \$10,970 in 2012 [3], [44].

Therapeutic education in diabetes (TED) helps patients to take responsibility for self-control of their disease. Patients need support systems to facilitate TED. The World Health Organization (WHO) defines TED as an educational process that is integrated in the treatment, whereby the competencies (knowledge, skills and attitudes) and the necessary support for self-control of the disease are provided to people with diabetes and their families. The aim is for patients to acquire knowledge about their disease and the basis for treatment in order to be able to integrate them into their daily lives in order to be able to prevent, recognize, and act in situations of acute risk and to prevent cardiovascular risk factors [45]. This education is key for proper control of the disease [9]. According

to Ferrer-García et al. [46] the minimum content required for adequate TED includes: 1) knowledge about eating habits and physical activity; 2) issues related to self-control (self-monitoring of blood glucose, self-measurement of blood pressure and weight, and foot self-examination); 3) a description of the process of the disease and treatment options. According to WHO, health professionals dedicated to TED should have appropriate and specific training.

One of the conclusions of the DAWN2TM study [42] is that the vast majority (81%) of people with diabetes who had attended education programs considered them to be helpful. However, only 49% were participating in any such programmes. For family members, the gap was even greater. Approximately three quarters of family members found diabetes education programmes helpful, but only 23% participated in any diabetes educational programs. According to the DAWN2TM study, more than 40% of people with diabetes have never participated in training programs about their disease. This percentage rises to 78% in the case of relatives. When health professionals responded to the same questions, 65% of them were in favor of increasing the training of patients and families, and 66% of them demanded more diabetes educators. A total of 85% of the healthcare professionals stated that the only training resources available for patients and their relatives were printed brochures. Only 47% referred to face-group activities and 45% to web pages. The DAWN2TM study concludes that, as a result of this data, communication between doctors and patients, regardless of resources can be greatly improved. That study also indicated that both patients and families and health professionals agree on their demand for more training to enhance self-control of patients with diabetes.

Meanwhile, Elliott et al. [47] carried out a study to assess diabetes self-management and education among people living with type 2 diabetes in Oman. Their study involved 309 patients. One of their conclusions was that "many patients displayed dangerous diabetes self-management and education knowledge gaps". Their findings suggested "a need for improving knowledge transfer to people living with diabetes". In the same line, Schäfer et al. [48] carried out a study for analyzing patients' attitudes towards diabetes education. One of their conclusions stated that "physicians should encourage patients to participate in diabetes education".

Proper control of nutrition is essential for the prevention of insulin resistance in order to slow its development and to prevent the occurrence of vascular and neurological complications due to poor glycemic control. For this reason, food is an essential part of educational programs for all patients with any form of diabetes. Nutritional recommendations focus on controlling daily intake in caloric terms, and its distribution in the number of meals as well as the distribution among proteins, fats, and carbohydrates. Carbohydrates have a direct relationship with the level of blood glucose. Therefore, knowing the number of carbohydrates that should be taken at each of the meals is essential for proper control of the disease. This control makes it possible to achieve a balanced diet and to maintain blood glucose levels that are close to normal.

On the other hand, there is clear evidence that interventions during the childhood and adolescence of diabetics have beneficial effects on glycemic control and psychosocial behavior, being even more effective in children than in adults [9]. Educational interventions for children and adolescents (and their families), must provide the basic and common principles of any quality education. They must be motivating and take into account where the learning takes place. They should be user-centric, usable, reliable, fun, entertaining,

interesting, and understandable. The content must have smooth transitions (from easy to difficult) and be highly interactive, repetitive, and very practical. There must be clear objectives that solve real problems, and there must be reviews and summaries. The content must be evaluable by external review, and subsequent continuing education should be available. The interventions that have proven to be the most effective are those that can be integrated into the daily routine, those that adapt to the patient's characteristics (age, etc.), those that focus on individualization for self-management by the patient, and those that make use of new technologies as a motivational tool [9]. All of these aspects were taken into account in the design of our game.

The use of games can improve learning outcomes [49] and they are a promising tool for motivating and engaging students [50]. Children are digital natives and enjoy everything that involves the use of technology. According to Glover [51], video games are especially appealing and motivating for children. Augmented Reality (AR) has also been used in games for educational purposes (e.g., [52]) and it has been demonstrated that AR promotes enhanced learning achievement [53]. Therefore, based on the enthusiasm of young for technology, the possibilities offered by AR, and the need of tools for TED, we present an AR game to support TED for children. The first objective of this work was to develop an AR game to support TED for children. The second objective was to carry out a study of children with diabetes to determine the effectiveness of the game in terms of learning, perceived satisfaction, and usability. The first hypothesis is that children will increase their knowledge about carb choices of foods by playing our game. The second hypothesis is that there will not be statistically significant differences if the post-test questionnaire is the same as or different from the pre-test questionnaire.

2.3 Games, mobiles and augmented reality as educational tools

The terms gamification, game-based learning or serious games are commonly used interchangeably to refer to the use of games or game elements in education. Gamification as a term was originated in the digital media industry in 2008. According to Deterding et al. [54], gamification refers to the use of design element characteristics for games in non-game contexts. Gamification in education has received increasing interest in recent years. For example, Martí-Parreño et al. [50] carried out a review in which they analyzed 139 papers published in journals indexed in JCR for the years 2010-2014. In that study, the authors identified the themes of research related to the use of games in education that had already been considered (effectiveness, acceptance, engagement and social interaction), among other aspects. They also suggested missing research themes such as personal drivers, emotions and design. They concluded that most of the papers were focused on the positive effects of gamification (e.g., increasing students' motivation and interest in their learning process), and that negative effects remain unexplored.

The use of mobile devices for different purposes has been increasing. Specifically, the interest in mobile devices for education has been the target of several studies (e.g., [55]–[57]). Current mobile devices have a power that was unimaginable just 5 years ago. This is an optimal time for users/players to enjoy incredible experiences in the palm of their hands. There are two reasons for the success of mobile devices: the hardware that is available and the tools that are available for programming. Mobile devices not only include fast CPUs,

large displays, cameras with 16 MP, graphics acceleration, compass/accelerometers, GPS sensors or gyroscopes, but they can also include depth and motion tracking sensors. The possibility to combine head-mount viewers with smartphones and have an AR platform has opened a new niche for research and the market, especially for education. Previous works have reported that mobile learning is highly motivating for students (e.g., [56]). Mobile devices can help in the learning process by creating more interactive and engaging environments [58]. Teachers can connect with their students on a more personal level with devices that the students use practically every day [59]. Mobile devices could facilitate versatility in the learning process since the learning activity could be performed at any place and time without requiring supervision [20]. Mobile apps can be personalized to each student [60]. Some reviews focused on specific aspects of mobile learning (e. g., [57], [61]). In the review carried out by Highfield & Goodwin [61], they analyzed the most popular Apps from the "education" section of the iTunes App Store at six-month intervals from April 2010 to October 2012. After classifying the Apps by the curriculum content, they observed that most of the Apps were identified as Literacy content (21%), followed by Science content (19%). They also identified less explored content (Economics and History), followed by Geography, Foreign Language, and Creative Arts.

With regard to games for diabetes education, several video games have been presented whose target audiences were children and adolescents (e. g., [62], [63]). Those games were designed to be played online (e.g., Captain Novolin, <http://www.playretrogames.com/3283-captain-novolin>), on consoles (e.g., Packy & Marlon [64]; Detective & Blocks Buildup [65]; Didget [66]), on computers (e.g., Egg Breeder [62], [65]), or on mobile phones (e.g., INSULOT [67]).

Android and iOS Apps for TED have also been presented. For example, mySugr (<https://mysugr.com/>) and Monster Manor (<https://ayogo.com/blog/monster-manor>, Kamel Boulos et al. [68]). Most of the games for TED have a common bond, which is that they require players to balance food and insulin in order to keep the blood glucose character of the game within a normal range. Due to the proliferation of mobile devices, there are also numerous diabetes-related applications that can be downloaded (e.g., Play Store for Android and App Store for iOS). However, many of them are just informative and do not have any interaction. Others allow the storage of patients' clinical data and generate graphs or reports, and even send this data to the specialist.

AR allows the inclusion of virtual elements in a real environment. A more precise definition is that AR combines reality and virtuality, allows real-time interaction, and has registration that is in 3D [69]. Current mobile devices can provide AR experiences in real time, which helps the users by adding information to the real scene to assist them in the tasks they are performing. Users can have the experience in any place and time. To achieve this, the device camera captures the real-world image and is overlapped by virtual elements. Even though AR has been used successfully in various fields (e.g., psychology [70]), it is not a technology that has been widely exploited in education. Nevertheless, AR for education has received increasing interest in recent years. Bacca et al. [71] conducted a review that includes 32 papers published in journals indexed in JCR between 2003 and 2013. One of their goals was to identify the fields of education in which AR was already being applied. The target fields were based on the International Standard Classification of Education [72]. Their analysis indicated that most of the studies (40.6%) were in the field of "Science". Examples in this field are mathematics and geometry [73] or learning about the water cycle [52]. "Humanities & Arts" was the second field of education in which

AR was applied the most (21.9%). Examples in this field are language learning [74] or learning about numismatics [21]. AR was applied in "Engineering, Manufacturing and Construction" (15.6%). AR was applied in "Social Sciences, Business and Law" (12.5%). AR was applied in "Services and Others (travel, transport, security services and hotel)" (6.3%) and in "Health and Welfare" (3.1%). An example in "Health and Welfare" is learning about dental morphology [75]. No studies have been presented in the fields of "Educational (teacher training at all levels of education)" or "Agriculture". Another review was presented by Akçayır & Akçayır [53], in which they analyzed 68 papers about AR for education that were published in journals indexed in JCR. One of Akçayır & Akçayır's [53] conclusions is that the most reported advantage of AR is that it promotes enhanced learning achievement.

To our knowledge, the only AR work that is related to diabetes was presented by Domhardt et al. [35]. In that work, the authors developed an AR system for mobile devices to estimate the carbohydrate portions (carb choices) of different real foods. Its main contribution is that the application is able to determine the volume of real food and infer its weight. The application uses a marker that is placed in front of the dish to be measured. The application shows a virtual mesh on real food. The user can interact with the virtual mesh to fit the exact volume. Their study involved 8 patients. According to Domhardt et al. [35], in 44% of the estimations, the error was reduced by at least 6 grams of carbohydrates. The participants identified several problems. Three of them were: "the drawing of the food was too complex; the precision of a measurement performed with the app was too imprecise; it was not possible to use the app for a dish of several mixed foods". Similarly to Domhardt et al.'s work, our game uses AR for TED. However, the developments are totally different. From our point of view, AR realizes its full potential when virtual objects are 3D objects that look real and the user is interested in seeing these virtual objects from different points of view (360°). In other words, it is not the same seeing a 3D object that looks real than seeing a colored wireframe mesh. Moreover, seeing these virtual objects integrated with the real world offers added value. For example, it is not the same seeing an orange with a neutral background (e.g., blue) on the screen of a mobile device as seeing that orange on a real dish. When users are observing the augmented scene, they should feel that they are observing real food on a real dish. Our game includes these two features.

2.4 Materials and methods

2.4.1 Description of the game

The game shows virtual food on a real dish. The goal is for the user to perceive food as if it were real food that was on a dish (without using any glasses). The game runs on a mobile device with an Android Operating System. When the game detects the target (an image in the center of the dish, e.g., Figures 2.1, 2.2 or 2.3), food appears in the center of the physical dish above the target. At this point, the user can zoom, rotate, raise, lower, or move the mobile device to observe the food from any position (360°). Another possibility is to move the physical dish in order to see the food from different positions and to zoom in or out. The steps in the game are as follows. Figure 2.1 shows a general scheme of the functionality of the game.

1. **Introduction of information.** Initially, the child must indicate his/her age. After that, the game shows the carb choices recommended for his/her age for the whole

day as well as the carb choices for breakfast (1 carb choice =10 grams of carbs). This equivalence is currently being used in Spain and most of Europe. However, this equivalence is different in other countries. For example, in the US, Mexico, and most of Latin America, the equivalence is 1 carb choice =15 grams of carbs. In Austria, the equivalence is 1 carb choice =12 grams of carbohydrates.

2. **The game.** The game has 3 levels, each of which focuses on a food group. Specifically, the three food groups are: dairy products, farinaceous products (grains), and fruits. In the first level (dairy products), there are 6 foods. In the second level (grains), there are 8 foods, and in the third level (fruits), there are 10 foods. Each level has an initial learning phase in which foods are shown in real size along with their real weight and the number of carb choices are also shown. Figures 2.2 and 2.3 present two fruits that are shown in the learning phase of the third level. After this first learning step at each level, the user's level of knowledge is checked (testing phase). In the testing phase, the user is asked about half of the foods used in the training phase. The food is shown in the center of the dish and the user has to choose the number that corresponds to the right carb choices among three possible options (numbers that appear in the lower area of the screen). Figure 2.4 shows an orange and Figure 2.5 shows a piece of bread in the testing phase. Figure 2.6 shows a piece of bread and Figure 2.7 shows three strawberries (see close up in the testing phase). The user must correctly guess 70% of all of the foods of each level in order to move to the next level; otherwise, the user returns to the training phase of that level.
3. **The final challenge.** After passing the three levels, a final challenge is proposed, which consists of identifying as many different breakfasts as possible in a given time (a minute and a half). The carb choices for each breakfast should be the ones recommended for the age of the child. To achieve this goal, the user has to choose foods from at least two different food groups. In Figure 2.8, the user chose a green apple, a slice of bread, and a glass of milk for a breakfast. The user has to press the button at the top right (with a fork and a spoon) to complete a breakfast.

2.4.2 Design & development

For the design of the AR game, we counted on the advice of five experts in diabetes. The aspects that an educational intervention should have according to Lange et al. [9] were also considered for the design of our game. After knowing the problem and identifying the needs of this group, the functional specifications and the design of the game were defined. The development of the AR game was performed using the defined design. For this development, we used Unity engine (also called Unity3D, <http://unity3d.com>) and Vuforia SDK.

The Vuforia SDK (<https://www.vuforia.com>) has an extension for Unity 3D, which facilitates the inclusion of animations and very complex virtual objects. These inclusions are not as easy if only Vuforia SDK is used. Vuforia uses computer vision techniques to recognize and track various types of fiducial elements in real time. In our case, we used the image that appears in Figure 2.2 as the Image Target. Unity and Vuforia make possible to develop applications for Android and iOS devices. We developed our own AR game for Android devices. However, once the application has been developed, the platform for which the application has been built can be selected and the same code can be used for building applications for Android or iOS devices.



Figure 2.1: Example of fruits shown in the learning phase (A banana).



Figure 2.2: Example of fruits shown in the learning phase (A banana).



Figure 2.3: Example of fruits shown in the learning phase (An apple).



Figure 2.4: Example of an orange shown in the testing phase.



Figure 2.5: Example of a piece of bread shown in the testing phase.



Figure 2.6: Example of a piece of bread seen close up in the testing phase.



Figure 2.7: Example of three strawberries seen close up in the testing phase.



Figure 2.8: The final challenge.

The development and testing of the AR game were achieved using a mobile device and a tablet with the Android operating system. The game is not device dependent and it can run on nearly any Android device. The recommended resolution for the camera is 5 MP or more. The only limitation is that, with a camera with low resolution (e.g., 2 MP), the application could have more problems recognizing the target. These problems can be solved with the appropriate illumination and the appropriate distance between the camera and the target. The models used in the game were obtained mainly from two websites: www.blendswap.com and www.turbosquid.com. The models downloaded from Blend Swap were free, while the models downloaded from Turbo Squid required payment. After obtaining the models, it was necessary to perform modifications. We created several of the models. For the modification or creation of models, we used Blender (<https://www.blender.org/>), which is a free and open software for creating 3D models.

2.4.3 Description of the study

This section presents the characteristics of the children that used the game, the measurements used during the study, and the steps followed.

Participants

A total of 70 children participated in the study. There were 29 boys (41.4%) and 41 girls (58.6%). They were between five and fourteen years old. The mean age was 9.19 ± 2.38 years old. The total sample was divided into two groups. The children were randomly assigned to each group. In the first group (Group A), there were 24 boys (57.1%) and 18 girls (42.9%). In the second group (Group B), there were 17 boys (60.7%) and 11 girls (39.3%). These children were attending a conference for patients with diabetes and relatives in 2016.

Measurements

To retrieve the data for the analysis, three different questionnaires were used. There was a pre-test questionnaire (A) with the images of nine foods, in which the children should indicate the number of carb choices for the different foods. Figure 2.9 shows an example of three foods that were included in the knowledge questionnaire. This pre-test was designed to measure the knowledge the children had before using our game. Afterwards, the knowledge questions were asked again using two different questionnaires (B and C). All the foods that appear on the B and C questionnaires were included in our game. The B questionnaire had the same foods as the A questionnaire. The C questionnaire had different foods than the A questionnaire. Finally, the children filled out a satisfaction and usability questionnaire (D).

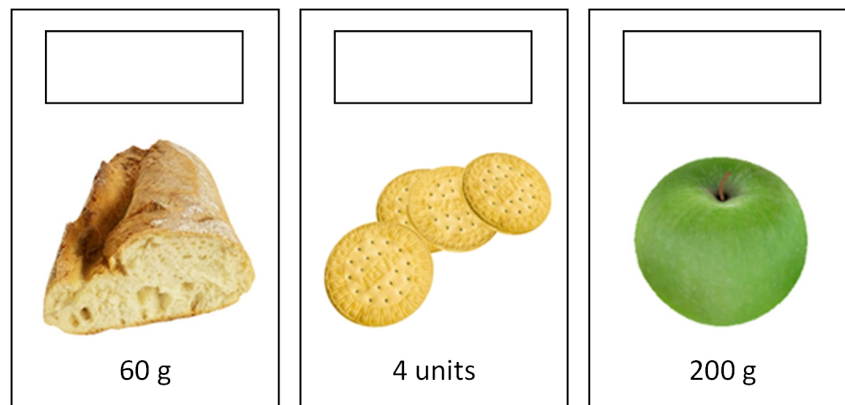


Figure 2.9: Example of three foods included in the knowledge questionnaire. The children must indicate the number of carb choices for the foods by filling out the upper box.

Procedure

The study was conducted according to the principles stated in the Declaration of Helsinki. The University Ethics Committee of the Technical University of Valencia approved the research protocol and the written informed consent form that the parents signed. The procedure can be summarized as follows:

- Group A: Children that filled out a post-knowledge questionnaire (B) that was same as the pre-knowledge questionnaire (A).
- Group B: Children that filled out a post-knowledge questionnaire (C) that was different from the pre-knowledge questionnaire (A).

Figure 2.10 shows graphically the procedure for both groups. The following protocol was used:

1. The children filled out the pre-knowledge questionnaire (A).
2. The children from both groups (Group A and Group B) played the game.
3. Then, the children from Group A filled out the post-knowledge questionnaire (B).
4. The children from Group B filled out the post-knowledge questionnaire (C).
5. Finally, all of the children filled out the satisfaction and usability questionnaire (D).

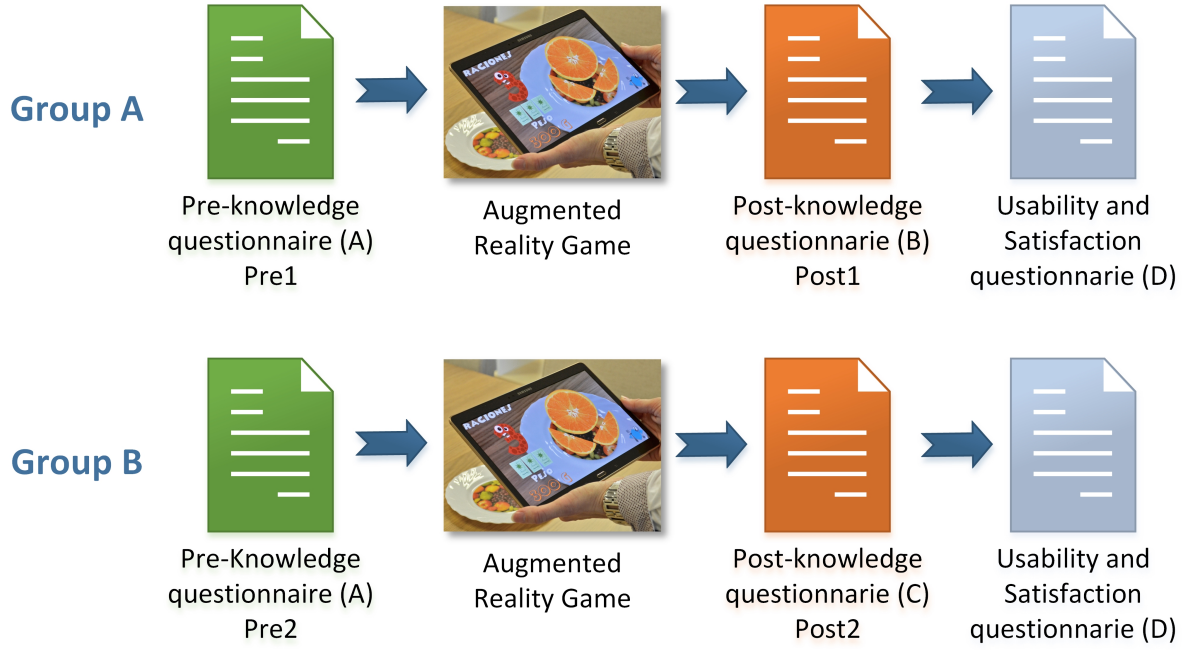


Figure 2.10: Study procedure.

2.5 Results

This section presents the analysis of the data collected from our study. In order to explore means, standard deviations, and other measurements, an initial descriptive analysis was carried out. Then, data normality was checked, and the pertinent statistical tests were carried out based on those results. Before using inferential tests, Shapiro-Wilk ($W = 0.909$, $p < 0.001^{**}$), Kolmogorov-Smirnov ($D = 0.142$, $p = 0.007^{**}$), and Anderson-Darling ($A = 3.507$, $p < 0.001^{**}$) tests were performed to check data normality. The three tests reported that our data did not fit the normal distribution. For this reason, the tests used were non-parametric (the Mann-Whitney U test for unpaired data, the Wilcoxon Signed-rank sum test for paired data, and the Kruskal-Wallis test instead of ANOVA). The data from the study was analyzed using the statistical open source toolkit R (<http://www.r-project.org>).

2.5.1 Learning outcomes

In order to measure how much the children had learned, the knowledge variable was analyzed before playing (Pre-test) and after playing (Post-test). The knowledge variable was created by counting the number of correct answers for the nine foods. The statistical data are presented in the format (median; interquartile range), and all tests are presented in the format (statistic U/W , normal approximation Z , p -value, r effect size). ** indicates the statistical significance at level $\alpha = 0.05$.

To determine whether or not there were differences between the initial knowledge of the two groups, an unpaired test was performed between the knowledge variable in Pre1 (1.95; 3) and the knowledge variable in Pre2 (2.5; 3.25) ($U = 491$, $Z = -1.197$, $p = 0.234$, $r = 0.143$). These results revealed that there were no statistically significant differences between the knowledge of the two groups in the pre-test. A paired test between Pre1

and Post1 (7.45; 3) showed that there were statistically significant differences between the scores that the children obtained before and after using the game and answering the same knowledge questionnaire ($W = 0$, $Z = -5.661$, $p < 0.001^{**}$, $r = 0.618$). Another paired test revealed that there were also statistically significant differences between the scores of Pre2 and Post2 (6.86; 2) ($W = 0$, $Z = -4.606$, $p < 0.001^{**}$, $r = 0.616$), which refers to before and after using the game and answering a different knowledge questionnaire. Finally, to determine whether or not there were differences between the two post-knowledge questionnaires, an unpaired test was performed between Post1 and Post2 (6.86; 2) ($U = 723$, $Z = 1.662$, $p < 0.098$, $r = 0.199$). These results showed that there was no statistically significant difference between the two post-knowledge questionnaires. Figure 2.11 shows the box plot for the scores for the two groups before and after playing the game.

The Kruskal Wallis test was also performed to take into consideration several other factors including Gender and Age. The results shown in Table 2.1 reveal that the knowledge acquired was independent from the Gender and the Age factors.

Table 2.1: The Kruskal-Wallis tests for the knowledge variable.

Factors	Kruskal-Wallis χ^2	d.f.	p -value
Gender	0.202	1	0.654
Age	6.847	9	0.653

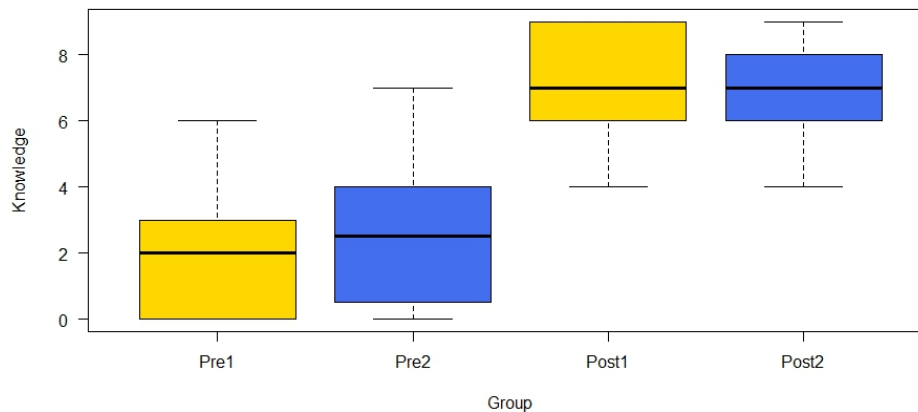


Figure 2.11: Scores of the knowledge variable before and after playing the game (the same post-knowledge questionnaire (Post1) vs. a different post-knowledge questionnaire (Post2)).

2.5.2 Satisfaction and usability outcomes

The D questionnaire was used for the usability and satisfaction aspects. Table 2.2 shows this questionnaire, and the median and the interquartile range of the scores for each question. The answers used a Likert scale with values from 1 to 5. From the results of the questions, it can be observed that the median of perceived satisfaction and usability with our game was very high, with all the values being between 4 and 5.

Table 2.2: The results for satisfaction and usability. The possible answers for the questions were: 1. Strongly disagree; 2. Disagree; 3. Neither agree nor disagree; 4. Agree; 5. Strongly agree. The possible answers for question SA#7 were: 1. Never; 2. Hardly ever; 3. Sometimes; 4. Almost every day; 5. Every day. The possible answers for question SA#8 were: 1. Very bad; 2. Bad; 3. Regular; 4. Good; 5. Very good.

Id	Question	Median	Interquartile range	Answer
US#1	I found the game easy to use	4	2	Agree
US#2	I have gotten used to the game quickly	5	2	Strongly agree
US#3	I have concentrated more on playing than on the Tablet	5	2	Strongly agree
US#4	I could get close enough to the food	4	1	Agree
US#5	I could see the food from different positions	5	2	Strongly agree
SA#1	I have had a good time	5	0.25	Strongly agree
SA#2	I liked how the food looked on the dish	5	1	Strongly agree
SA#3	It seemed to me that the food on the dish could be real food	5	1	Strongly agree
SA#4	I think I have learned with this game	5	1	Strongly agree
SA#5	I would like to use these games to learn more about diabetes	5	1	Strongly agree
SA#6	I would invite my friends to use the game	4	1.25	Agree
SA#7	I would use this game again	5	1	Every day
SA#8	Score the game from 1 to 5	5	1	Very good

The global score variable combines all the answers of questions related to satisfaction and usability. To determine whether or not gender affected the global score, an unpaired Mann-Whitney U test was performed ($U = 510.5$, $Z = -0.378$, $p = 0.710$, $r = 0.046$). The results showed that there were no statistically significant differences for the global score between boys and girls. When the satisfaction variable ($U = 447.5$, $Z = -1.199$, $p = 0.233$, $r = 0.146$) and the usability variable ($U = 482$, $Z = -0.749$, $p = 0.458$, $r = 0.092$) are considered, there were no statistically significant differences for gender, in either case.

A Kruskal-Wallis test was performed to determine whether or not age affected the global score ($\chi^2[3] = 11.821$, $p = 0.008^{**}$, $r = 0.749986$). We grouped the children into four age ranges (5-6, 7-8, 9-10 and 11-14). The results indicate that age affected the global score. The younger children gave higher scores. Figure 2.12 shows the box plot for the global score for the four age groups. When age is considered without grouping ($\chi^2[9] = 18.841$, $p = 0.027^{**}$, $r = -0.2942207$), the conclusion is the same. When satisfaction variable for the four age groups is considered ($\chi^2[3] = 12.609$, $p = 0.0056^{**}$, $r = 0.7734914$), the younger children were more satisfied with the game. When age is considered without grouping, the same conclusion is obtained for the satisfaction variable ($\chi^2[9] = 19.894$, $p = 0.019^{**}$, $r = -0.2267709$). With regard to the usability variable, when the four age ranges are considered ($\chi^2[3] = 9.955$, $p = 0.019^{**}$, $r = 0.659886$), there were statistically significant differences in favor of the younger children. When the age variable is considered without grouping, the same conclusion is obtained for the usability variable ($\chi^2[9] = 20.001$, $p = 0.018^{**}$, $r = -0.3346588$).

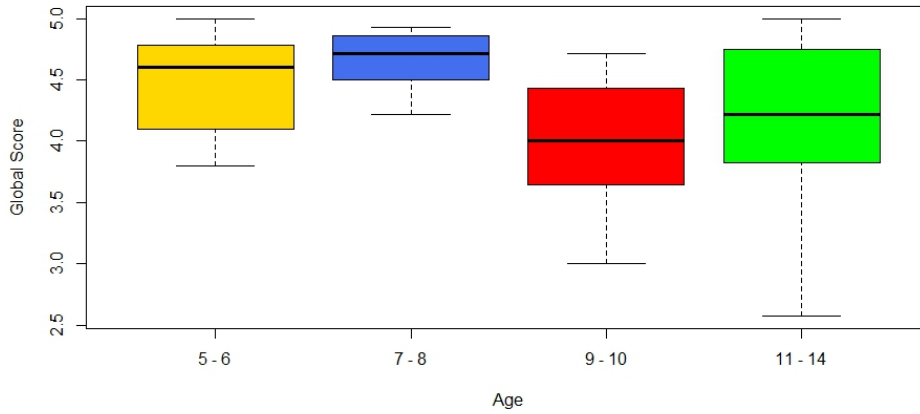


Figure 2.12: Boxplots of the global score variable for the four age groups.

2.5.3 Comparison of the augmented reality game with the ARSM task

To determine the usability and satisfaction of our game, we compared the scores for usability and satisfaction using the same questions as those used in the ARSM task [76]. The ARSM task is an augmented reality system that involves a user's movement to assess spatial short-term memory in healthy children. Similarly to our game, the ARSM task uses mobile Augmented Reality with children. A total of 76 children between 5 and 8 years old participated in the study of the ARSM task. The same age range was considered for the comparison carried out in this paper. When a global score variable that combines all of the

answers of questions related to satisfaction and usability is considered in the two studies, there was no statistically significant difference between them ($U = 893$, $Z = -0.544$, $p = 0.589$, $r = 0.054$). Table 2.3 shows a comparison of our questions with the questions asked in the study of the ARSM task.

When gender is considered for the global score, there were no statistically significant differences for the boys ($U = 197.5$, $Z = -0.061$, $p = 0.961$, $r = 0.009$) or the girls ($U = 243.5$, $Z = -0.595$, $p = 0.559$, $r = 0.084$) between the two studies. The children are grouped into two groups (the 5- to 6-year-old group and the 7- to 8-year-old group). A Mann-Whitney U test was applied. There were no statistically significant differences for the 5- to 6-year-old group ($U = 166$, $Z = -1.864$, $p = 0.064$, $r = 0.259$) or the 7- to 8-year-old group ($U = 288.5$, $Z = 1.421$, $p = 0.159$, $r = 0.205$) for the global score.

Table 2.3: Equivalence of the usability and satisfaction questionnaires between our study and the study of the ARSM task.

Study	Question identifiers					
	SA#1	SA#2	SA#6	SA#7	SA#8	US#1
Our game	SA#1	SA#2	SA#6	SA#7	SA#8	US#1
ARSM Task	SA#1	SA#2	SA#4	SA#5	SA#6	US#1

A Mann-Whitney U test was applied to the satisfaction variable in both studies ($U = 1218.5$, $Z = 2.049$, $p = 0.041^{**}$, $r = 0.205$). There was a statistically significant difference in favor of our game. When gender is considered for satisfaction, there were no statistically significant differences for the boys ($U = 239$, $Z = 0.965$, $p = 0.341$, $r = 0.136$) or the girls ($U = 365$, $Z = 1.961$, $p = 0.051$, $r = 0.277$). When the 5- to 6-year-old group is considered, there was no statistically significant difference ($U = 218$, $Z = -0.766$, $p = 0.450$, $r = 0.106$). When the group of the 7- to 8-year-old group is considered, there was a statistically significant difference ($U = 381$, $Z = 3.610$, $p < 0.001^{**}$, $r = 0.521$) in favor of our game.

A Mann-Whitney U test was applied to the usability variable in both studies ($U = 988$, $Z = 0.215$, $p = 0.833$, $r = 0.021$). There was no statistically significant difference between the two studies. When gender is considered for usability, there were no statistically significant differences for the boys ($U = 188.5$, $Z = -0.300$, $p = 0.774$, $r = 0.042$) or the girls ($U = 309.5$, $Z = 0.809$, $p = 0.425$, $r = 0.114$). When the 5- to 6-year-old group is considered, there was no statistically significant difference ($U = 224$, $Z = -0.671$, $p = 0.510$, $r = 0.093$). When the 7- to 8-year-old group is considered, there was no statistically significant difference ($U = 279$, $Z = 1.242$, $p = 0.219$, $r = 0.179$).

We analyzed the usability and satisfaction questions individually to determine whether or not there were statistical differences between our game and the ARSM task regarding age. There were no statistically significant differences for the 5- to 6-year-old group and for all the questions. There were statistically significant differences for the 7- to 8-year-old group and for the following questions (in all cases in favour of our game): SA#2 ($U = 305.5$, $Z = 2.398$, $p = 0.017^{**}$, $r = 0.346$), SA#8 ($U = 344.5$, $Z = 2.965$, $p = 0.003^{**}$, $r = 0.428$) and SA#9 ($U = 346.5$, $Z = 3.091$, $p = 0.002^{**}$, $r = 0.446$).

2.6 Discussion

In this paper, we present an innovative mobile AR game to support therapeutic education for patients with diabetes. The goal of our game is for children to learn about carb choices. Our game shows virtual food on a real dish and the patient has the perception of seeing a real dish with real food. Our work focusses on the positive effects of gamification, which is in line with current research [50]. Our game runs on mobile devices that the children are familiar with [59] so that initially they can engage with the game [58]. Moreover, considering that over a fourth of people in the world had access to a smart phone in 2016, a mobile game is the best option to reach as many people as possible. In this work, we supervised the learning process, but the game could be used at any place and time without our supervision, facilitating versatility in the learning process as has been point out in other works [20].

Several mobile AR systems for learning different topics have been presented in Section 2. However, to our knowledge, this is the first AR mobile game that helps patients learn about carb choices by combining a real dish and virtual foods. According to the review about AR trends in education carried out by Bacca et al. [71], one of the less explored fields is Health (3.1%), which is the field to which our AR game contributes. The initial knowledge about carb choices of the children who participated in the study was low (a mean of 2 on a scale from 0 to 9). This indicates that therapeutic education for children with diabetes is needed. This result is in line with one of the conclusions of the DAWN2TM study [42], which indicated that patients, families, and health professionals agree on their demand for more training to enhance self-control of patients with diabetes.

With regard to learning about carb choices by playing our game, the statistically significant differences between the children’s knowledge before and after playing the game proved that games of this kind are suitable for transmitting knowledge. Therefore, our first hypothesis was corroborated. These results are in line with other studies that have demonstrated that, in general, gamification has good learning effects [77] and promotes interest in the learning process [50]. These results are also in line with other AR studies that have stated that the use of mobile AR for learning purposes can improve the learning process [20], [52], [53].

When the knowledge score after using the two different post-knowledge questionnaires was compared (one using the same elements as in the pre-test and the other using different elements from the pre-test), no statistically significant difference was found. Therefore, it can be concluded that the use of a post-questionnaire that uses the same or different foods than the initial questionnaire is not relevant. In any case, the children learned using our game. This indicates that the children were not only aware of recognizing the carb choices of the foods asked on the pre-test, but they also paid attention to all the foods shown in the game. Therefore, our second hypothesis was corroborated.

In this study, we did not compare the improvements in knowledge using our game with traditional methods or other types of methods (e.g., a video game with the same content, but without AR). In this regard, other works have compared the learning outcomes using AR systems and traditional methods. For example, Furió et al. [13], [20] obtained no statistically significant differences between AR systems and traditional methods for learning outcomes. Chiang et al. [78] compared two groups of students: an experimental group that used a mobile AR game and a control group that used a mobile game without AR. Their results showed that the average learning achievement of the experimental group

was significantly better than that of the control group. Therefore, in previous works, an AR game compared to a game without AR or traditional methods offers greater or equal learning achievements. This observation suggests that the learning outcomes obtained using our AR game vs. non-AR game or traditional methods could offer greater or equal learning outcomes in favor of our AR game. However, a future study should be carried out to determine whether or not this hypothesis is corroborated.

Controlling eating is important for everyone in order to lead a healthy life; however, for a diabetic, self-control of food intake is a necessity [46]. The carb choices eaten at each meal are directly related to the insulin to be dosed. Therefore, knowing the number of carb choices contained in different foods would help patients to take responsibility for self-control of their disease and would improve their glycemic control. In this study, we did not focus on the improvements in the glycemic control of patients when using our game. However, this is a future work to consider.

To our knowledge, the work that is most closely related to ours is the work presented by Domhardt et al. [35]. As mentioned in the related work section, our proposal is totally different. However, it may be possible to join the ideas of these two works. In the work of Domhardt et al. [35], real dishes and real cooked foods are used. In our case, the dish is real and the uncooked food is virtual. A new version of our game could incorporate cooked foods.

With regard to usability, several authors have considered usability to be an important factor that affects educational effectiveness [79]–[81]. Sun et al. [82] argued that systems that are easy to use help students to focus their attention on the content. In our case, our game was easy to manipulate (with a mean above 4 on a scale of 1 to 5 in US#1). In addition, the people observing the children during the study stated that a great majority of children did not have any problems interacting with the game. Therefore, based on these considerations, our game does help students to focus their attention on carb choices. Moreover, we compared our data about usability with the data obtained in the study of the ARSM task [76]. There were no statistically significant differences between our game and the ARSM task. Both mobile AR systems offer a high degree of usability and for two different purposes.

With regard to satisfaction, there were no statistically significant differences between boys and girls, but the younger children were more satisfied with our game. We compared our data about satisfaction with the data obtained in the study of the ARSM task [76]. There was a statistically significant difference in favour of our game. The children indicated that they would like to use these games to learn more about diabetes with a mean of 4.58 (on a scale of 1 to 5). This implies that the game would be well received as a therapeutic educational tool. In our opinion, the designed game can be an important educational resource because of its close relationship with the needs of children with diabetes and its highly motivational component as a tool to introduce or reinforce content about carb choices.

Finally, the current situation of AR in particular and ICT (Information and Communications Technology) in general and their presumable evolution suggest that the range of possibilities for the development of new tools for therapeutic education in diabetes is great. For example, Nao robots as pets have already been used to personalize health education for children with Type 1 diabetes [83].

2.7 Conclusions

This work presents a mobile AR game to support therapeutic education for children with diabetes. From the results, we can affirm that the children acquired new knowledge about carb choices in the short-term by playing our game. Games of this kind facilitate versatility in the learning process since the learning activity could be performed at any place and time. The children only need a minimum setup with some images printed on paper and the handheld device. The features of our AR game and its minimal requirements position it as a pervasive educational game with great potential for therapeutic education in diabetes. In this paper, we have studied whether the game can help in therapeutic education in diabetes. However, several comparisons are possible for future work (e.g., long-term learning). To do this, two groups (with or without training) could be considered. The game could be enhanced by adding more foods, and by adding other meals and not just breakfast. Also, other languages could be incorporated, and the number of grams equivalent to a carb choice could be adjusted based on the user's country. Validation in other countries could also be performed. We hope to benefit therapeutic education in diabetes with the work and ideas presented here.

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Chapter 3

Augmented reality for therapeutic education in patients with diabetes: short- and mid-term learning benefits

Calle, M., Abad, F., & Juan, M.-C. (2025). Augmented reality for therapeutic education in patients with diabetes: short- and mid-term learning benefits. *Sensors*, 25(4), 1017. <https://doi.org/10.3390/s25041017>

3.1 Abstract

This work aims to evaluate the effectiveness of knowledge transfer through an Augmented Reality (AR) application, assessing short- and mid-term retention in children and adults with Type 1 diabetes. One objective is to determine if the AR application helps patients learn about the carbohydrate content of different foods ($N = 27$ Ecuadorian patients). Another objective is to evaluate the usability and satisfaction perceived by the patients. An additional objective is to compare the data from our study in Ecuador with data from a similar study conducted with Spanish children ($N = 42$). The results show that the AR application is effective for short-term knowledge transfer ($p < 0.001$) and has a suggestively significant effect on mid-term retention ($p < 0.05$). The AR application had an equalizing effect on knowledge outcomes between the groups (Ecuador and Spain) despite initial differences. The AR application significantly increased patients' knowledge ($p < 0.001$) and was effective for both children and adults. Patient satisfaction was high, and learning outcomes were not influenced by age or gender. The AR application is effective for short-term knowledge transfer and mid-term retention, benefiting children and adults regardless of gender. The patients' experience was very positive. Therefore,

the AR application is a valuable tool for therapeutic education in diabetes since it offers support that is easily accessible on mobile devices, enabling autonomous learning, and it contributes to the creation of innovative, patient-centered healthcare solutions.

3.2 Introduction

Diabetes mellitus, often called diabetes, is a chronic condition characterized by the body's inability to produce enough insulin or to use the insulin it produces effectively. Insulin, a hormone generated by the pancreas, facilitates the entry of glucose from food into the body's cells for storage or conversion into energy. Insufficient insulin leads to excessively high blood glucose levels (hyperglycemia), which can cause severe long-term macrovascular and microvascular complications. The three main types of diabetes are Type 1, Type 2, and gestational diabetes mellitus. In Type 1 diabetes, the pancreas produces little or no insulin. This is because the body's immune system attacks and destroys the beta cells responsible for insulin production. Type 1 diabetes primarily affects children and young adults, requiring continuous insulin therapy for survival. Type 2 diabetes develops when the body either does not produce enough insulin or becomes resistant to its effects. It primarily develops in adults, though its prevalence among adolescents is increasing. Treatment includes control of diet and exercise and oral antidiabetic medications; in advanced stages, insulin therapy may be required. Gestational diabetes mellitus happens when the body is unable to produce or properly use enough insulin during pregnancy.

According to the World Health Organization, approximately 422 million people worldwide are affected by diabetes, most of whom live in low- and middle-income countries. Diabetes is directly linked to 1.5 million deaths annually. According to the International Diabetes Federation (<https://diabetesatlas.org/data/en/> (accessed on 10 December 2024)), the global prevalence of diabetes is projected to increase to 643 million by 2030 and 783 million by 2045.

Therapeutic education in diabetes (TED) refers to a structured process of teaching people with diabetes about the nature of their condition, how to manage it, and how to integrate effective self-care practices into their daily lives. This education includes understanding diabetes, blood glucose monitoring, insulin administration, nutrition and diet, physical activity, prevention of complications, psychosocial support, and self-management skills. TED encourages patients to take responsibility for their disease management.

Proper nutritional management is critical in preventing insulin resistance, slowing its progression, and avoiding neurological and vascular complications resulting from poor glycemic control. Therefore, nutrition is a key component of educational programs for all diabetes patients. Nutritional guidelines emphasize regulating daily caloric intake and its distribution across meals, as well as balancing fats, proteins, and carbohydrates. Because carbohydrates directly affect blood glucose levels, understanding the appropriate carbohydrate intake for each meal is essential for effective disease management. This regulation helps achieve a balanced diet and maintain near-normal blood glucose levels.

The integration of assistive technology systems can enhance TED. Extended reality (encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)) offers promising avenues to enhance TED. Notably, AR has been widely employed in educational applications (e.g., [53], [84]), where virtual elements are superimposed onto real-world images [85] to enhance the learning experience. Previous works have demonstrated

that AR can improve learning outcomes [53]. In addition, numerous review publications, both general [53], [84] and specific, have highlighted the applications of AR in areas such as language learning [86], mathematics [87], chemistry [88], natural sciences for preschool and primary education [89], education for students with educational needs [90], support for individuals who are deaf or hard of hearing [91], and even in the military training contexts [92].

The motivation for this research arises from the growing need for innovative solutions to enhance TED for patients. Traditional educational methods often fail to engage patients effectively. Developing autonomous, easily accessible, and user-friendly tools would enable patients to access these resources more conveniently. The contributions of this work include the adaptation of an AR application tailored for diabetes patients in Ecuador, offering an engaging and accessible approach to therapeutic education in diabetes. The study sample comprises both children and adults. Short- and mid-term learning outcomes are assessed, and the results of learning through the AR application are compared with traditional educational methods. Furthermore, data from Ecuadorian patients are compared with those from Spanish patients. In summary, this work demonstrates the potential of AR-based tools to provide a more engaging complement to conventional methods and highlights their applicability across diverse cultural and demographic contexts. The findings aim to pave the way for broader implementation of similar tools, addressing the global challenge of improving chronic disease management through innovative, patient-centered approaches.

3.3 Related work

3.3.1 Virtual Reality

VR is a technology with significant potential to assist diabetes patients, attracting considerable interest from researchers, as highlighted by recent reviews [25], [26]. Hao et al. [25] conducted a systematic review to identify, critically evaluate, and synthesize the effects of VR on balance in individuals with diabetes. They concluded that VR-based rehabilitation shows promising effects in enhancing balance among individuals with diabetes. Vaughan [26] offers a comprehensive review of VR and AR applications in diabetes, highlighting key areas of use and providing a foundation for future developments in VR tools for diabetes management. He concluded that VR and AR in diabetes show potential to improve the training of diabetologists while advancing education, prevention, and treatment strategies for both adults and children with Type 1 or Type 2 diabetes. This section explores the use of VR as a tool for managing and treating diabetes, focusing on its applications in education, prevention, and patient care for individuals with Type 1 and Type 2 diabetes.

For individuals with Type 1 diabetes, different VR tools have been presented. For instance, a platform incorporating a variety of scenarios was created to train individuals with diabetes [26]. These include training for exercising safely in a VR gym while preventing hypoglycemia for individuals with Type 1 diabetes, advice on carbohydrate counting in a VR kitchen, training on finger-prick techniques for newly diagnosed patients, and a workplace scenario for glucose monitoring. The platform was tested on Android smartphones using Google Cardboard. Similarly, a virtual world game was created to support children with Type 1 Diabetes, suggesting that virtual games should incorporate three essential elements: (1) The player's connection with the game's protagonist; (2) a reward system for adhering to medication and diet; and (3) a focus on the disease's biochemical basics [27]. Lanning

et al. [28] created a four-part VR intervention to expose adults with Type 1 diabetes to expected Closed Loop system barriers: perceived hassles of using Closed Loop, body image, unwanted social attention, and deskilling fears. The authors concluded that the VR intervention showed great potential for addressing expected barriers in the uptake and use of Closed Loop systems while maintaining enthusiasm and preserving positive expectations toward Closed Loop.

For individuals with Type 2 diabetes, VR tools have also been developed. For instance, Diabetes Island was developed within a virtual world in Second Life [29]. This virtual island provides a range of diabetes self-care education activities and resources. The users, identified by their avatar name, could communicate through voice and text chat tools. On Diabetes Island, the participants accessed various educational resources, including scenarios on nutrition labels, educational signage, and a learning center with written materials and videos. Four interactive scenarios focused on healthy eating and physical activity. Health professionals, as avatars, led real-time formal and informal sessions on topics like healthy eating, medication adherence, physical activity, and diabetes care. The participants earned points for engaging in activities, which could be traded for avatar clothing. The study focused on African American women with Type 2 diabetes, characterized by low levels of physical activity and high-fat diets. The impact of the intervention was evaluated using a single-group repeated measures design, with assessments at three time points: (1) baseline; (2) three months (mid-intervention); and (3) six months (immediately post-intervention). The Diabetes Island intervention showed (1) good participant acceptance and regular usage; (2) a reduction in diabetes-related distress, body mass index, and environmental barriers to self-care; and (3) improvements in dietary habits and physical activity. All of this was observed among a group of low-income patients. Nintendo Wii Fit Plus (Nintendo Co., Ltd., Kyoto, Japan) has been used to develop educational games to promote physical activity and improve health outcomes in adults with diabetes. A study involving adults with Type 2 diabetes used a Wii Fit Plus game for 12 weeks [30]. The conclusions were that the Wii Fit Plus interactive exercise game effectively motivated patients to enhance physical activity, improve glucometabolic control, and boost their quality of life. Reducing diabetes-related distress is another application of VR. With this objective in mind, Ghosal et al. [31] proposed the development of a VR-based mindfulness application to reduce diabetes distress for patients with Type 2 Diabetes. On the therapeutic side, Lee et al. [32] investigated the impact of a VR exercise program (VREP) on patients with Type 2 diabetes. The program used IoT sensors attached to an indoor bicycle connected to a smartphone, allowing the participants to engage in immersive VR exercises via a headset. The study, conducted three times weekly over two weeks, found significant reductions in mean blood glucose and serum fructosamine levels in the VREP and indoor bicycle exercise (IBE) groups compared to the control group. Although body mass index showed no significant changes, muscle mass notably increased in the VREP and IBE groups. The effects of various feedback modalities on balance within immersive VR have also been explored. For example, Mahmud et al. [33] investigated the effects of various feedback modalities (auditory, vibrotactile, and visual) on balance within immersive VR. The study included participants with balance impairments due to Type 2 diabetes as well as those without balance impairments. During standing reach-and-grasp tasks, auditory and vibrotactile feedback significantly enhanced balance for all of the participants, while visual feedback showed significant improvement only for those with balance impairments. Cinematic VR has also been explored. For example, Beverly et al. [34] carried out a pilot study to assess the effectiveness of a cinematic VR training program aimed at care

providers. The program centered on an elderly patient with Type 2 diabetes and multiple geriatric syndromes, highlighting the risk of elder abuse and neglect.

3.3.2 Augmented Reality

While AR has shown promise in healthcare, its applications in TED remain relatively underexplored. Previous research works on AR that are not directly related to our work are as follows: The first one is an AR application for learning about antihypertensives for people with Type 2 diabetes [36]. The AR application scans pre-defined patterns (e.g., a medication package) and shows the augmented information. The second one is Jerry the Bear, a teddy bear toy with image targets embedded in his body [37] to provide TED to children with Type 1 diabetes. For example, the AR application on a mobile device recognizes the areas of the teddy bear's body where image targets are located. It allows the blood glucose to be measured by simulating a prick in the bear's hand or administering insulin with a pen or pump in Jerry's belly. The process of learning to count carbohydrates is not carried out with AR. The third one was presented by Kurniawan et al. [38], who developed a mobile AR application to provide diabetes drug information using QR codes to display 3D representations. The study, involving pharmacy students, found that AR technology supported 76.2% of student learning, demonstrating its effectiveness in enhancing educational outcomes. The fourth was presented by Fajriyah et al. [39], who conducted a study to analyze the effect of AR-based therapeutic patient education on Health Locus of Control in Type 2 diabetes patients. The AR application utilized barcode markers to trigger interactive content, focusing on the five key areas of diabetes management: education, diet, physical activity, blood glucose monitoring, and medication. It also featured quizzes to assess patient knowledge and provided explanations on managing diabetes. The intervention was administered three times a week over a period of three months. The participants were split into two groups: half in the intervention group and half in the control group. Their findings indicated that AR-based Therapeutic Education significantly improved Health Locus of Control scores in Type 2 Diabetes patients. However, no significant difference was found between the intervention and control groups in terms of overall Health Locus of Control improvement.

Previous research works that are directly related to our work are the following. The first one was presented by Domhardt et al. [35], who developed an AR application for mobile devices that estimates carbohydrate choices in real food. The application superimposes a virtual mesh over those foods. The users can interact with this virtual mesh to adjust it to the volume of the real food. The application measures the volume of real food and estimates its weight. For the correct functioning of the application, a marker must be placed in front of the food to be measured. Eight patients took part in the study. In 44% of the assessments, the margin of error decreased by a minimum of 6 g of carbohydrates. The second one is from one of our previous works [93], in which we developed the first version of the AR application for Spanish children. In the study, two post-knowledge questionnaires were used: one containing the same foods as the pre-knowledge questionnaire and a second one containing different foods from those in the pre-knowledge questionnaire. There were no statistically significant differences between the results of these two different post-knowledge questionnaires. In this work, the AR application has been adapted to food for patients from Ecuador; the sample includes children and adults. Short- and mid-term memories were evaluated. The AR outcomes were compared with traditional ones. We have also compared the Spanish data [93] with our study conducted in Ecuador.

3.4 Materials and methods

3.4.1 Augmented reality application

The AR application shows virtual food on a real dish using a mobile device. The goal is to make users believe that they are real foods. When the application recognizes the image in the center of the dish, the virtual food is shown in the center of the physical dish. The users can place the dish wherever they like and view the food in the desired location. Users can freely move their mobile device or dish to view the virtual food from any angle (360°). The users can zoom in or out to view the food closer or farther away. The users can use the application at home to complete the training recommended by their therapists. To do so, they simply need to install the application on their mobile phone and print the image to attach to the dish they wish to use. Figure 3.1 provides a graphical summary of the steps that patients must follow in the AR application, while Figure 3.2 presents a flowchart illustrating its functionality in detail.

- (1) Filling out personal information: Initially, the patients must enter their age and gender. Following this, the application shows the recommended carbohydrate choices for their age for the whole day and the carbohydrate choices for breakfast (1 carbohydrate choice = 15 g of carbohydrates). This equivalency is currently used in Ecuador, the United States, Mexico, and most of Latin America. However, it varies in other countries. For example, in Spain, one carbohydrate choice equals 10 g of carbohydrates, and in Austria, one carbohydrate choice equals 12 g of carbohydrates.
- (2) The AR application: The application has three levels, each of which focuses on a distinct food category. Specifically, these categories are dairy products, grains, and fruits. The first level (dairy products) includes seven different foods, while the second level (grains) includes eight foods, and the third level (fruits) includes 10 foods. Each level begins with a learning phase where foods are shown in real size along with their weight, carbohydrate choices, glycemic level, and homemade portions of food, such as a tablespoon or cup (this is the additional information that the Foundation shows in its educational materials). After this initial learning phase, the patients undergo an assessment phase to test their knowledge. During this phase, the patients are shown each food in the center of the screen and must select the correct number of carbohydrate choices from the three options provided.
- (3) The final challenge: After completing the three levels, the patients face a final challenge, which is to identify as many unique breakfast combinations as possible within a set time (one and a half minutes). Each breakfast must adhere to the recommended carbohydrate choices for the users' ages. To succeed, the patients must select foods from at least two groups. Each breakfast entry is completed by pressing the button in the upper right corner (represented by a fork and spoon).

The AR application was developed using Unity (<https://unity.com> (accessed on 10 December 2024)) as the primary development platform, with Vuforia Engine (<https://developer.vuforia.com> (accessed on 10 December 2024)) integrated for its AR tracking and registration capabilities. Vuforia Engine provides tracking capabilities for a selection of items and areas, which can be grouped into Images, Objects, and Environments. Specifically, for the development of our AR application, we used an image target, which is glued to a real dish to make it look like it is a design of the dish itself. Another option would have been to select a dish with a design that is suitable for recognition with Vuforia

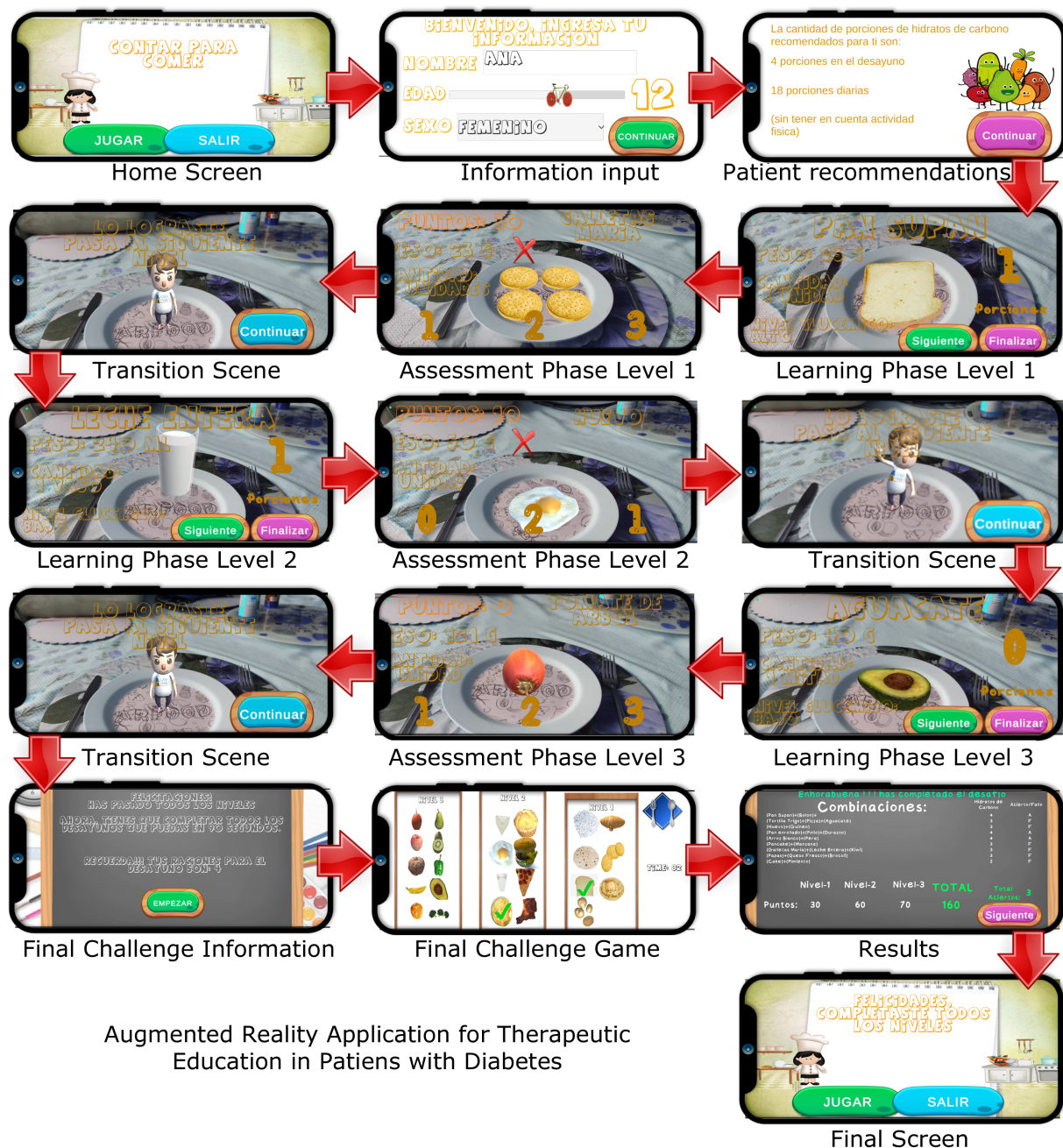


Figure 3.1: A graphical summary of the steps to be followed for the correct use of the AR application.

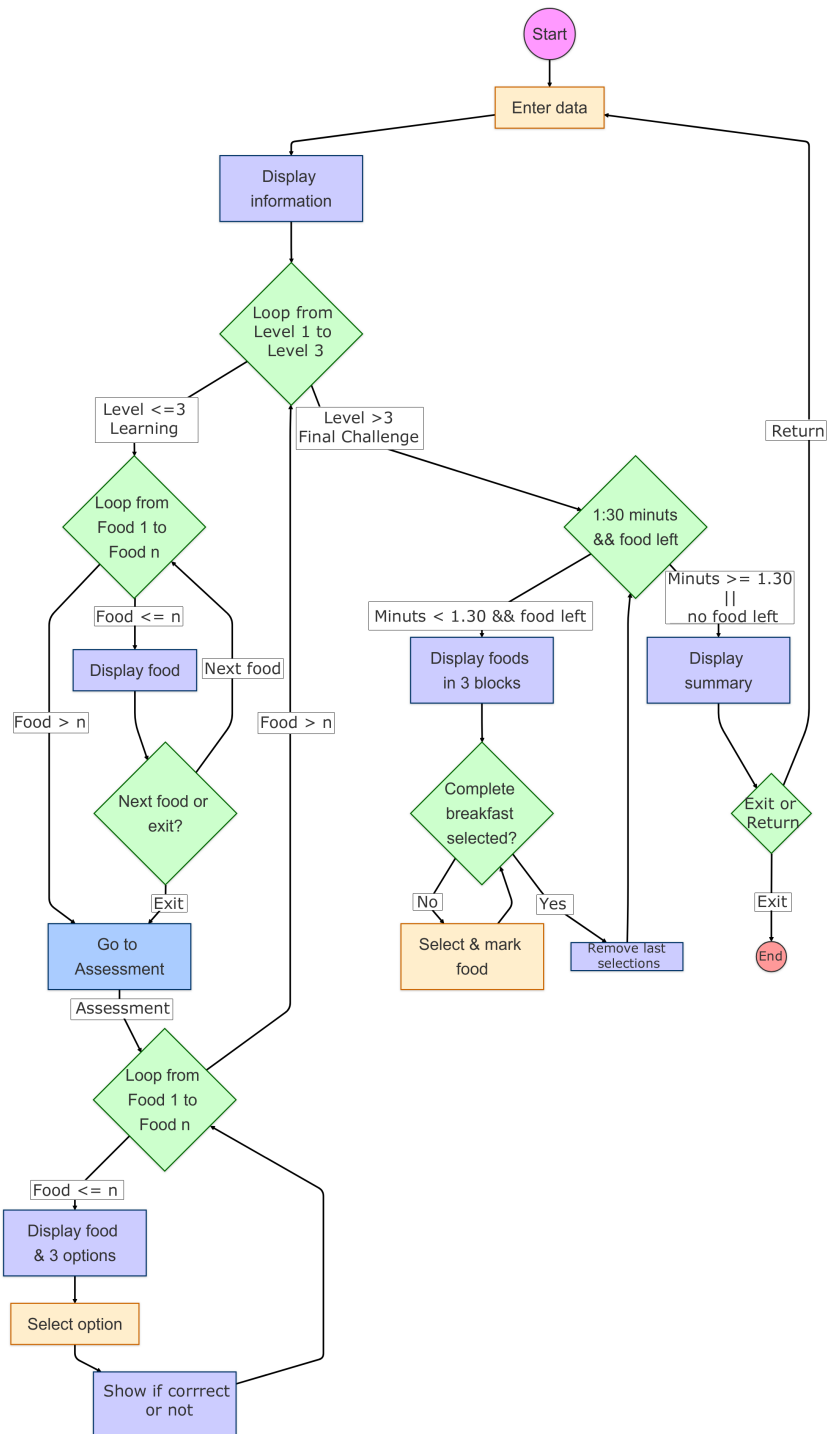


Figure 3.2: A flowchart detailing the functionality of the AR application.

Engine. This image target is recognized and tracked by the Vuforia Engine in real time using the image captured by the device’s camera. This is achieved by the Image Target Observer, which begins tracking the image target upon detection. The image is tracked by comparing the natural features extracted from the camera image with a known target stored in the active database. Once the image target is detected, the Vuforia Engine calculates its position and orientation in 3D space. If Extended Tracking is active, the pose information of an image target remains available even when it is no longer visible in the camera’s field of view, is occluded, or cannot be tracked for other reasons. Extended Tracking uses the device’s pose to improve tracking performance and ensure continuity of tracking, even when the target is out of view. In practice, Extended Tracking means that once the device is moved away from the original target, the augmentations stay in place relative to the real world and remain consistent with the reference frame defined by the target. The Device Pose Observer obtains tracking information about the device’s position and orientation in the physical world by analyzing the visual features of the environment captured by the camera and, in certain cases such as Extended Tracking, by using the built-in inertial measurement unit (IMU) sensor to determine the device’s six-degree-of-freedom pose. Typical sensors in a mobile device IMU include an accelerometer, gyroscope, and magnetometer. For virtual content mapping, Vuforia Engine anchors the virtual food to the image target’s position and dynamically adjusts the rendering to maintain proper alignment as the user or the device moves. The virtual elements (food) were adjusted in Unity on the image target so that when displayed on the screen, they are shown in real size according to their carbohydrate portions. The physical dish, as a movable, rotatable, and inclinable object, serves as a Tangible User Interface by enabling intuitive interaction with the digital representation of food in AR, seamlessly bridging the physical and digital worlds. The virtual guide is displayed using the center of the image target as the origin of the coordinate system to show the other information, providing users with step-by-step instructions or contextual information. Vuforia Engine supports different operating systems, tools, and device versions for developing and running AR applications (<https://developer.vuforia.com/library/platform-support/supported-versions> (accessed on 10 December 2024)). Our AR application can run on mobile devices with an Android operating system and an iOS operating system. In our study, we used a Xiaomi POCO X3 NFC smartphone (Xiaomi Corporation, Beijing, China).

3.4.2 Participants

The study participants are patients who attended one of the activities organized by the Diabetes House, which is based in the cities of Cuenca and Portoviejo (Ecuador). The Diabetes House (<https://casadeladiabetes.org.ec> (accessed on 10 December 2024)) has therapeutic learning activities as well as educational material that can be accessed from its website for patients with Type 1 diabetes. A total of 27 patients from Ecuador with Type 1 diabetes (14 men and 13 women), ranging in age from 5 to 28 years old, participated in the study. The mean age was 15.85 ± 5.92 years old. Information about the study was provided to the patients or their parents (in cases where the patients were minors). Informed consent forms were signed by the patients or their parents before participating. The study adhered to the principles of the Declaration of Helsinki and received approval from the Ethics Committee of the University of Cuenca (Ecuador).

3.4.3 Measures

Assessment of the knowledge: To assess the knowledge about carbohydrate choices, there was a knowledge questionnaire in which the patients should indicate the number of carbohydrate choices for nine foods with images selected from the 25 foods shown in the application. All of the foods that appeared on the questionnaire were included in our AR application and the traditional session, and the patients were informed of their carbohydrate choices. The same questionnaire was used to measure the level of knowledge of carbohydrate choices at different stages of the study. The knowledge variable is the sum of correct answers (from 0 to 9) and can be expressed mathematically as the following:

$$\text{Knowledge Score} = \sum (\text{Correct Answers})$$

Where each correct answer is assigned a value of 1, and each incorrect answer a value of 0.

The following questionnaires were used:

- (1) Short-UEQ (User Experience Questionnaire) [94]: The UEQ consists of eight items on a 7-point Likert scale, grouped into three variables: Pragmatic Quality, Hedonic Quality, and Overall. We used the short questionnaire instead of the long one with 26 items so that the session would not be too tedious.
- (2) Questions: Thirteen questions were included to assess usability and satisfaction with the application. These questions were the same as those used in [93].
- (3) Data: This questionnaire gathered data from the participants, including their age and gender.

3.4.4 Protocol

The initial study design was a between-subjects design. This implied two separate groups: a control group using traditional learning and an experimental group using the AR application for learning. The study began with the control group. The knowledge outcomes were analyzed, and it was observed that the patients had not significantly increased their knowledge about carbohydrate choices. As a result, it was decided to continue with this group of patients and use a within-subjects design. The objective was to test whether the same patients could learn significantly using the AR application. Therefore, the protocol used in the study presented in this manuscript involved three sessions.

Session 1: The patients learn by attending a traditional class. The steps followed by the patients were as follows:

- Fill out the knowledge questionnaire;
- Attend a traditional session;
- Fill out the knowledge questionnaire.

Session 2: The patients learn by using the AR application. The session took place one week after Session 1. The steps followed by the patients were as follows:

- Fill out the knowledge questionnaire;
- Learn by using the AR application;

- Fill out the knowledge questionnaire;
- Fill out the rest of the questionnaires (usability, satisfaction, and data questionnaires).

Session 3: The patients fill out the knowledge questionnaire to test their recall of what has been learned. The session took place two weeks after Session 2. This test focused on the effects of learning on mid-term memory. A nutritionist taught the traditional class as she usually does in her regular classes. The session lasted one hour. In the class, images of the food were shown on a real scale and cut out in the shape of the food. The nutritionist talked about the foods included in the AR application and presented all of the data shown in the AR application. All of the foods included in the test were included in the class. This class also explained other concepts, such as the healthy plate. For example, she explained how these foods can be combined to make a healthy meal. A round of questions was also included after the explanation of each food. Some of them were: Can I eat my healthy dish in parts? Is it advisable to eat five meals a day? How can I determine the food choices that are not in the guide? The patients also asked for recommendations on preparing food (homemade recipes and deviating from the guide). The nutritionist answered all of the questions.

The study was conducted at the Diabetes House facilities in Cuenca and Portoviejo (Ecuador) in one session on a Saturday morning (from 10:00 a.m. to 12:00 a.m.). The patients required approximately 30 min to use the AR application and complete the questionnaires.

3.5 Results

The Shapiro-Wilk test was employed to assess the normal distribution of the variables. Most variables exhibited a non-normal distribution. Non-parametric tests were used for the entire dataset, as they are more appropriate for such distributions. The statistical data are reported as (Mdn: median; IQR: interquartile range), and all test results are provided as (test U: Mann-Whitney U/test W: Wilcoxon Signed-rank, normal approximation Z, p-value, r effect size). Results with $p < 0.005$ are considered to be statistically significant and are highlighted in bold with the symbol '*'. Results with $0.005 \leq p < 0.05$ are considered to be suggestively significant and are highlighted in bold [95]. Statistical analysis of the data was conducted using the R (4.1.3) statistical toolkit (<http://www.r-project.org> (accessed on 10 December 2024)).

3.5.1 Short-term learning outcomes

Assessing short-term learning outcomes is crucial for understanding the immediate impact of the educational method. To evaluate this, the Wilcoxon Signed-rank test was used to test whether the patients learned using the traditional method ($W = 43.5, Z = -1.178, p = 0.355, r = 0.160$). This was performed by comparing the scores obtained before (Mdn = 4.0; IQR = 2.0) and after the traditional learning session (Mdn = 4.0; IQR = 2.0).

As mentioned, since no statistical differences were found between the pre-test and the post-test, the same patients used the AR application one week later. The Wilcoxon Signed-rank test was used to test whether the students learned using the AR application ($W = 0.0, Z = -4.526, p < 0.001*, r = 0.616$). This was performed by comparing the

scores obtained before ($Mdn = 4.0$; $IQR = 3.0$) and after ($Mdn = 8.0$; $IQR = 1.0$) using the AR application.

The Wilcoxon signed-rank test was used to check whether there were differences in the scores of the same patients when using the two learning methods ($W = 0.0$, $Z = -4.546$, $p < 0.001^*$, $r = 0.619$). This was performed by comparing the score obtained using the traditional method ($Mdn = 4.0$, $IQR = 2.0$) and the score obtained using the AR application ($Mdn = 8.0$, $IQR = 1.0$). Figure 3.3 shows a box plot for the scores obtained by the patients after learning using the AR application and the traditional method.

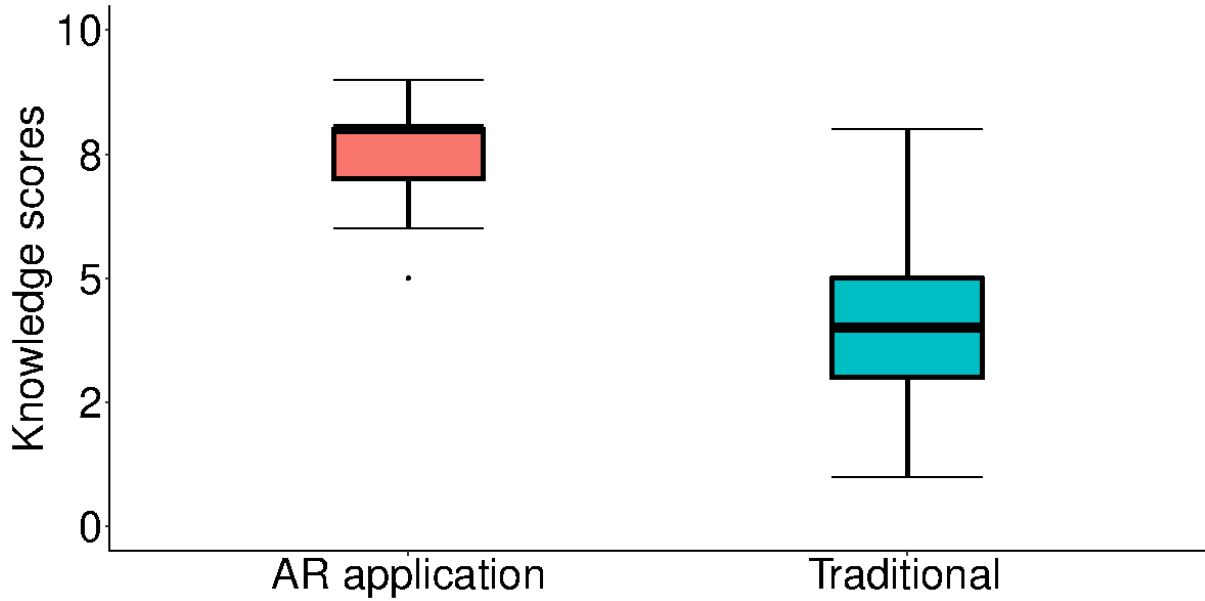


Figure 3.3: Box plot for the scores obtained by the patients after learning to use the AR application and the traditional method.

From these results, we can conclude that using the AR application for short-term knowledge transfer was effective and offered a statistically significant improvement over the traditional method.

To determine the learning performance, we compared the knowledge outcomes of our study with those of a similar study of Spanish children [93]. The same experimental conditions were recreated in both studies. The main difference between the two AR applications was the food used, which in both cases was adapted to the country in which the studies were conducted. The steps in the studies related to the validation of the AR application were similar. The objective of this comparison was to determine whether the application was effective in both countries, taking into account their cultural, educational, social, and healthcare system access disparities. These factors may influence the effectiveness of the AR application in both countries. The Spanish study [93] compared the use of the same and different questionnaires for the pre-test and the post-test. In our study, the group of 42 children that used the same questionnaire as pre-test and post-test is used for comparison. The children ranged in age from five to fourteen years old. The mean age was 8.74 ± 2.56 years old. There were 24 boys (57.1%) and 18 girls (42.9%).

The initial knowledge assessment establishes a baseline that accounts for potential differences related to the time elapsed between the two studies, as well as inherent differences

between the two populations (Spanish and Ecuadorian) and other factors, such as cultural, educational, social, and healthcare system access disparities. Mann-Whitney U tests were applied to test whether there were differences between the initial knowledge of the Ecuadorian and Spanish children and their knowledge after using the AR applications. When comparing the initial knowledge of the group of children from Ecuador ($Mdn = 4.0; IQR = 3.0$) with the group of children from Spain ($Mdn = 2.0; IQR = 3.0$), the results were as follows: $U = 870, Z = 3.782, p < 0.001^*, r = 0.455$. This difference in favor of the Ecuadorian patients can not only be attributed to advances in educational resources and technology but also to differences in the health education strategies applied in each country. When comparing the knowledge after using the AR applications of the group of children from Ecuador ($Mdn = 8.0; IQR = 1.0$) with the group of children from Spain ($Mdn = 7.0; IQR = 3.0$), the results were as follows: $U = 577.5, Z = 0.133, p = 0.899, r = 0.016$. The small difference in favor of the Ecuadorian children can be explained by the significant difference in initial knowledge. In any case, although the initial knowledge of the two groups was different, the knowledge demonstrated after using the AR applications was not significantly different statistically. These results also suggest that the AR applications significantly increased patients' knowledge to high levels, with many scores at or near the maximum.

Since the ages of the two groups (Spaniards and Ecuadorians) differ, a subgroup of Ecuadorians was selected to include only participants aged 14 or younger. Mann-Whitney U tests were applied to test whether there were differences between the initial knowledge of the Ecuadorian subgroup and the Spanish children, as well as differences in their knowledge after using the AR applications. Comparing the initial knowledge of the group of children from Ecuador ($Mdn = 5.0; IQR = 2.25$) with the group of children from Spain ($Mdn = 2.0; IQR = 3.0$), the results were as follows: $U = 429.5, Z = 3.784, p < 0.001^*, r = 0.515$. When comparing the knowledge after using the AR applications of the subgroup of children from Ecuador ($Mdn = 8.0; IQR = 1.0$) with the group of children from Spain ($Mdn = 7.0; IQR = 3.0$), the results were as follows: $U = 260.5, Z = 0.18, p = 0.863, r = 0.025$. Therefore, after removing participants older than 14 years old from the Ecuadorian group, the results remain consistent with the previous ones: statistically significant differences in initial knowledge were observed between the groups, but no differences were found in final knowledge after using the AR applications.

Mann-Whitney U tests were applied to test whether there were differences between the knowledge of the groups of Ecuadorian adults (aged 18 or older) and Ecuadorian children after using the AR applications. Comparing the knowledge demonstrated after using the AR application of the Ecuadorian adult group ($Mdn = 8.0; IQR = 0.75$) with the Ecuadorian children group ($Mdn = 8.0; IQR = 1.0$), the results were as follows: $U = 85.0, Z = 0.0, p = 1.0, r = 0.0$. Mann-Whitney U tests were applied to test whether there were differences between the knowledge of the groups of Ecuadorian adults (aged 18 or older) and Spanish children after using the AR applications. Comparing the knowledge demonstrated after using the AR applications of the Ecuadorian adult group ($Mdn = 8.0; IQR = 0.75$) with the Spanish children group ($Mdn = 7.0; IQR = 3.0$) the results were as follows: $U = 215.5, Z = 0.132, p = 0.905, r = 0.018$. These results suggest that AR applications are effective for both children and adults.

3.5.2 Mid-term learning outcomes

Assessing mid-term learning outcomes is crucial for understanding the method’s ability to promote sustained knowledge retention over time. To evaluate this, only the patients who completed all of the learning questionnaires were included in the analyses of this section. The pre-session test with the AR application was used to verify the patient’s retention of what was learned in the traditional learning session. The Wilcoxon Signed-rank test was used to check this retention ($W = 19.5, Z = 1.760, p = 0.071, r = 0.347$) with the post-test of the traditional session ($Mdn = 4.0; IQR = 3.0$) when compared with the pre-test of the AR session ($Mdn = 4.0; IQR = 3.0$). The Wilcoxon Signed-rank test was also used to check the difference between the initial knowledge ($Mdn = 4.0; IQR = 3.0$) before using the traditional method and one week after the learning session ($Mdn = 4.0; IQR = 3.0$), with the results: $W = 8, Z = 1.041, p = 0.345, r = 0.204$. The results demonstrate that there were no statistically significant differences between the two analyses. While the patients exhibited slight learning in the traditional session, this learning was not maintained after one week, resulting in a return to a level of knowledge similar to that observed at the beginning.

The test performed two weeks after the learning session with the AR application was used to verify the patients’ retention of what was learned in that session. The Wilcoxon signed-rank test was used to test this retention ($W = 65, Z = 2.887, p < 0.005^*, r = 0.566$), comparing the post-session test using the AR application ($Mdn = 8.0, IQR = 1.0$) with the two-week post-session test ($Mdn = 6.0, IQR = 2.0$). The Wilcoxon signed-rank test was also used to test the difference between the initial knowledge before the learning session with the AR application ($Mdn = 4.0; IQR = 3.0$) and two weeks after the learning session ($Mdn = 6.0; IQR = 2.0$), with the results: $W = 10, Z = -1.974, p = 0.044, r = 0.387$. The results demonstrate that there were significant differences in both analyses. The results of the first analysis indicate that the patients had statistically significant less knowledge than they did two weeks earlier. The results of the second analysis indicate that the patients had suggestively significant more knowledge than they had before the learning session with the AR application. Therefore, the patients retained a significant amount (but not all) of what they learned using the AR application in the mid-term. From all of these analyses, it can be concluded that the use of the AR application did indeed have a suggestively significant effect on mid-term knowledge retention.

3.5.3 User experience

The patient’s responses to the short-UEQ questionnaire after using the AR application were analyzed using the UEQ Data Analysis Tool (<https://www.ueq-online.org/> (accessed on 10 December 2024)). By using one of the UEQ downloadable Excel sheets, a graph was created (Figure 3.4) to evaluate the quality of our AR application in comparison to the products in the benchmark dataset included in the UEQ Data Analysis Tool [96]. This graph shows that the AR application performs exceptionally well relative to the UEQ benchmark. Based on the interpretation guidelines provided in the UEQ tool and in [96], our AR application ranks within the top 10% for all three variables or scales.

Table 3.1 shows that 7 of the 13 comparisons show significant differences in favor of the Ecuadorians (three of them are statistically significant, and four of them suggestively significant). However, the scores are high enough to indicate that both groups are highly satisfied with the AR applications.

Table 3.1: Mann–Whitney U tests for the satisfaction and usability variables between the Ecuadorians and the Spanish patients after using the AR applications. Statistically significant results ($p < 0.005$) are shown in bold with the symbol ‘*’. Suggestively significant results ($0.005 \leq p < 0.05$) are shown in bold.

Variables	Ecuado.	Spanish	U	Z	p	r
US#1. I found the AR application easy to use	5; 0.5	4; 2	1078.5	2.909	0.004 *	0.314
US#2. I have gotten used to the application quickly	5; 0	4; 2	1130.5	3.564	0.001 *	0.384
US#3. I have concentrated more on playing than on the Tablet	5; 1	5; 2	901.0	1.088	0.279	0.117
US#4. I could get close enough to the food	5; 1	4; 2	1076.5	2.815	<0.005 *	0.304
US#5. I could see the food from different positions	5; 1	5; 2	967.5	1.786	0.075	0.193
SA#1. I have had a good time	5; 0	5; 1	863.5	0.804	0.425	0.087
SA#2. I liked how the food looked on the dish	5; 0	5; 1	897.0	1.184	0.239	0.128
SA#3. I felt that the food on the dish could be real food	5; 1	5; 1	801.5	0.054	0.961	0.006
SA#4. I think I have learned with this application	5; 0	5; 1	1035.0	2.598	0.010	0.280
SA#5. I would like to use these applications to learn more about diabetes	5; 0	5; 1	887.0	1.068	0.288	0.115
SA#6. I would invite my friends to use the application	5; 1	4; 2	1060.5	2.701	0.007	0.291
SA#7. I would use this application again	5; 0	5; 1	1030.5	2.498	0.013	0.269
SA#8. Score the application from 1 to 5	5; 0	5; 1	972.5	2.077	0.038	0.224

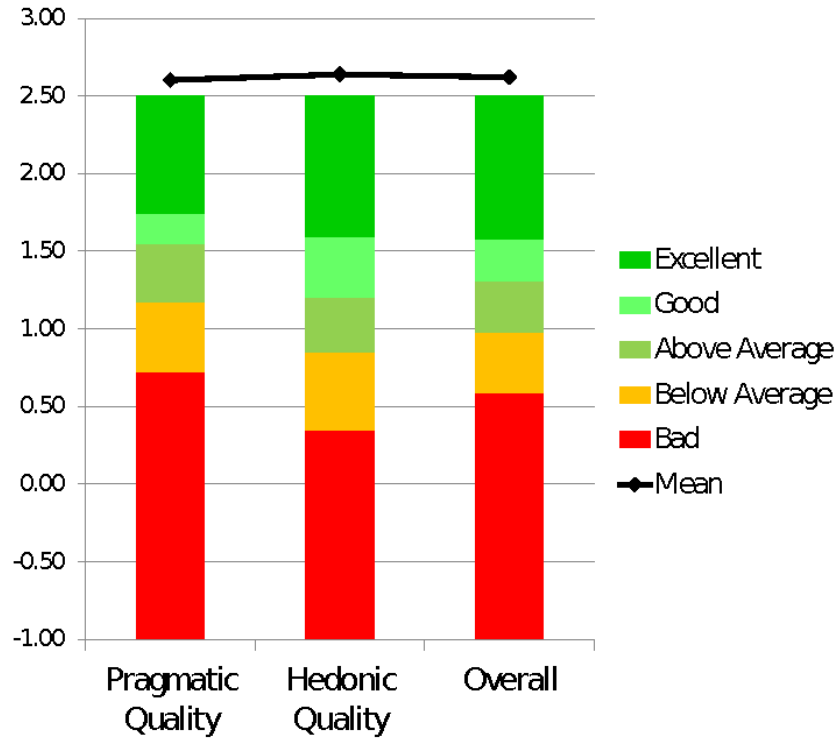


Figure 3.4: Comparison of the patient’s responses after using the AR application with the benchmark provided in the UEQ Data Analysis Tool.

3.5.4 Gender and age

To determine if gender influences the outcomes obtained by the patients, we applied the Mann–Whitney U tests. The learning outcomes of women and men were compared after using the traditional method and after using the AR application. The results are shown in Table 3.2. No significant differences were found for either of the two analyses. Figure 3.5 shows box plots for the scores obtained by women and men after learning using the traditional method and the AR application.

Table 3.2: Mann–Whitney U tests to assess whether gender affects the scores obtained using the traditional method and the AR application.

	Women (<i>Mdn</i> ; <i>IQR</i>)	Men (<i>Mdn</i> ; <i>IQR</i>)	<i>U</i>	<i>Z</i>	<i>p</i>	<i>r</i>
Traditional method	4; 2	5; 2	60.0	1.530	0.132	0.294
AR application	8; 1	8; 1	115.5	1.276	0.211	0.246

We used the Mann-Whitney U tests to assess whether gender affects the UEQ variables. The UEQ variables for women and men were compared. Table 3.3 shows the results. None of the analyses revealed significant differences. We used the Mann-Whitney U tests to assess whether gender affects the satisfaction and usability variables. These variables for women and men were compared. None of the analyses revealed significant differences and are not included in this paper.

The Kruskal-Wallis tests were applied to assess whether age has an impact on any of the learning questionnaires filled out by the patients (Table 3.4). Kruskal-Wallis tests

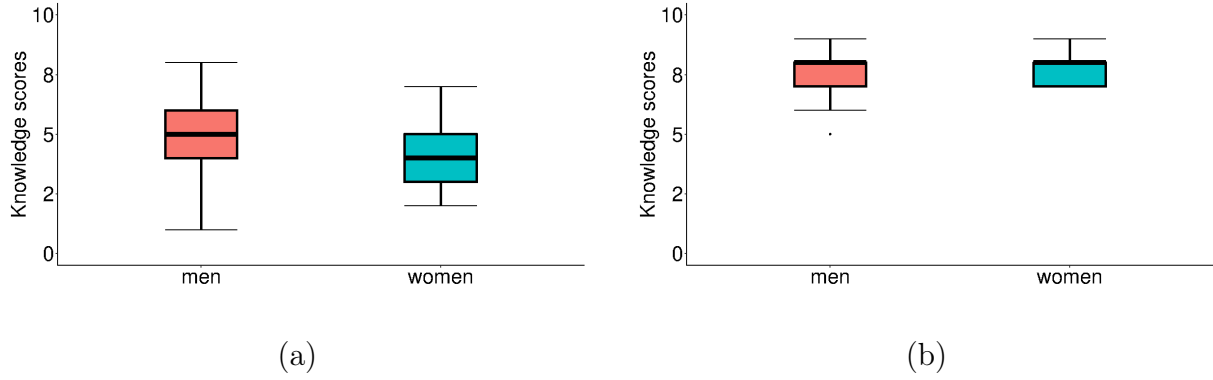


Figure 3.5: Box plots for the scores obtained by men and women after learning using (a) the traditional method and (b) the AR application.

Table 3.3: Mann–Whitney U tests assess whether gender affects the UEQ variables.

	Women (<i>Mdn</i> ; <i>IQR</i>)	Men (<i>Mdn</i> ; <i>IQR</i>)	<i>U</i>	<i>Z</i>	<i>p</i>	<i>r</i>
Pragmatic Quality	2.75; 0.25	3; 0.6875	86.0	0.260	0.815	0.050
Hedonic Quality	3.00; 0.5	2.625; 0.6875	105.5	0.752	0.468	0.145
Overall	2.875; 0.375	2.75; 0.5	94.0	0.150	0.901	0.029

were also used to determine whether age affected the UEQ variables (Table 3.5) and the usability and satisfaction questionnaire variables. None of the analyses revealed significant differences.

Table 3.4: Kruskal–Wallis tests for the knowledge scores considering age.

	d.f.	H	p
Pres-test Traditional	15	15.494	0.416
Post-test Traditional	15	13.357	0.575
Pre-test AR application	15	13.315	0.578
Post-test AR application	15	9.7032	0.838

Table 3.5: Kruskal–Wallis tests for the UEQ variables considering age.

	d.f.	H	p
Pragmatic Quality	15	12.203	0.664
Hedonic Quality	15	21.842	0.112
Overall	15	18.992	0.214

3.6 Discussion

In this work, we present a mobile AR application to support TED and to help patients learn to count carbohydrates. Our AR application recognizes a real dish and shows virtual food on it, giving the patient the feeling that both are real. The food was adapted for patients from Ecuador. In general, managing one’s diet is crucial for maintaining good health.

Monitoring their food intake is essential [97] for patients with diabetes. The quantity of carbohydrates consumed during meals directly affects the insulin dosage required. Therefore, knowing the amount of carbohydrates in foods would empower patients to manage their condition independently and enhance their glycemic control. Carbohydrate counting is often challenging for patients with Type 1 diabetes, and inaccurate counting is the primary identified cause of poor postprandial glycemic control [98]. The nutrition guidelines for patients with Type 1 diabetes recommend teaching them how to count carbohydrates using tools tailored to their preferences [98]. Our AR application could serve as one of these tools, providing an interactive and personalized approach to support patients in carbohydrate counting. Our study did not examine enhancements in patients' glycemic control using our app. Nonetheless, this remains a significant area for future research.

Our application runs on mobile devices. Considering that the global smartphone penetration rate was estimated at 69% in 2023, a mobile application is an optimal option for reaching the widest audience possible. In our study, we monitor the learning process. Still, the application can be used independently at any time and any place, enhancing flexibility in learning as highlighted in other research [20]. Additionally, previous works also suggest that flexible and technological approaches could be used to reach young audiences [99]. Such applications can be particularly beneficial in rural areas, where challenges such as lower health literacy and limited access to diabetologists often hinder effective diabetes management [34].

In terms of learning about carbohydrate choices through our AR application in the short-term, the statistically significant differences in patients' knowledge before and after using the application demonstrate that such tools are effective for knowledge transfer. This result aligns with other studies on AR, which have shown that using mobile AR for educational purposes can enhance the learning process [20], [53]. The AR application is also effective for both children and adults, regardless of gender.

In terms of learning about carbohydrate choices through our AR application in the mid-term, the patients retained a suggestively significant amount (but not all) of what they learned using the AR application in the mid-term. Similarly, Alhamad & Agha [100] conducted a study comparing knowledge acquisition and retention between mobile learning and traditional learning in teaching respiratory therapy to third-year students. The lesson focused on arterial blood gases. Knowledge assessments were conducted before the class, immediately after, and again two weeks later. Their findings on mobile learning align with those of our study on the AR application, indicating that students gained knowledge after training and retained it over time, though retention declined compared to the immediate post-training assessment. Another study that also assessed knowledge retention two weeks after a learning session was conducted by Gargrish et al. [101]. They assessed memory retention among K-12 students using AR for geometry. The first evaluation took place immediately after the learning session, the second was conducted two weeks later, and the third occurred after two months. Their results showed that the highest scores were obtained immediately after learning, followed by a decline in retention at the two-week mark, with a slight further decrease at the two-month mark. Their findings regarding the initial knowledge gain and the decline in knowledge retention at the two-week mark align with our study's results.

Using the traditional method, the patients did not significantly improve their initial

knowledge. Our explanation for this result is that the length of the session, which was one hour and included more information beyond just carbohydrate choices, potentially overwhelmed the patients, hindering their ability to remember specific data such as the carbohydrate choices of the foods used in the test. However, it is important to acknowledge that traditional teaching methods are effective and have been successfully used for many years. Moreover, other works have compared the learning outcomes using AR applications and traditional methods and found no statistically significant differences [13], [20]. Therefore, a new study should be conducted to determine the optimal type and duration of traditional sessions needed to achieve knowledge equivalent to an AR session of 30 min. Chiang et al. [78] compared a group using a mobile AR application and a group using a mobile application without AR. Their findings indicated that the average learning outcomes were significantly higher in the AR group compared to the non-AR group. This demonstrates the potential of AR in enhancing educational outcomes, which is in line with the results obtained in our work.

In terms of usability, several researchers have highlighted its significant impact on educational effectiveness [81]. According to Sun et al. [82], systems that are user-friendly enable learners to concentrate more on the content. In our study, our application was highly intuitive (a median of 5 on a scale from 1 to 5 in US#1), and the patients rated their user experience on the Short-UEQ questionnaire as excellent, scoring in the top 10% on all three variables relative to the UEQ benchmark [96]. Therefore, we can argue that our application helps patients focus on learning about the carbohydrate content of different foods.

The patients expressed a strong interest in using these applications to expand their knowledge about diabetes, scoring a median of 5 with an interquartile range of 0 (on a scale of 1 to 5). This suggests that the application would be widely welcomed as a valuable educational tool in therapy. We consider our application to be a valuable educational resource due to its tailored approach to the needs of diabetes patients and its strong motivational impact in presenting or reinforcing information about carbohydrate choices.

Finally, the current state of AR, MR, and robotics, as well as their expected evolution, suggests that the range of possibilities for developing new tools for therapeutic education in diabetes is vast. With headsets such as Apple Vision Pro offering advanced capabilities, the potential for creating immersive, interactive, and effective therapeutic education tools has never been greater.

3.7 Conclusions

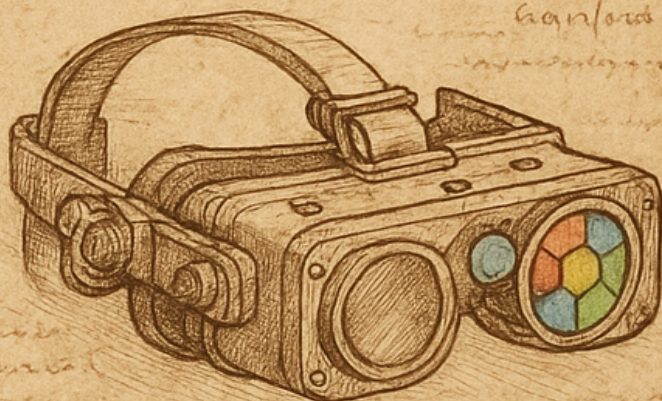
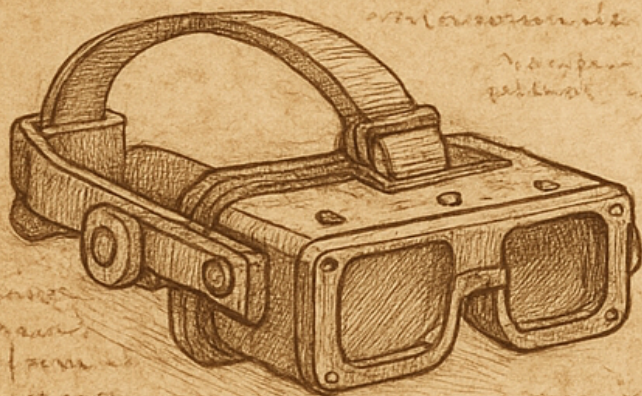
This work introduces a mobile AR application that is designed to aid in therapeutic education for diabetes patients. Our findings indicate that patients gained statistically significant new knowledge about carbohydrate choices in the short term using our AR application, and it has a suggestively significant impact on mid-term retention. The AR application benefits both children and adults, regardless of gender.

AR applications of this type offer great flexibility in the learning process, as the activity can be conducted anywhere and at any time. Patients only require a minimal setup involving a few printed images and a mobile device. The features of our AR application and its minimal requirements make it a highly accessible educational tool with great potential for therapeutic diabetes education. In this work, we explored the application

potential for diabetes therapeutic education. However, there are several avenues for future improvement. Our study assessed participants' knowledge retention two weeks after the activity. Future research should aim to include a larger sample size and conduct a larger longer-term evaluation, assessing knowledge retention at intervals such as one month, six months, and one year. This would provide deeper insights into the long-term effectiveness of the AR application. Additionally, it should examine how this knowledge acquisition and retention, and consequently carbohydrate counting, affect the patient's health, for example, by examining glycated hemoglobin (HbA1c) levels. Based on all of those findings, integrating AR applications like ours or other technology-based tools into therapeutic education could be considered, especially to support patients in carbohydrate counting and improve dietary self-management. Furthermore, a larger sample size could support the application of machine learning models to complement the statistical analyses, enabling more advanced insights, such as predictive modeling and pattern recognition in participant behavior and learning outcomes. The application could be improved by adding support for multiple languages and adjusting the carbohydrate choice equivalents based on the user's country.

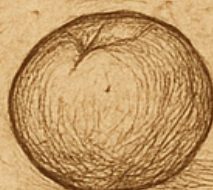
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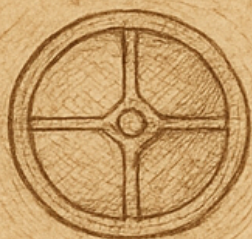
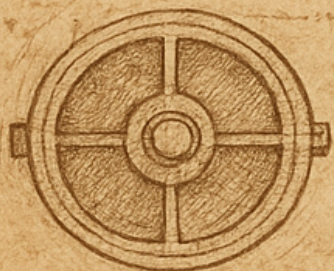
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Chapter 4

Mixed reality in therapeutic education for diabetes: grayscale and color passthrough compared with augmented reality and traditional methods

Calle, M., Abad, F., & Juan, M.-C. (2025). Mixed reality in therapeutic education for diabetes: grayscale and color passthrough compared with augmented reality and traditional methods. *Applied Sciences*, 15(7), 4021. <https://doi.org/10.3390/app15074021>

4.1 Abstract

This publication presents the development of a new mixed reality (MR) application for headsets, using grayscale and color passthrough to support therapeutic education in diabetes. Passthrough technology allows users to see their real-world environment through cameras on the headset. A comparative study was conducted to assess the effectiveness of our application in its two visualization modes against traditional learning and an augmented reality (AR) application. The study assessed the increase in patients' knowledge of the carbohydrate content of different foods, as well as the usability of and satisfaction with each application, with 92 Ecuadorian patients with Type 1 diabetes participating. The results indicate that all four learning methods positively influenced patient increase in knowledge (post-pre). However, pairwise comparisons of post-knowledge scores showed that the MR color passthrough and AR applications significantly outperformed the traditional method, with patients using color passthrough achieving greater post-learning outcomes than those

using grayscale or AR. Positive post-knowledge outcomes were observed across all age and gender groups. The patient feedback on their experience with the MR application using color passthrough was significantly higher than with the grayscale version. Therefore, while all methods demonstrated positive effects on knowledge gain, the findings presented in this publication suggest that color passthrough offers great potential for creating engaging, context-rich, and interactive learning environments that have a positive effect on both learning and user experience.

4.2 Introduction

Diabetes mellitus, commonly known simply as diabetes, is a long-lasting condition where the body struggles either to produce enough insulin or to use it effectively. Insulin is a hormone secreted by the pancreas that facilitates the transport of glucose from food into the body's cells to be stored or converted into energy. Without sufficient insulin, blood glucose levels can become dangerously high, a state known as hyperglycemia, which over time can lead to serious complications affecting both large and small blood vessels. Diabetes is mainly categorized into three forms: insulin-dependent diabetes (Type 1), Type 2, and gestational diabetes mellitus. In individuals with Type 1 diabetes, the immune system incorrectly attacks and damages the beta cells in the pancreas that produce insulin, leaving the body with very low or no insulin. This form is most common in children and young adults, who must rely on lifelong insulin therapy. In people with Type 2 diabetes, the pancreas either fails to produce enough insulin or the body becomes resistant to its action. Although it is mostly seen in adults, its occurrence is rising among younger populations. Management often includes dietary adjustments, physical activity, and oral medications, with insulin therapy needed in advanced cases. Gestational diabetes mellitus arises during pregnancy when the body cannot produce or use sufficient insulin to meet the heightened demand [102].

Global data on diabetes shows a concerning rise in prevalence. According to the International Diabetes Federation (<https://idf.org> (accessed on 18 February 2025)), around 537 million adults aged 20 to 79 were affected by diabetes in 2021. It is anticipated that this figure will grow significantly, with 643 million people projected to have diabetes by 2030, and 783 million by 2045. The rise is particularly pronounced in low- and middle-income countries, where three out of four adults live with diabetes. These statistics underscore the increasing global burden of diabetes, driven by factors such as urbanization, aging populations, and rising obesity levels. According to the World Health Organization (<https://www.who.int> (accessed on 18 February 2025)), diabetes is a major contributor to serious health complications, including strokes, blindness, kidney failure, heart attacks, and lower limb amputations.

Therapeutic education in diabetes (TED) is a structured educational process that helps individuals with diabetes understand their condition, manage it effectively, and adopt essential self-care practices into their daily routines. TED covers key areas such as understanding diabetes, monitoring blood glucose, administering insulin, planning nutrition and diet, engaging in physical activity, preventing complications, accessing psychosocial support, and building self-management skills. This educational approach aims to empower patients to take an active role in managing their diabetes [103].

Effective nutritional management plays a crucial role in avoiding insulin resistance, delaying

its advancement, and reducing the risk of vascular and neurological complications that arise from poor blood glucose control. As a result, nutrition is a fundamental aspect of education for individuals living with diabetes. Nutritional guidelines focus on managing daily energy consumption and its distribution throughout meals, in addition to maintaining a proper balance of fats, proteins, and carbohydrates. Since carbohydrates have a direct impact on the levels of glucose in blood, knowing the right amount of carbohydrates to consume with each meal is essential for managing the condition. This regulation supports the achievement of an optimal diet and helps maintain the levels of glucose in blood within a near-normal range.

Integrating assistive technology systems can significantly improve therapeutic education. These systems, which may incorporate extended reality technologies such as Mixed Reality (MR), Augmented Reality (AR), and Virtual Reality (VR), can enhance the user experience. VR generates completely immersive digital worlds, fully isolating users from their physical surroundings [14]. AR overlays virtual elements onto the real world, which requires precise spatial alignment to integrate digital and physical components seamlessly [14]. MR does not have a universally agreed-upon definition, but in this publication, the term will be used to refer to an interactive and immersive blend of real and virtual elements, allowing both environments to coexist and interact dynamically [14], [15]. No MR system for TED has been presented to date. While VR has been the most widely used technology in education [104], healthcare [105], and TED [26], AR has also been applied in educational applications [13], healthcare [106], and TED [107].

This research is motivated by the increasing need for innovative tools to improve therapeutic education for patients. Conventional learning methods often fail to maintain patients' engagement effectively. The development of user-friendly and self-guided applications would provide patients with more engaging and accessible resources. This research provides several contributions, including the development of the first MR application specifically designed for individuals with diabetes in Ecuador, providing an interactive and easily accessible tool for diabetes education. The study presented here evaluates learning outcomes by comparing the effectiveness of the MR application (using both grayscale and color passthrough) with the equivalent AR application and traditional educational methods. The results highlight the potential of MR-based applications as a more captivating alternative to conventional approaches. Ultimately, this work seeks to promote the adoption of innovative, patient-focused solutions as part of the global effort to improve chronic disease management.

4.3 Related work

4.3.1 Augmented reality

Research on the integration of AR into TED is still limited, with only a few studies addressing its effectiveness. One such study by Domhardt et al. [35] created a mobile AR application designed to estimate the carbohydrate content of real foods. The AR application overlays a virtual mesh onto food items, allowing users to resize it to match the real food volume. The application calculates the food's volume and provides an estimation of its weight. For accurate results, a marker needs to be positioned in front of the food. In their study, eight patients participated, and, in 44% of the evaluations, the error margin decreased by no less than 6 g. In a prior work [93], we presented the first version of an AR

application for carbohydrate counting, designed for children in Spain. The study included two post-knowledge questionnaires: one with different foods and another that included the same foods as the pre-knowledge questionnaire. No statistically significant differences were found between the results of the two questionnaires. As a continuation of this AR application, a version tailored for Ecuadorian patients was developed [107]. Using this updated version, a study was conducted to evaluate its effectiveness in learning about carbohydrate content to Type 1 diabetes patients in Ecuador, with results compared to a similar study conducted in Spain. In the study [107], patients did not learn using traditional methods. The AR application improved short-term knowledge transfer and demonstrated a significant impact on mid-term retention. The results of learning were not influenced by age or gender, and patient satisfaction was high. The AR application used in the study presented here is the same as the one described in [107]. Other studies, though not directly related, are worth mentioning. The first is an AR application designed to help people with Type 2 diabetes learn about antihypertensive medications [36]. This application scans predefined patterns (e.g., a medication package) using a mobile device and displays augmented digital content. The second is a teddy bear toy (Jerry the Bear®(Providence, RI, USA)) with image targets integrated into its body [37], designed to support therapeutic education for children managing Type 1 diabetes. The mobile AR application recognizes the image targets on the bear's body and allows users to simulate measuring blood glucose or administering insulin via a pump or pen. However, the carbohydrate counting component is not integrated into AR. The third study [38] introduced a mobile AR application aimed at delivering information about diabetes medications, using QR codes to show 3D models. The findings from their study, which involved pharmacy students, revealed that AR technology played a significant role in student learning, accounting for 76.2% of their progress, highlighting its effectiveness in improving educational results. The fourth study [39] explored how AR-based therapeutic education influenced the Health Locus of Control in Type 2 diabetes people. Their application employed barcode markers to activate interactive content, covering five essential aspects of management of diabetes: medication, education, nutrition, exercise, and monitoring of blood glucose. The application included quizzes to evaluate individual knowledge and offered guidance on managing diabetes. The intervention was conducted three times per week for a duration of three months. The patients were divided into two separate groups: one group received the intervention, while the other served as the control group. The results demonstrated that AR-based education significantly enhanced Health Locus of Control scores in Type 2 diabetes patients. Nevertheless, no statistically significant difference was observed in the overall improvement of Health Locus of Control between the control and intervention groups.

4.3.2 Mixed reality using passthrough

To date, no MR application using passthrough technology has been developed for therapeutic education in diabetes. Moreover, only a few MR applications using passthrough technology have been presented and validated. The first of these MR applications was for learning to play the piano using Meta Quest 2 and passthrough in grayscale [23]. The MR application described in [23] used passthrough in grayscale to create an immersive learning experience. Two visualization modes were implemented: Wireframe and Solid. In Wireframe mode, the piano keys were outlined with border lines, while in Solid mode, a solid color hid the real keys. A comparison of both modes revealed that, although users recognized the limitations of grayscale passthrough, both visualization methods

provided a satisfactory user experience. The second of these MR applications was also for learning to play the piano, but using Meta Quest 3 and color passthrough [24]. A study compared the MR application with Synthesia, showing both were effective, but students performed significantly better with MR. The MR application provided a more satisfying experience, independent of age and gender, with high presence and minimal adverse effects. Students preferred MR, as it allows direct keyboard view with integrated visual aids, keeping their focus on playing. The third of these MR applications aimed to enhance the ecological validity of eating and sensory behavior research [40]. They developed an MR application that used passthrough VR, using the headset’s external cameras to capture and display the real-world environment within the virtual space. To blend real-world objects into the virtual space, specific surfaces were chosen to project the passthrough feed instead of standard textures. In their work, two passthrough planes were attached to a virtual tabletop (one flat on the surface and the other perpendicular), allowing users to see real-world objects as if they were part of the virtual scene. Experts assessed the MR application to study eating and sensory behavior. An initial evaluation compared three virtual environments: a lab booth, a basic restaurant, and a fully textured restaurant. Feedback led to refining the virtual restaurant, which was later re-evaluated. Experts recommended adding social cues for greater realism. The updated environment was preferred over a sensory booth but rated lower than a real restaurant. Our research seeks to advance beyond prior studies on technology-assisted carbohydrate counting. No previous studies have applied MR to carbohydrate counting using both grayscale and color passthrough.

4.4 Materials and methods

4.4.1 Description of the MR application

Our MR application is designed for patients with Type 1 diabetes, allowing direct interaction with virtual food in a real-life environment. Thanks to the passthrough technology of the Meta Quest 2 and Meta Quest 3 headsets, patients can visualize food in their real environment and manipulate it with their own hands (Figures 4.1 and 4.2). The real environment is displayed in color (Meta Quest 3) or grayscale (Meta Quest 2), but the virtual elements embedded in the scene are displayed in color on both devices (Figures 4.1 and 4.2). The application detects the position and movements of the hands, allowing users to pick up the virtual food, examine it from different angles, and facilitate a better understanding of the carbohydrate choices. The immersive approach makes it easier for patients to focus on the learning task.

The use of hands as a visual and physical reference in an MR environment enhances understanding of proper portion size. By interacting with 3D models superimposed on the real world, users can easily compare suggested portions with those they might consume. The patients completed the following steps. A graphical summary of the steps is shown in Figure 4.3.

1. **Enter personal details.** To start, the patients are required to provide their age and gender. Based on this information, the application then displays the recommended carbohydrate choices per day and specifically for breakfast, where 1 carbohydrate choice equals 15 g of carbohydrates. This standard is widely used in Ecuador, Mexico, the United States, and most of Latin America, though it differs in some

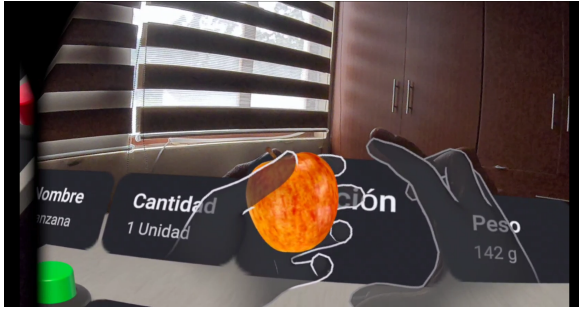


Figure 4.1: Two examples of virtual food manipulation with the user's hands using color passthrough.



Figure 4.2: Virtual food manipulation with the user's hands using grayscale passthrough.

other countries. For instance, in Spain, 1 carbohydrate choice equals 10 g, while in Austria, it equals 12 g.

2. **The MR application** is organized into three levels, each focusing on a different food category: the first level covers dairy products, the second level addresses grains, and the third level focuses on fruits. The first level includes 7 foods, the second level presents 8 foods, and the third level consists of 10 foods. At each level, a realistic simulation of the foods is presented, allowing for tactile interaction, and the content is organized in two phases:
 - (a) **the learning phase**, where patients observe the foods in real size and can see their name, quantity, weight, glycemic index, carbohydrate choices, and homemade portions of food, like a cup or tablespoon (these details are provided by the Foundation in its educational resources) (Figure 4.4);
 - (b) **the assessment phase**, where the patients must remember the learning information. Each of the 25 foods is shown, and the patient is required to choose the correct number of carbohydrate choices from the three available options (Figure 4.5). The application then informs the patient whether the answer is correct or not. The decision to provide three options for selection was made to speed up the process, as requiring the patient to write the carbohydrate choices for each food item would significantly increase the time needed for a learning session.



Mixed Reality Application for Therapeutic Education in Patients with Diabetes

Figure 4.3: A visual overview outlining the steps to be followed by the patients.

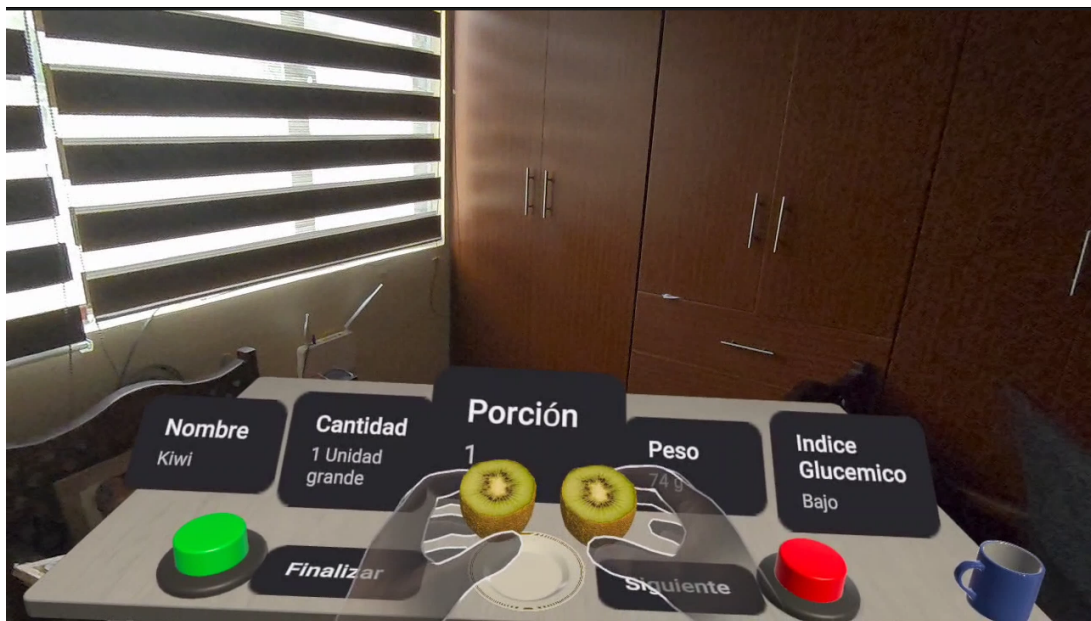


Figure 4.4: Example of the learning phase at level 3.



Figure 4.5: Example of the assessment phase at level 3.

4.4.2 Design and development

During the design of the MR application, we consulted five diabetes experts. Additionally, we incorporated elements that, according to Lange et al. [9], are essential for an effective educational intervention. Once the problem was understood and the needs of this group were identified, we established the application's functional specifications and overall design. With regard to hardware, the Meta Quest 2 provides a lower-resolution grayscale passthrough, which reduces clarity when viewing the physical environment, whereas the Meta Quest 3 offers a high-resolution color passthrough for enhanced visual quality.

Our MR application was developed in Unity 2021.3.11f1 (<https://unity.com/> (accessed on 18 February 2025)), a powerful and versatile development platform that enables developers to create interactive 2D and 3D experiences. In our case, it allowed us to build interactive AR and MR applications for deployment across multiple devices. Additionally, we imported the Oculus Integration package from the Unity Asset Store. Figure 4.6 shows the architecture of the MR application. The Oculus Integration package facilitates the integration of advanced MR features by providing an all-in-one source for core MR components, scripts, and plugins, which enhances the application development process in Unity. It includes several SDKs, such as the Platform SDK, Interaction SDK, Utilities package, Voice SDK, and more, offering advanced rendering, social, and community-building capabilities and tools for creating immersive experiences (<https://developers.meta.com/horizon/documentation/unity/unity-import/> (accessed on 18 February 2025)). Notably, the package provides GameObjects (e.g., OVRCameraRig) and scripts (e.g., OVRManager), which are essential for enabling features such as passthrough and Mixed Reality Capture on Meta Quest headsets. By using Oculus Integration, the interaction of users with virtual objects in a real physical environment is optimized, implementing advanced technologies that enhance their experience.

When VR support is enabled in Unity, the headset automatically transfers head and positional tracking information to Unity, allowing the camera's position and orientation to align closely with the user's real-world position and orientation. The camera's transform

values are overridden by the head-tracked pose data, so the camera stays in a position relative to the user's avatar. In a standard first-person configuration, rather than relying on a fixed camera, the camera must move along with or track the user's avatar, as implemented in our application. This is achieved by making the camera a child object of the user avatar. In our application, we attached the `OVRCameraRig` script to the `OVRCameraRig` GameObject (<https://developers.meta.com/horizon/documentation/unity/unity-ovrcamerarig/> (accessed on 18 February 2025)).

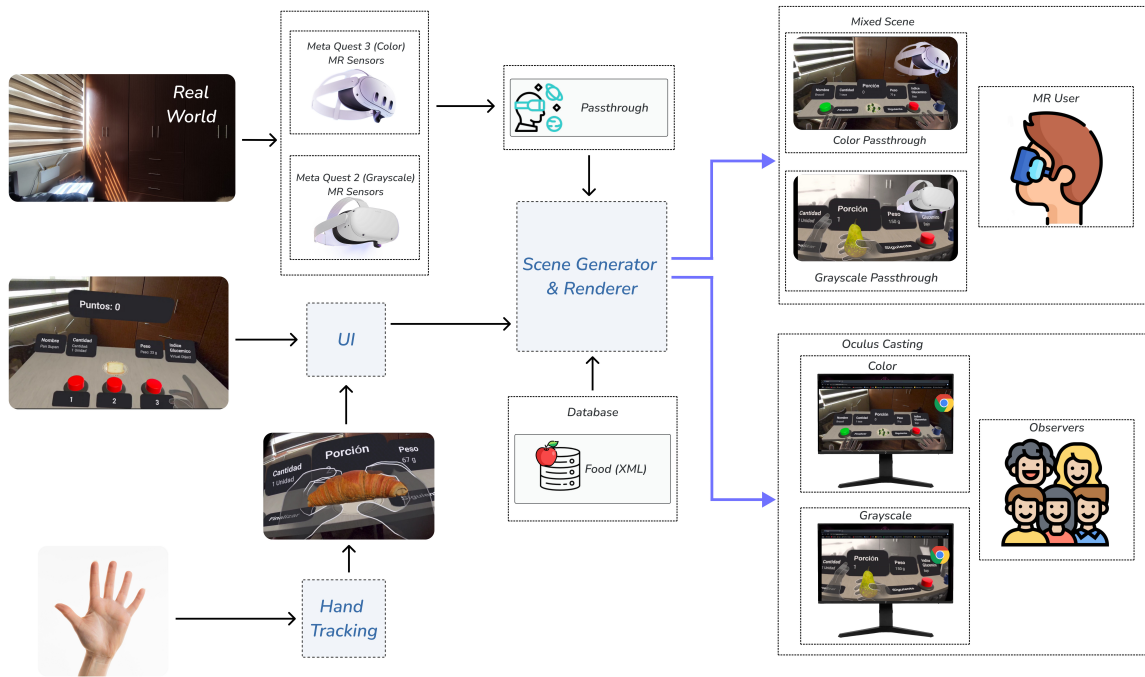


Figure 4.6: Architecture of the MR application.

The `OVRCameraRig` GameObject contains the Transform object that defines the tracking space for the headset. Within the primary child of `OVRCameraRig`, known as `TrackingSpace` GameObject, are several anchors: `RightEyeAnchor` and `LeftEyeAnchor` (which serve as anchors for each eye), `CenterEyeAnchor` (which serves as the anchor for the main Unity camera), and `RightHandAnchor` and `LeftHandAnchor` (which act as anchors for the controllers).

The `OVRManager` script is attached to `OVRCameraRig` GameObject and is a key part of the application development. This script facilitates the interaction between the hardware (Meta Quest 2/3) and our application, configuring and managing essential functions such as passthrough and Mixed Reality Capture. `OVRManager` script acts as an intermediary between our application and advanced viewer configurations, allowing the integration of the user's physical world with virtual elements. By enabling the `OVRManager` in our application, it is possible to do the following:

1. Control VR activation and user tracking: The `OVRManager` allows real-time adjustment of the user's position and rotation to ensure a smooth experience when interacting with virtual food in their physical environment.
2. Optimize visual quality and performance: Configure the graphic level and performance to make the experience as natural as possible, without interruptions or frame

drops.

Passthrough is an essential feature that is incorporated through the OVRManager by enabling the `isPassthroughEnabled` property. This feature allows the users to view their physical environment while interacting with overlaid virtual objects. With passthrough, users can do the following:

1. View their physical environment and manipulate virtual objects: When passthrough is enabled, patients can view their actual space, such as a table or their hands, while manipulating virtual food.
2. Interact safely: Passthrough allows the user to be aware of their physical environment, avoiding the risk of collision with real objects and making the experience safer.
3. Superimpose virtual elements on the real world: By viewing the physical world through passthrough, patients can directly compare virtual food with the real objects around them, improving their understanding of real-life portion sizes.

Mixed Reality Capture (MRC) is managed through the OVRManager, which activates its functionality by enabling the `useMixedRealityCapture` setting. MRC is used to capture the user's image with an external camera, synchronize the VR camera view with the real-world camera, and seamlessly blend the application environment with live video. In our application, MRC is used to capture and blend the user's environment with virtual elements, while Oculus Casting is a capability that enables the real-time streaming of the user's MR experience to an external display (e.g., a computer or laptop screen), allowing others to observe exactly what the user is experiencing in the mixed reality environment. This capability is essential for assessing and documenting the patient's interaction with the application, as it allows others to see exactly what the patient is seeing and doing. It is crucial for the supervisor to observe the patient's actions and assist if any issues arise and for healthcare professionals to monitor the patient's learning process. In our case, we use oculus.com/casting in a Chrome browser to display the MR experience.

In our MR application, the combined use of the OVRManager, passthrough, Mixed Reality Capture, and Oculus Casting provides a complete and immersive experience. For example, when selecting a virtual food, the passthrough feature enables the patient to see their hands as they pick up the virtual food and examine it within the physical environment. At the same time, Mixed Reality Capture blends the user's physical environment with virtual elements, and Oculus Casting streams the MR experience to an external screen so that other users can see what the user is seeing, for example, allowing healthcare professionals to analyze the patient's performance in real time. This approach facilitates learning about portion sizes, allowing users to compare virtual portions with their own perceptions and adjust their practice of managing carbohydrate choices in everyday situations. The AR application adapted for Ecuadorian patients [107] was used for comparison with the MR application. The foods included in the AR application were those recommended by the specialists who contributed to its design for Ecuadorian patients, and they were the same as those used in the MR application. The Meta Quest 2 and Meta Quest 3 were used for development and validation. Meta Quest 2 offers a resolution of 1832×1920 pixels per eye, up to a 90 Hz refresh rate, grayscale passthrough, and a 97-degree horizontal field of view. Meta Quest 3 features a resolution of 2064×2208 pixels per eye at a 90 Hz refresh rate, color passthrough, and a 110-degree horizontal field of view.

4.4.3 Participants

The study involved patients who participated in one of two activities organized by the Diabetes House, located in Cuenca and Portoviejo, Ecuador. The first activity was carried out in the facilities of the Diabetes House in Cuenca and Portoviejo (Ecuador) during a single session on a Saturday morning (10:00 to 12:00). The second activity was carried out in one session, on a Saturday during the whole day at the Diabetes House camp held in August. The Diabetes House (<https://casadeladiabetes.org.ec> (accessed on 18 February 2025)) offers therapeutic learning sessions and provides educational resources available on its website for individuals with Type 1 diabetes. Ninety-two patients with Type 1 diabetes, aged between 5 and 36 years (51 men and 41 women), from Ecuador were involved in the study, with a mean age of 15.78 ± 6.142 years old. The patients were divided into four groups. One group used a traditional learning method, with 25 patients with a mean age of 16.28 ± 6.67 . The other three were experimental groups: a first group used the AR application, with 27 patients with a mean age of 15.81 ± 5.91 ; a second group used the application of MR with Quest 2, with 20 patients with a mean age of 14.7 ± 5.69 ; and a third group used the application of MR with Quest 3, with 20 patients with a mean age of 16.2 ± 6.53 . The patients or their parents (for minors) were given information about the study, and informed consent was obtained prior to participation. The study followed the principles outlined in the Declaration of Helsinki and was approved by the Ethics Committee at the University of Cuenca (Ecuador).

4.4.4 Measures

Knowledge questionnaire: To evaluate the acquired knowledge about carbohydrate choices, a questionnaire was administered. In this questionnaire, the patients were asked to write the number of carbohydrate choices for nine different foods, taken from the 25 items displayed in the application. The nine food items included in the questionnaire are a slice of pizza, three Maria cookies, a slice of white bread, an apple, a banana, half an avocado, a glass of milk, six pieces of broccoli, and a lightly fried sunny-side up egg. Figure 4.7 presents an example of two food items that were part of the knowledge questionnaire. All of the foods featured in the questionnaire were part of the four different learning methods (traditional, AR application, MR application with Quest 2, and MR application with Quest 3), and patients were provided with information about the carbohydrate content of each food. The same questionnaire was administered at two different stages of the study to evaluate the knowledge level regarding carbohydrate choices (pre-test and post-test). Specifically, the pre-test was used to determine prior knowledge and the post-test was used to determine post-session knowledge with the four learning methods. Knowledge was scored based on the total number of correct answers, ranging from 0 to 9.

Subjective questionnaires: The following questionnaires were administered:

1. The Short-UEQ (User Experience Questionnaire) [94] comprises eight items rated on a 7-point Likert scale, divided into three variables: Hedonic Quality, Pragmatic Quality, and Overall Evaluation. We opted for the short version instead of the longer 26-item questionnaire to keep the session engaging and less tedious.
2. The Usability and Satisfaction Questionnaire consists of thirteen questions designed to assess the application's usability and overall satisfaction, using the same questions as referenced in [107]. Table 4.1 presents these questions.

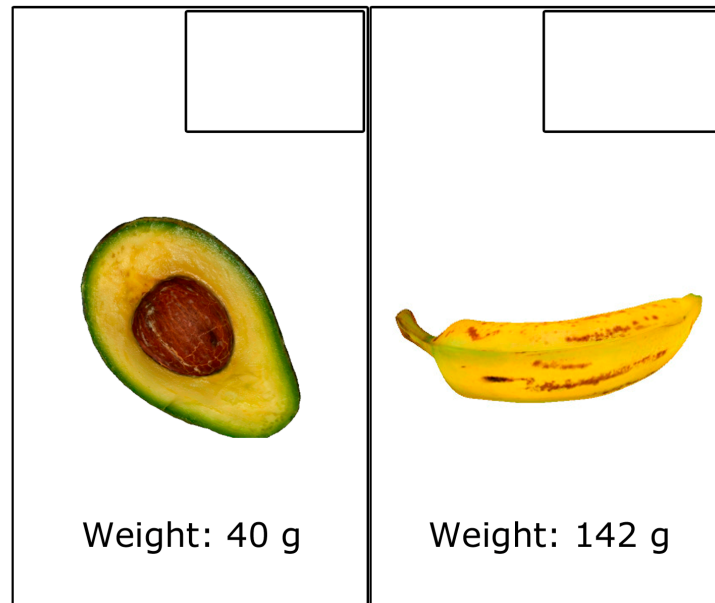


Figure 4.7: An example of two food items presented in the knowledge questionnaire. The participants were required to write the number of carbohydrate choices for each food by completing the top rectangle.

3. The Participant Data Questionnaire gathered demographic information from participants, such as age and gender.

Table 4.1: Usability and satisfaction questionnaire.

ID	Question Text
US#1	I found the application easy to use.
US#2	I have gotten used to the application quickly.
US#3	I have concentrated more on performing the task than on the interaction mechanisms.
US#4	I could get close enough to the food.
US#5	I could see the food from different positions.
SA#1	I have had a good time.
SA#2	I liked how the food looked on the dish.
SA#3	It seemed to me that the food on the dish could be real food.
SA#4	I think I have learned with this application.
SA#5	I would like to use these applications to learn more about diabetes.
SA#6	I would invite my friends to use the application.
SA#7	I would use this application again.
SA#8	Score the application from 1 to 5.

4.4.5 Protocol

The study followed a between-subjects design. This involved four separate groups (a control group that used traditional learning and three experimental groups). The three experimental groups used a mobile AR application, an MR application using Meta Quest

2 (grayscale passthrough), and the same MR application using Meta Quest 3 (color passthrough). The patients followed these steps:

- Complete the pre-knowledge questionnaire, filled out on paper with physical writing.
- Learn by using one of the four different learning methods (traditional, AR application, MR application with Quest 2, and MR application with Quest 3).
- Complete the post-knowledge questionnaire, also filled out on paper.
- Complete the remaining questionnaires (usability, satisfaction, and data questionnaires), all of which are filled out on paper.

In the traditional method, a nutritionist conducted the class as she typically does in her regular sessions. She presented the food items one by one and explained them, with the students taking notes during the lesson, but at this stage, they did not handle the food items. During the class, the nutritionist presented 2D color images of food at real size on plastic-coated paper and cropped to match the shape of each food item. The duration of the class was one hour. The nutritionist discussed the foods featured in the applications and presented all of the information included in the applications. All of the foods tested were also covered in the class. Additionally, the session covered other important concepts, such as the healthy plate. For instance, she demonstrated how to combine these foods to create a healthy meal. After explaining each food, there was a question-and-answer section where patients could ask questions. Some questions included: "Is it advisable to have five meals a day?", "Can I eat my healthy meal in parts?", and "How can I identify food choices that are not listed in the manual?". Patients further requested suggestions for meal preparation, including home-cooked recipes and alternatives to the manual. The nutritionist addressed all of the questions thoroughly. After the traditional class and before the knowledge assessment, patients were allowed to observe and handle the paper-printed food items for as long as they wished, typically spending up to 30 s per item. There was no limit on the number of rounds. Participants could spend as much time as they wanted with each food item and revisit them as many times as they wished.

The study was conducted in two parts. The first part was carried out in the facilities of the Diabetes House in Cuenca and Portoviejo (Ecuador) during a single session on a Saturday morning (10:00 to 12:00). The second part was carried out in one session, on a Saturday during the whole day at the Diabetes House camp held in August. Patients needed approximately 30 min to use the MR and AR applications, and fill out the questionnaires.

4.5 Results

To assess the normality of the variables, the Shapiro-Wilk test was conducted. The majority of them showed a non-normal distribution. Consequently, non-parametric tests were employed for the full dataset. The statistical results are shown as (*Mdn*: median; *IQR*: interquartile range), with all test outcomes reported as (*U* test: Mann-Whitney *U/W* test: Wilcoxon Signed-rank, *Z* value for normal approximation, *p*-value, *r* effect size). The results with a *p*-value below 0.05 are considered statistically significant and are emphasized in bold. The statistical analysis was performed using the R software package (<http://www.r-project.org> (accessed on 18 February 2025)).

4.5.1 Short-term learning outcomes

First, we checked whether the patients in the different groups learned using the learning method of their group (traditional, mobile AR application, MR application using Meta Quest 2, MR application using Meta Quest 3). The Wilcoxon Signed-rank test was applied to determine if patients showed learning improvements through the traditional method ($W = 0$, $Z = -4.396$, $p < \mathbf{0.001}$, $r = 0.622$). This analysis involved comparing the scores before the traditional learning session ($Mdn = 3.0$; $IQR = 4.0$) with those obtained afterward ($Mdn = 7.0$; $IQR = 2.0$). The Wilcoxon Signed-rank test was applied to evaluate whether students learned using the mobile AR application ($W = 0.0$, $Z = -4.526$, $p < \mathbf{0.001}$, $r = 0.616$). This analysis compared the scores from before ($Mdn = 4.0$; $IQR = 3.0$) and after using the AR application ($Mdn = 8.0$; $IQR = 1.0$). The Wilcoxon Signed-rank test was applied to evaluate whether students learned using the MR application with Quest 2 ($W = 0$, $Z = -3.917$, $p < \mathbf{0.001}$, $r = 0.619$). This analysis compared the scores from before ($Mdn = 4.0$; $IQR = 2.25$) and after using the MR application with Quest 2 ($Mdn = 7.0$; $IQR = 2.0$). The Wilcoxon Signed-rank test was applied to evaluate whether students learned using the MR application with Quest 3 ($W = 0$, $Z = -3.925$, $p < \mathbf{0.001}$, $r = 0.621$). This analysis compared the scores from before ($Mdn = 3.5$; $IQR = 3.0$) and after using the MR application with Quest 3 ($Mdn = 8.0$; $IQR = 2.0$).

Second, the Kruskal-Wallis test was applied to assess whether the patients' initial knowledge differed among the different groups (traditional, mobile AR application, MR application using Meta Quest 2, MR application using Meta Quest 3). This analysis revealed that there were no significant differences among the different groups ($d.f. = 3$, $H = 4.7155$, $p = 0.1939$).

Third, the Kruskal-Wallis test was applied to assess whether the knowledge after using the different learning methods (traditional, mobile AR application, MR application using Meta Quest 2, MR application using Meta Quest 3) differed between the different groups. This analysis revealed that there were significant differences among the different groups ($d.f. = 3$, $H = 17.061$, $p < \mathbf{0.001}$). For this reason, the different methods were compared two by two using Mann-Whitney U tests. The results of these tests are shown in Table 4.2. Significant differences were found for three of the comparisons: for learning between the traditional method and the mobile AR application, in favor of mobile AR application; for learning between the traditional method and the MR application with Quest 3, in favor of the MR application with Quest 3; and for learning between the MR application with Quest 2 and the application of MR with Quest 3, in favor of Quest 3. The means (standard deviations) of post-learning knowledge scores after using the different learning methods are shown in Table 4.3. The highest post-learning knowledge means, in descending order, are for MR Quest 3, Mobile AR, MR Quest 2, and Traditional.

Fourth, the Kruskal-Wallis test was used to assess whether the increase in knowledge (score after learning with the method minus the initial score) differed when using the different learning methods. This analysis revealed that there were no significant differences among the different groups ($d.f. = 3$, $H = 1.7449$, $p = 0.627$). The means (standard deviations) of knowledge increase after using the different learning methods are shown in Table 4.4. The highest knowledge increase means, in descending order, are for MR Quest 3, MR Quest 2, Traditional, and Mobile AR.

Figure 4.8 presents a box plot for the scores obtained by the patients before and after learning with the different learning methods. Figure 4.9 presents a box plot of the learning

Table 4.2: Mann-Whitney U tests were applied to compare the knowledge scores after using the different learning methods.

Method	<i>Mdn; IQR</i>	Method	<i>Mdn; IQR</i>	<i>U</i>	<i>Z</i>	<i>p</i>	<i>r</i>
Traditional	7; 2	Mobile AR	8; 1	172.0	-3.125	0.002	0.433
Traditional	7; 2	Quest 2	7; 2	184.5	-1.532	0.128	0.228
Traditional	7; 2	Quest 3	8; 2	100.5	-3.508	<0.001	0.523
Mobile AR	8; 1	Quest 2	7; 2	344.5	1.670	0.097	0.244
Mobile AR	8; 1	Quest 3	8; 2	229.0	-0.937	0.355	0.137
Quest 2	7; 2	Quest 3	8; 2	117.5	-2.321	0.021	0.367

Table 4.3: Means (standard deviations) of knowledge scores after using the different learning methods.

Traditional	Mobile AR	MR Quest 2	MR Quest 3
6.40 (1.50)	7.63 (0.97)	7.10 (1.21)	7.95 (0.83)

Table 4.4: Means (standard deviations) of knowledge increase after using the different learning methods.

Traditional	Mobile AR	MR Quest 2	MR Quest 3
3.68 (2.10)	3.63 (1.94)	3.75 (1.94)	4.2 (2.04)

gains with the different learning methods. From all of these results, we can conclude that the use of all four learning methods was effective for short-term knowledge transfer. The method that contributed to the most learning was the use of MR using Meta Quest 3.

4.5.2 User experience

After using the AR and MR applications, the patients completed the short-UEQ questionnaire, and their responses were analyzed using the UEQ Data Analysis Tool (<https://www.ueq-online.org> (accessed on 18 February 2025)). Three graphs were generated (Figure 4.10) using one of the downloadable Excel templates from UEQ to assess the quality of our MR and AR applications in comparison with the products included in the UEQ benchmark dataset [96]. The graphs indicate that the Mobile AR application and the two MR applications with Quest 2 and Quest 3 significantly outperform the UEQ benchmark. According to the interpretation guidelines in the UEQ tool and reference [96], the three applications rank in the top 10% across all three variables.

Mann-Whitney U tests were used to check whether the learning application affected the three UEQ variables. The results of the analyses and the pairwise comparisons are presented in Table 4.5. From these analyses, it can be observed that there are significant differences in favor of the MR application with Quest 3 and the AR application when compared to the MR application with Quest 2. Furthermore, considering the data included in Table 4.5, the results favor the experience with Quest 3.

Mann-Whitney U tests were used to check whether the learning application affected the

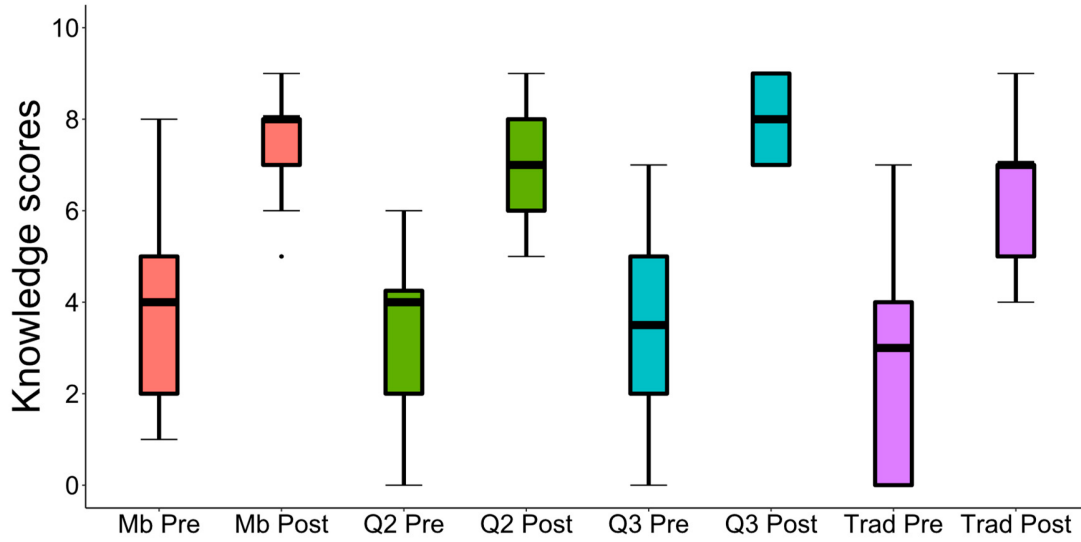


Figure 4.8: Box plot for the scores obtained by the patients before and after learning with the different learning methods. Abbreviations: Pre, initial score; Post, score after learning with the different methods; Mb, mobile AR; Q2, MR Quest 2; Q3, MR Quest 3, and Trad, traditional method.

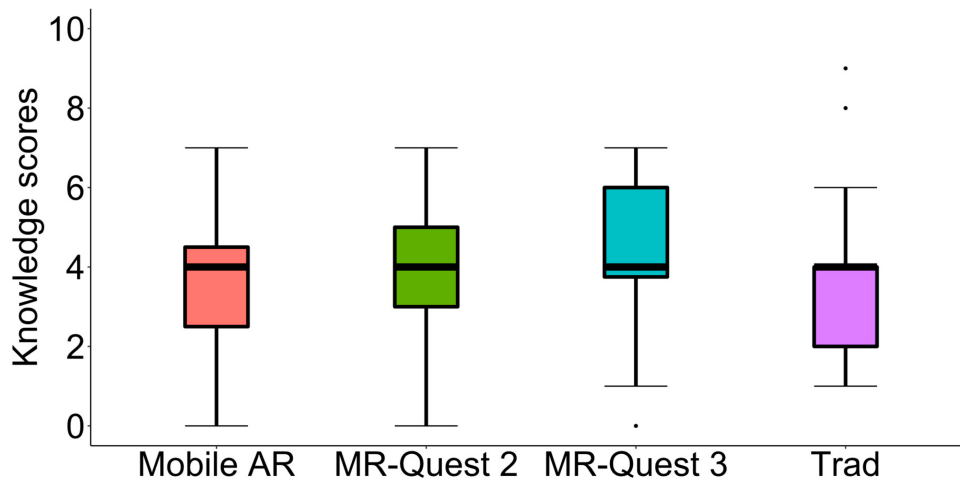


Figure 4.9: Box plot showing the learning gains with the different learning methods.

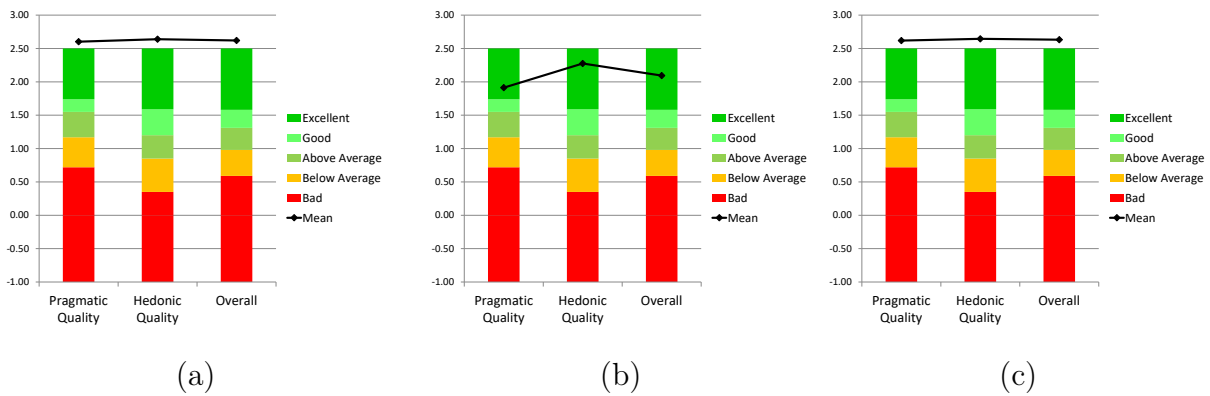


Figure 4.10: Comparison of the patients' responses after using the AR and MR applications with the benchmark data from the UEQ Data Analysis Tool. (a) Mobile AR application; (b) MR application with Quest 2; (c) MR application with Quest 3.

Table 4.5: Mann-Whitney U tests were applied to the three UEQ variables when using the three learning applications and comparing them two by two.

Variable	Application	<i>Mdn; IQR</i>	Application	<i>Mdn; IQR</i>	<i>U</i>	<i>Z</i>	<i>p</i>	<i>r</i>
Pragmatic Quality	Mobile AR	2.75; 0.375	Quest 2	2; 1.438	390.0	2.665	0.008	0.389
Hedonic Quality	Mobile AR	2.75; 0.5	Quest 2	2.5; 0.625	355.0	1.899	0.059	0.277
Overall	Mobile AR	2.75; 0.5	Quest 2	2.19; 0.69	380.5	2.420	0.016	0.353
Pragmatic Quality	Mobile AR	2.75; 0.375	Quest 3	3.0; 0.5	233.0	-0.574	0.574	0.085
Hedonic Quality	Mobile AR	2.75; 0.5	Quest 3	3.0; 0.5	236.5	-0.484	0.637	0.071
Overall	Mobile AR	2.75; 0.5	Quest 3	2.875; 0.56	237.0	-0.452	0.659	0.067
Pragmatic Quality	Quest 2	2; 1.4375	Quest 3	3; 0.5	101.0	-2.619	0.009	0.382
Hedonic Quality	Quest 2	2.5; 0.625	Quest 3	3; 0.5	121.5	-2.004	0.047	0.321
Overall	Quest 2	2.19; 0.69	Quest 3	2.875; 0.56	114.5	-2.176	0.031	0.348

usability and satisfaction questions listed in Table 4.1. After applying the test to the three applications compared two by two, it can be observed that in most of the tests, no significant differences were found. Significant differences were only obtained for three of these comparisons, which are shown in Table 4.6. From these analyses, it can be observed that there are significant differences in favor of the AR application when compared with the MR application with Quest 2 for US#2 and SA#4, and the MR application with Quest 3 for US#2. With regard to question US#2, "I have gotten used to the application quickly", the patients got used to the AR application more quickly given that a tablet was used and users are very familiar with devices of this type. With regard to question SA#4, "I think I have learned with this application", the patients believed they had learned more with the AR application than with the MR application with Quest 2, and, indeed, the learning results indicate that this was the case, although no statistically significant differences were found for such learning (Table 4.2).

Table 4.6: Mann-Whitney U tests were applied to the three usability and satisfaction variables when using the three learning applications and comparing them two by two.

Variable	Application	<i>Mdn; IQR</i>	Application	<i>Mdn; IQR</i>	<i>U</i>	<i>Z</i>	<i>p</i>	<i>r</i>
US#2	Mobile AR	5; 0	Quest 2	5; 1	347.5	2.257	0.025	0.329
SA#4	Mobile AR	5; 0	Quest 2	5; 1	346.5	2.062	0.041	0.301
US#2	Mobile AR	5; 0	Quest 3	5; 1	338.0	2.047	0.042	0.299

4.5.3 Gender and age

We applied the Mann-Whitney U test to assess whether gender had an impact on the patients' outcomes. The post-learning scores of women and men were compared across the traditional method, the AR application, and the MR applications with Quest 2 and Quest 3. No significant differences were found for any learning method considering gender (Table 4.7). Figure 4.11 shows box plots for the post-knowledge scores obtained by women and men after learning with the four different methods.

Table 4.7: Mann-Whitney U tests were applied to determine if gender affects the post-knowledge scores obtained using the traditional method, the AR application, and the MR applications with Quest 2 and Quest 3.

Method	Women (<i>Mdn</i> ; <i>IQR</i>)	Men (<i>Mdn</i> ; <i>IQR</i>)	<i>U</i>	<i>Z</i>	<i>p</i>	<i>r</i>
Traditional method	5; 4.5	7; 1	54.5	-0.525	0.621	0.105
Mobile AR	8; 1	8; 1	115.5	1.276	0.211	0.246
MR with Quest 2	7; 1	7; 3	41.0	-0.666	0.531	0.149
MR with Quest 3	8; 0.75	7.5; 1.75	60.5	0.842	0.423	0.188

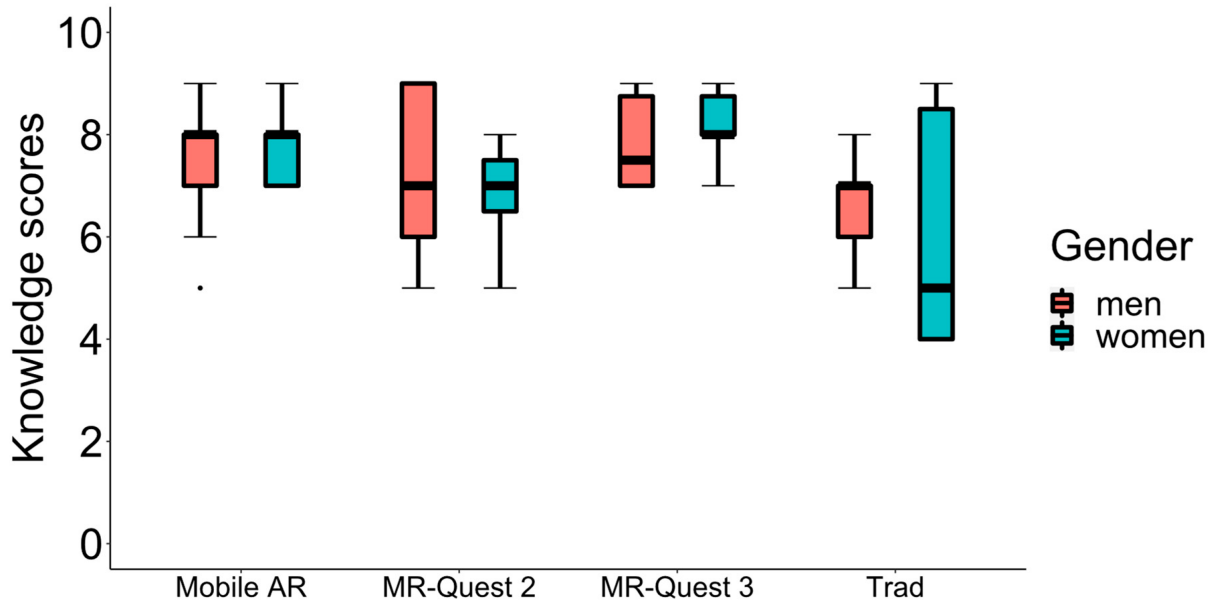


Figure 4.11: Box plots of post-knowledge scores for men and women after learning with the four learning methods.

The Mann-Whitney U tests were applied to determine if gender affected the UEQ, the satisfaction and usability variables for the three different applications. All of these variables were compared for women and men. No significant differences were found in any of the analyses and they are not included in this publication.

To assess whether age had an impact on the post-learning questionnaires completed by the patients, the Kruskal-Wallis tests were conducted (Table 4.8). Kruskal-Wallis tests were also applied to evaluate if age influenced the UEQ, as well as the usability and satisfaction variables. No significant differences were found in any of the analyses and they are not included in this publication.

Table 4.8: Kruskal-Wallis tests were applied to the post-knowledge scores considering age.

Method	d.f.	H	p
Post-test Traditional	12	14.992	0.242
Post-test AR application	15	9.703	0.838
Post-test MR-Quest 2	14	9.236	0.816
Post-test MR-Quest 3	15	15.286	0.431

4.5.4 Correlations

For clarity and relevance, only the correlations that offer valuable insights have been included in this section. Table 4.9 shows the correlation among some of the variables using data from all of the patients who used the AR, MR with Quest 2, and MR with Quest 3 applications. Table 4.9 also indicates the only significant correlation obtained when analyzing all of the experimental groups separately. Similarly, four additional correlations are indicated where the use of Quest 2 and Quest 3 provided significant correlations.

Table 4.9: Correlation matrix among some of the variables using data from all of the patients who used the AR, MR with Quest 2, and MR with Quest 3 applications. Notes: Significant correlations with a p -value below 0.05 are emphasized in bold. The superscript 'a' indicates that a correlation was found in all groups analyzed separately for these two variables. The superscript 'q' indicates that a correlation was found in the groups that used Quest 2 and Quest 3, analyzed separately for these two variables. Abbreviations: know, knowledge. The abbreviations of the other variables are shown in Table 4.1.

Variables	Know	SA#1	US#1	US#2	US#3	SA#4	SA#5	SA#6
SA#1	-0.03							
US#1	0.28	0.29						
US#2	-0.10	0.46	0.39					
US#3	0.17	0.34	0.44^q	0.44^a				
SA#4	0.12	0.29	0.36^q	0.34	0.35^q			
SA#5	0.18	0.25	0.27	0.33	0.47	0.46		
SA#6	-0.11	0.23	0.11	0.38	0.14	0.32	0.36	
SA#7	-0.13	0.41	-0.06	0.22	0.11	0.35	0.34	0.52^q

4.6 Discussion

In this publication, we present the first MR application that uses both grayscale and color passthrough to assist TED and aid patients in learning how to count carbohydrates. Our MR application blends virtual food, specifically designed for patients in Ecuador, into a real environment. Diet management plays a vital role in maintaining overall health, and for individuals with diabetes, controlling food intake is essential [23]. The amount of insulin needed is directly affected by the quantity of carbohydrates ingested during meals. Thus, understanding the carbohydrate content in food enables patients to better manage their condition autonomously and to enhance their glycemic control. While our study did

not assess the impact of the application on patients' glycemic control, this remains a key area for future research.

Our application exploits MR technology to enhance the learning experience in a way that traditional methods cannot. While the task of associating a number with a food item to indicate the amount of carbohydrate choices may seem simple, the use of MR offers several key advantages that enhance the learning experience. The immersive nature of MR increases participant engagement and attention, which can lead to better retention and understanding of the knowledge. Additionally, MR facilitates more realistic and dynamic interactions with 3D models of food items, providing a lifelike experience that helps participants better contextualize and transfer their learning to real-world situations. This interaction strengthens the ecological validity of the learning process, ensuring that the skills learned are more readily applicable in real-life contexts. The use of passthrough technology further enhances the experience by seamlessly blending virtual elements with the real environment, something that traditional 2D images or simpler learning methods cannot achieve.

Incorporating MR technology, the Meta Quest 3 introduces hardware advancements that further enhance user immersion. Meta Quest 3 has higher resolution and a larger field of view that enhances the immersive user experience. However, with respect to MR, a key improvement in the Meta Quest 3 is its color passthrough, which offers a significantly enhanced experience. This improvement is not only due to the addition of color but also the increased image stability. On the other hand, with the Meta Quest 2, image distortion begins below 0.6 m [23]. While distortion still occurs with Meta Quest 3, it only appears at much closer distances, such as when a hand is brought close to the face or the headset is near a real table. Meta Quest 3 remains stable at distances of over 40 cm. The distance used by users for food handling is usually greater than this distance. If users picked up the food and brought it close to their faces, they could perceive this distortion even when using Meta Quest 3. Another advantage of Meta Quest 3 over its predecessor, Meta Quest Pro, is that the Meta Quest 3 controllers use replaceable batteries, similar to those of Meta Quest 2. In contrast, Meta Quest Pro uses self-recharging controllers, which have been reported to cause problems in previous works [24].

In our research, even though we track the learning process, the application is designed for independent use at any time and location, providing greater flexibility in learning, as noted in other studies [13]. Moreover, previous research also indicates that flexible, technology-driven methods could effectively engage younger audiences [99].

To evaluate the practical implications of our MR-based application, we conducted a study comparing the effectiveness of short-term learning of carbohydrate choices using Meta Quest 3, Meta Quest 2, mobile AR, and traditional methods. The significant differences in the knowledge of patients before and after using the four learning methods indicate that all four methods have been effective for knowledge transfer. When comparing the different learning methods two by two to assess the post-learning knowledge scores, it was observed that the MR application using Meta Quest 3 and the mobile AR application significantly outperformed the traditional method. The patients using the MR application with Meta Quest 3 also learned significantly more than those using Meta Quest 2. There were also greater learning outcomes than those using the mobile AR application. Considering all of the data shown in Table 4.2, the learning methods can be ranked in order of effectiveness: MR using Meta Quest 3, the mobile AR application, the MR with Meta Quest 2, and the

traditional method. Considering the data from Tables 4.3 and 4.4, Meta Quest 3 is the method that yields the best results.

The potential demonstrated by the MR applications aligns with previous research on AR applications, which has shown that mobile AR applications can enhance the learning process [13], [53]. Furthermore, studies comparing AR applications with traditional learning methods did not reveal any statistically significant differences in learning outcomes [13], suggesting that both approaches can be at least equally effective under certain conditions. Additional research, such as that by Chiang et al. [78], found that groups using mobile AR applications achieved significantly higher average learning outcomes compared to non-mobile AR applications, which is consistent with our findings.

A limitation of our study is that the post-learning knowledge scores for MR Quest 3 are heavily concentrated at the upper end of the scale, with a considerable proportion of participants achieving the maximum score of 9. Specifically, 30% of participants achieved the highest possible score of 9, while 35% scored 8, which is also near the top of the scale, and the remaining 35% scored 7. In contrast, only 8% of participants in the traditional group, 14% in the mobile AR group, and 15% in the MR Quest 2 group scored 9. The clustering of scores at the upper limit for MR Quest 3 suggests the presence of a ceiling effect, which occurs when the measurement tool lacks sufficient range to capture further differences in participants' performance. As a result, participants who reach the maximum score are unable to demonstrate higher levels of knowledge, even if such improvements are possible. This reduces the ability to detect true differences between the groups or methods, as many participants are already at the highest possible score. In the case of MR Quest 3, the high concentration of scores at the maximum (9) implies that once participants reach this ceiling, any further knowledge gains cannot be captured by the assessment. Consequently, although MR Quest 3 shows the highest post-learning score mean (7.95), the ceiling effect likely limits the detection of additional improvements in knowledge. Furthermore, statistical analysis of the learning gains (post-pre) does not reveal significant differences between methods, reinforcing the notion that the ceiling effect may have masked any further potential improvements in knowledge for participants using MR Quest 3. In conclusion, while MR Quest 3 demonstrates the highest post-learning knowledge scores, as well as the highest medians and means, the ceiling effect may have influenced the results, potentially limiting the ability to capture further improvements in knowledge. Nonetheless, these findings highlight the effectiveness of the method compared to others. In any case, to address this limitation, future studies could consider increasing the number of questions in the questionnaire to allow for a greater scoring range, which would provide more capacity to capture further knowledge improvements and reduce the potential for a ceiling effect.

All four of the learning methods were effective in increasing knowledge (post-scores), regardless of gender or age. However, the role of gender in learning outcomes and preferences remains a debated issue. The findings of this study align with the broader, mixed results reported in the literature. Numerous studies have explored gender differences in learning outcomes and preferences within immersive environments like VR, AR, and MR, yet no consensus has been reached. For instance, some research indicates gender-based disparities in attitudes and performance. Studies in VR environments, found men reporting more positive attitudes [108] or outperforming women in specific tasks [109]. Similarly, in AR-based studies, differences in spatial abilities [110] and preferences have been observed, with some results favoring men in terms of spatial abilities and others favoring women

with regarding preferences [111], [112]. Conversely, other research highlights the absence of significant gender differences in performance within both VR (e.g., [113], [114]) and AR environments (e.g., [115]), as well as in AR acceptance [116]. Furthermore, studies in MR contexts, such as Petrusse et al. [117], have consistently reported no significant impact of gender on academic performance. The inconsistent findings across these studies suggest that the influence of gender may be context-dependent, varying with the specific tasks, technologies, and educational settings involved. Our results contribute to this ongoing discourse by examining gender as a potential factor influencing learning outcomes and preferences. Considering the complexity and variability of previous findings, further research is needed to better understand the relationship between gender and the use of immersive technologies in educational settings, aiming to achieve gender equality in outcomes.

Usability has been widely recognized as a key factor in enhancing educational effectiveness [81]. Sun et al. [82] suggest that user-friendly systems allow learners to focus more deeply on the content. In our study, patients evaluated their experience on the Short-UEQ questionnaire as excellent, with scores placing our applications within the top 10% across all three benchmarked UEQ variables [96]. These findings suggest that the MR and the AR applications effectively support patients in concentrating on learning about carbohydrate content in different foods. However, when comparing the three applications two by two (Table 4.5), the MR with Quest 3 and the AR applications provide significantly better ratings than the MR application with Quest 2. When comparing AR and MR with Quest 3, no statistically significant differences are observed, but patients rated the MR experience with Quest 3 better.

With regard to the correlations (Table 4.9), it is worth mentioning that the number of significant correlations differs when using the entire sample compared to analyzing the correlations within the three experimental groups. A higher number of correlations are observed when the entire sample is analyzed together. The relatively small sample size in each group could reduce the statistical power to detect significant correlations. As a result, in the separate group analyses, only the strongest correlations may be detected, and many potential relationships between variables might go unnoticed due to data variability and the smaller number of participants. This could be further explored in future studies with larger sample sizes to gain a deeper understanding of these relationships. In light of this, the analysis of the correlation matrix reveals several significant findings. A total of twenty-three correlations are statistically significant when using the sample of the three experimental groups, indicating meaningful relationships among variables. One of these significant correlations is between the knowledge acquired after using the applications (know) and ease of use (US#1). This suggests that when users interact with these technologies, the ease of use enhances their learning process. However, when the samples are analyzed separately, this correlation is not observed. As mentioned above, this correlation could be further explored in future studies with larger sample sizes. Notably, the correlation between "I have adapted quickly to the application" (US#2) and "I have focused more on the task than on the interaction mechanisms" (US#3) is significant across all of the three groups analyzed separately. This suggests that participants who adapt more quickly to the different applications tend to focus more on the task itself, rather than on the interaction mechanisms. Furthermore, according to Table 4.9, in addition to the above correlations, there are four other significant correlations when the groups that used Quest 2 and Quest 3 are analyzed separately. They are as follows:

- Correlation between "I have focused more on the task than on the interaction mechanisms" (US#3) and "The application is easy to use" (US#1). This significant correlation suggests that users who find the MR applications easy to use are more likely to focus on the task rather than on the mechanisms of interaction. This implies that ease of use may lead to a smoother, more intuitive experience, allowing users to concentrate on the primary objective of the application instead of struggling with interaction.
- Correlation between "I believe I have learned from this application" (SA#4) and "The application is easy to use" (US#1). This significant correlation indicates that participants who found the MR applications easy to use were more likely to report having learned from it. This suggests that a seamless and intuitive user experience not only improves usability but also fosters a greater sense of learning. When users can easily interact with the application without frustration, they may feel more engaged and confident in the educational process, ultimately leading to a more positive perception of their learning outcomes.
- Correlation between "I believe I have learned from this application" (SA#4) and "I have focused more on the task than on the interaction mechanisms" (US#3). This significant correlation suggests that when users concentrate more on the task rather than the interaction mechanisms, they are more likely to report having learned from the MR applications. This reinforces the idea that sustained focus on the content rather than on how to interact with the technology may enhance the learning experience. If users are not distracted by the mechanics of the applications, they can engage more deeply with the educational material, leading to the belief that better learning outcomes have been achieved.
- Correlation between "I would use this application again" (SA#7) and "I would invite my friends to use this application" (SA#6). This significant correlation indicates that users who are willing to use the applications again are also more likely to recommend it to others. This relationship highlights the importance of user satisfaction and the likelihood of positive word-of-mouth. When users have a good experience and feel that the application is valuable, they are not only motivated to continue using it but also eager to share it with others. This kind of user engagement is crucial for the long-term success and widespread adoption of educational applications.

These correlations suggest that the ease of use, task focus, and overall user satisfaction play a vital role in enhancing the learning experience and encouraging continued use and recommendation of the MR applications. These findings emphasize that a positive user experience in using the Quest 3 or the Quest 2 is closely linked to both the perceived effectiveness of the applications and its potential for sustained engagement. In conclusion, our MR-based approach adds significant value by creating a more engaging, context-rich, and interactive learning environment, which favors effective learning.

Finally, the current and expected advancements in AR, MR, and robotics point to a wide range of opportunities for developing new tools for TED. The potential to develop immersive, interactive, and impactful educational tools for therapy has never been more promising.

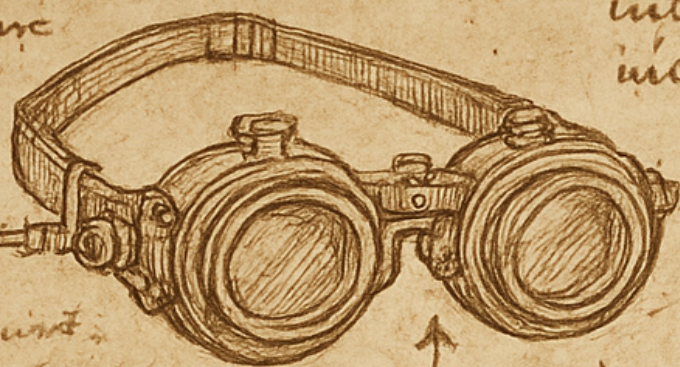
4.7 Conclusions

This publication presents an MR application that utilizes grayscale and color passthrough, developed to support therapeutic education for diabetic patients. A study was conducted to assess the effectiveness of the MR application in transmitting knowledge, as well as its usability and user satisfaction, comparing its two visualization modes with AR and traditional methods. The results show that patients' knowledge about short-term carbohydrate choices increased significantly across all four learning methods. However, the patients using the MR application using Meta Quest 3 achieved the highest post-learning outcomes. Additionally, those using the MR application using Meta Quest 3 provided significantly more positive feedback compared to those using the MR application using Meta Quest 2. This suggests that, given that the application itself is identical, the use of color passthrough had a positive impact on both learning and user experience. These findings highlight the growing potential of technology in educational contexts. In an increasingly digitalized society, interest in technology-mediated learning continues to grow, offering a valuable complement to traditional education and positioning it as an appealing and effective instructional approach.

Regarding the MR application, a possible improvement would be to replace the virtual table with a real physical table and a real dish, while keeping only the food and additional information virtual. Finally, MR applications using headsets have great potential, as the activity can be performed anywhere and at any time. The user remains fully connected to reality at all times. In this publication, we have explored the potential of MR for therapeutic diabetes education by comparing it with other learning methods. However, our MR application could be used in other studies in the future.

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Chapter 5

Discussion

5.1 Introduction

This doctoral thesis, structured as a compendium of publications, presents a research trajectory focused on the design, development, validation, and comparative evaluation of advanced technological solutions, specifically AR and MR as tools for TED. One of the objectives of this thesis has been to improve patients' knowledge of carbohydrate counting, a fundamental skill for effective self-management of the disease. The research progressed from the design, development, and validation of an AR application to comparative studies involving different immersive modalities and traditional teaching methods.

The purpose of this discussion section is to synthesize the main findings derived from the three publications that constitute this compendium of articles, interpret their collective contribution to the field of TED, critically evaluate the strengths and limitations of the thesis as a whole, and identify the implications for future lines of research and potential clinical/educational practice.

To provide context for the discussion, Table 5.1 presents a comparative summary of the key elements from each of the three publications included in this thesis.

5.2 Extended reality for therapeutic education in diabetes

In this thesis, we present an innovative application to support therapeutic education for patients with diabetes. The application has three versions. The first was designed for mobile devices and included food items relevant to Spanish patients. The second, also mobile-based, adapted the content for Ecuadorian patients. The third MR version was developed for headset use. Although the core application remains unchanged, the passthrough experience varies depending on the device: Meta Quest 2 supports only grayscale passthrough, while Meta Quest 3 enables full-color passthrough. The mobile AR application runs on devices familiar to users of all age groups, particularly younger individuals, leveraging the widespread adoption of smartphones and tablets throughout the population. A 2023 survey involving 10,000 early adopters aged 15 to 69, who use smartphone AR apps and/or VR/AR/MR headsets or intend to do so within the next five years, revealed that the smartphone is the primary entry point for most AR experiences,

Table 5.1: Key elements of the three publications included in this thesis

Publication 1/Study 1
Objective: Design, develop and evaluate an AR application to learn carbohydrate counting. Technology: AR (Android, Unity, Vuforia) Population: 70 children (5-14 years) with Type 1 diabetes, Spain Comparison: Group A vs. Group B (different post-test) Finding (Learning): Significant knowledge improvement vs. pre-test, independent of age/gender. Finding (User experience): High satisfaction and usability (4-5/5), better in younger children. Limitations: Short-term learning only, no comparison with other methods, single environment.
Publication 2/Study 2
Objective: Evaluate effectiveness of adapted AR application and compare with traditional method and Spanish study. Technology: AR (Android, Unity, Vuforia; adapted to Ecuador) Population: 27 patients (5-28 years) with Type 1 diabetes, Ecuador Comparison: Traditional session vs. AR (within-subject); comparison with study1 Finding (Learning): AR better than traditional retention at 2 weeks. Finding (User experience): Excellent user experience, no effect of age/gender. Limitations: Small sample; no glycemic control assessment; difference in application versions.
Publication 3/Study 3
Objective: Evaluate MR app (grayscale/color) vs. AR and traditional method. Technology: MR (Meta Quest 2-3), mobile AR, traditional method Population: 92 patients (5-36 years) with Type 1 diabetes, Ecuador Comparison: Traditional vs. AR vs. Grayscale MR vs. Color MR Finding (Learning): All improved; Color MR > AR > Grayscale MR > Traditional. Finding (User experience): AR and MR surpassed UEQ benchmark; Color MR better than Grayscale MR. Limitations: Possible ceiling effect; small groups; no glycemic control assessment.

especially among younger users [118]. These findings reinforce that smartphones, widely adopted across age groups, are the leading platform for mobile AR applications.

The MR application blends virtual food, specifically designed for patients in Ecuador, into a real environment. By using MR, the application offers a learning experience that surpasses the capabilities of conventional educational approaches. Although identifying the carbohydrate choices of a food item might appear simple, MR introduces several critical

enhancements. Its immersive format draws users in, fostering greater concentration and engagement, factors closely linked to improved comprehension and memory retention. MR also enables users to interact dynamically with three-dimensional food representations, offering a more tangible and realistic learning scenario. Such interaction enhances the ecological validity of the learning process by aligning the training environment more closely with real-world conditions, thereby improving the practical applicability of the acquired skills. Furthermore, passthrough functionality merges digital and physical elements in real time, creating a cohesive environment that goes beyond the limitations of flat images or traditional learning techniques. The Meta Quest 3 integrates notable hardware upgrades that enhance the MR experience, particularly in terms of immersion. One of its standout features is the improved color passthrough, which significantly enhances realism, not merely through color fidelity, but also through better image stability. While the Meta Quest 2 exhibits visual distortion at distances under 0.6 meters [23], the Meta Quest 3 maintains clarity down to approximately 40 cm. Distortion on the Quest 3 only occurs when objects, such as a user's hand or a nearby surface like a table, are extremely close to the headset. This should not be a problem in our application, as typical food-handling distances exceed that threshold. Another practical advantage of the Quest 3 and Quest 2 is their use of replaceable batteries in the controllers, which offers greater convenience and reduces downtime compared to the Meta Quest Pro. The Pro headset relies on built-in rechargeable controllers, which have previously been associated with reliability issues in real-world use [24]. Improvements in resolution and field of view specifically in the Quest 3 further elevate the immersive visual experience, solidifying its role as a more advanced and effective tool for MR-based applications.

In the studies conducted in this thesis, the use of the application during the learning process was supervised; however, the application is designed for autonomous use, allowing users to access it anytime and anywhere, offering a high degree of flexibility, as highlighted in prior research [13]. Furthermore, earlier studies have shown that technology-enabled, adaptable learning formats are particularly effective in capturing the interest of younger users [99].

5.3 Effectiveness of extended reality technologies in knowledge acquisition

A key result repeated across the three studies is the positive and significant impact of the developed applications on patients' short-term knowledge about carbohydrate choices. The initial AR application demonstrated significant learning gains in children with diabetes compared to their baseline knowledge. This effectiveness was confirmed again in a different cultural context (Ecuador) and across a wider age range (children and adults), where the AR application not only significantly surpassed initial knowledge but also a traditional educational session led by a nutritionist in terms of short-term outcomes. The third study further reinforced this evidence, showing that AR, as well as MR in grayscale and MR with color passthrough, led to significant improvements in post-intervention knowledge.

When comparing extended reality technologies with traditional educational methods, the AR application produced significantly better short-term knowledge transfer than the traditional class. Likewise, the use of AR and MR with color passthrough was associated with significant improvements in post-learning scores compared to the traditional

approach. Although grayscale MR also showed improvement, its significant superiority over the traditional method was not explicitly established, unlike AR and color MR, which demonstrated clear advantages. These results suggest that, at least in the short term, interactive AR and MR applications are more effective than traditional didactic methods for this type of knowledge. All of this corroborates the hypothesis GH1.

The consistency of significant improvements in short-term learning, with different application versions, populations, and comparison methods, reinforces the robustness of the observed effect. That the effect holds despite changes in technology, user profiles, cultural context, and comparison methods suggests that these tools are reliable for improving short-term carbohydrate knowledge in the studied contexts.

Furthermore, the direct comparisons in studies 2 and 3 and consistently show how AR (and color MR) outperforms traditional teaching in short-term knowledge acquisition. This implies that the interactive, engaging, and visually intuitive nature of these technologies facilitates more effective information encoding for short-term recall compared to passive listening or viewing 2D images.

5.4 Comparative performance of different extended reality technologies (AR vs. MR)

This thesis provides relevant information on the advantages of different technologies. While the first two studies focused on validating mobile AR, the third study provided a direct comparison between mobile AR, headset-based MR with grayscale passthrough (Meta Quest 2), and MR with color passthrough (Meta Quest 3). The results indicated that, while all applications were effective, the MR application with color passthrough achieved better post-learning outcomes than grayscale MR and mobile AR.

This suggests that the level of immersion and the quality of integration with the real world (passthrough) can affect learning effectiveness. A more realistic context with color passthrough, enhanced sense of presence, and improved cognitive processing leads to better knowledge acquisition compared to less immersive AR or visually less engaging grayscale MR. These observations highlight the benefits of investing in higher-quality MR experiences for education, although this needs to be balanced with hardware accessibility and cost.

The superiority of color passthrough MR over grayscale MR and AR suggests that the *quality* of the experience matters for learning outcomes in this context. AR superimposes digital information onto the real world via a screen, while MR using passthrough aims to blend the digital and real worlds more seamlessly in the user's direct view. Showed that color MR produced better learning outcomes than grayscale MR and AR. Given that the main difference between color MR and grayscale MR is the quality of the real-world representation (passthrough), and AR (mobile) offers a less immersive view compared to headset-based MR, it suggests that providing higher fidelity in the experience of the real and virtual (as in color passthrough MR) correlates with better learning outcomes in this specific task. This could be due to a greater sense of presence, lower cognitive load when switching between views, or increased engagement.

It is worth noting the possible presence of a ceiling effect in the color passthrough MR group regarding the knowledge variable. Although this group achieved the best results,

the ceiling effect might have underestimated the true difference between color MR and other methods, as the assessment was not challenging enough for the best-performing participants. A ceiling effect occurs when a test is too easy for a significant portion of participants, preventing the score from accurately reflecting their true skill level or the full extent of their learning. This implies that the measured improvement of color MR might be *less* than its actual improvement, as some participants could have scored even higher if the test had allowed. Future studies comparing these technologies might require more challenging tests to more clearly assess the effectiveness of color MR.

5.5 Mid-term knowledge retention

Although short-term learning gains were consistent, results on long-term retention are less conclusive in this work. The first study only assessed short-term recall. The second study included a mid-term assessment two weeks after the AR intervention. It found "suggestively significant" retention ($p = 0.044$) compared to baseline, indicating some knowledge was retained. However, there was also a statistically significant decrease in knowledge compared to the immediate post-test ($p < 0.005$), suggesting some decay within just two weeks.

The second study also revealed that knowledge gained in the traditional session was not maintained after one week, suggesting that, although there was some decay, AR might promote better retention than traditional methods in the mid-term. The third study focused on immediate post-learning effects and did not report retention data. This suggests that although immersive technologies are effective for facilitating initial learning, their mid-term impact on knowledge retention is less clear and should be further explored, possibly by integrating reinforcement mechanisms or revised instructional approaches.

5.6 User experience (usability and satisfaction)

A consistent strength across the studies is the positive user experience with the applications. Children reported high satisfaction and usability with the first AR application. This positive response was replicated in the second study with Ecuadorian patients (children and adults), where the adapted AR application achieved excellent ratings on the Short-UEQ, placing in the top 10% of the benchmark for pragmatic and hedonic quality, in addition to high usability and satisfaction scores.

Similarly, the third study showed that MR applications (grayscale and color) and AR significantly surpassed the UEQ benchmark. All of these results corroborate hypothesis GH2. Interestingly, the third study revealed differences in user experience between immersive technologies: color passthrough MR (Quest 3) and the mobile AR application received significantly better user experience ratings than grayscale MR (Quest 2). This suggests that users are sensitive to the quality and modality of the immersive experience. Furthermore, the third study identified positive correlations between ease of use and knowledge acquisition, and between quickly adapting and focusing on the task, highlighting the potential link between good usability design and effective learning.

Consistently high user experience ratings across different platforms (mobile AR, MR headsets), populations, and cultural contexts suggest that immersive technologies are generally well-received and perceived as engaging for this educational purpose. However,

the differences found (Color MR/AR > Grayscale MR) indicate that user experience is not uniform across all immersive technologies and can be a key differentiator, potentially influencing learning indirectly. The consistency in high ratings (medians 4-5/5 in the first study, top 10% UEQ benchmark in the second study, surpassing UEQ benchmark in third study) suggests a general positive response to the interactive and immersive approach compared to traditional methods (though traditional user experience was not measured). Nevertheless, the significant user experience differences within immersive technology found in the third study imply that factors like visual fidelity (color vs. gray passthrough) or platform (mobile vs. headset) can significantly impact user perception. The correlation between ease of use and learning suggests user experience is not solely about enjoyment, but can directly support learning by reducing cognitive effort and increasing engagement.

In the first study was observed that younger children reported higher satisfaction and usability than older children. Although the second and third studies found no overall significant effect of age on user experience in their broader age ranges (5-28 and 5-36 years, respectively), the initial finding might suggest that the specific application design or AR novelty could be slightly more appealing to younger users, or that expectations differ with age.

5.7 Influence of demographics and context

The thesis demonstrates the broad applicability of these immersive educational tools. Studies consistently showed that learning outcomes were independent of gender and mostly independent of age, benefiting both children and adults. This suggests that AR and MR applications are robust against these demographic variables.

Furthermore, the successful validation of AR, initially in Spain and later in Ecuador, demonstrates cross-cultural applicability, provided the content is appropriately adapted (e.g., local foods, language, carbohydrate choices definitions). The results indicate that Ecuadorian children reached similar knowledge levels to Spanish children, despite starting from different baselines, which further reinforces the effectiveness of the adapted AR tool in different contexts.

In the second study, the AR application allowed Ecuadorian children (with significantly higher initial knowledge) to reach a final knowledge level statistically similar to that of Spanish children, suggesting an equalizing effect of the tool. The AR application might help those with less prior knowledge catch up more quickly, while also reinforcing learning in those starting from a higher baseline, leading to similar final knowledge levels. This supports the tool's potential to provide standardized education across diverse populations.

5.8 Interpretation of the collective contribution

This thesis demonstrates the feasibility, effectiveness, and acceptance of AR and MR technologies for a key aspect of TED: carbohydrate counting. It goes beyond theoretical potential to provide empirical evidence with three studies involving target users.

The thesis analyses the comparative effectiveness of different technological modalities. From the validation of AR to direct comparisons between AR, grayscale MR, color MR, and traditional methods, the results suggest that, although AR is effective and accessible

(mobile), the higher-quality MR, especially with color passthrough, offers better learning outcomes and user experience. These findings could guide technological decisions in the design of future educational interventions.

Furthermore, the thesis highlights the importance of user-centered design when implementing health education technology. The high usability and satisfaction ratings, along with the correlation between ease of use and learning outcomes, suggest that engagement and interaction are key factors contributing to their effectiveness over traditional methods. This reinforces the transition toward more patient-centered, engaging learning models with greater potential for technology-facilitated self-learning.

This thesis follows a coherent progression in evaluating educational technologies: from the initial validation of AR, through its comparison with traditional methods and adaptation to different cultural contexts, to a comparative study with emerging technologies like MR.

The research advances from the design, development and validation of a first AR application, to its adaptation and comparison with traditional methods in other contexts, and finally its contrast with emerging technologies such as MR. This structured progression allows for incremental evidence gathering and addressing increasingly complex questions about effectiveness and technological design.

5.9 Strengths and limitations

5.9.1 Strengths

- **Multi-study approach:** The thesis presents three distinct studies that share and expand upon their conclusions, thereby strengthening confidence in the findings.
- **Direct comparisons:** The thesis includes direct comparisons between different immersive technologies (AR vs. MR, grayscale MR vs. color MR) and between immersive technologies and traditional educational methods.
- **Emphasis on user experience:** The inclusion of validated user experience metrics (satisfaction, usability, UEQ) provides relevant insights into user acceptance.
- **Cross-contextual relevance:** Adaptation in different cultural contexts (Spain, Ecuador) and age groups (children, adults) allows for the generalization of findings.
- **Technological progression:** The thesis documents an evolution from mobile AR to headset-based MR, offering valuable conclusions on the application of emerging technologies.

5.9.2 Limitations

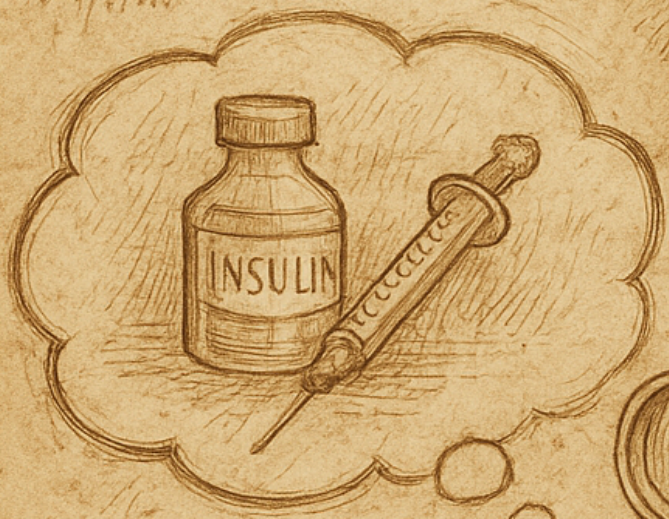
- **Short-term learning:** Across all studies, the primary learning measure was short-term knowledge acquisition. Although mid-term retention was assessed in the second study, long-term retention has not been addressed.
- **Absence of clinical outcomes:** The studies did not evaluate the impact of educational interventions on actual clinical outcomes, such as glycemic control (HbA1c levels) or self-management behaviors.

- **Sample sizes:** Sample sizes in the studies, particularly when divided into groups for comparison study 2 and 3, were relatively small (N=70 in study 1, N=27 in study 2, and N=92 in study 3), limiting statistical power and the generalization of results.
- **Content specificity:** Educational content focused primarily on carbohydrate counting for specific sets of foods (e.g., focus on breakfast). The specific carbohydrate choice definition (10g) might also limit direct applicability in regions using different standards.
- **Controlled environments:** Studies were conducted in specific settings (conference, clinical research environment) that may not fully reflect real-world usage patterns or challenges.

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Chapter 6

Conclusions

6.1 General conclusion

This doctoral thesis, composed of three publications, demonstrates the feasibility, effectiveness, and good acceptance of AR and MR as useful technologies for TED, focusing on learning carbohydrate counting. The results show that AR and MR applications significantly improve short-term learning about carbohydrate choices, with better outcomes than learning through traditional methods. Furthermore, these technologies have been positively received by patients of different ages and cultural contexts, showing high levels of usability and satisfaction. The results also suggest that the quality of the immersive experience, such as that offered by MR with color passthrough, enhances learning outcomes and user experience compared to AR or grayscale MR. Although areas for future research are identified, such as long-term impact and clinical outcomes, the thesis provides a solid empirical basis for integrating AR and MR as innovative and patient-centered tools to improve diabetes self-management.

6.2 Specific conclusions by publication

1. Publication 1:

- An AR application designed and developed for mobile devices is an effective therapeutic educational tool for short-term improvement of knowledge about carbohydrate choices in children (5-14 years) with Type 1 diabetes (Hypothesis H1 corroborated).
- Learning acquired through the AR application was independent of the children's gender and age (Hypothesis H2 corroborated).
- The AR application showed high levels of satisfaction and usability perceived by children, making it an attractive and accessible educational tool.
- The application's features and minimal requirements make it a versatile and ubiquitous educational tool with great potential for TED.

2. Publication 2:

- A culturally adapted mobile AR application proved effective for short-term knowledge transfer about carbohydrate choices in Ecuadorian patients (children and adults) with Type 1 diabetes, significantly surpassing the traditional teaching method (Hypothesis H3 corroborated).
- There is a suggestively significant impact of the AR application on mid-term knowledge retention (2 weeks), although a decrease is observed compared to short-term retention (Hypothesis H4 corroborated; suggestively significant result with $p = 0.044$).
- The AR application shows consistent benefits for both children and adults, with gender or age not significantly influencing learning outcomes or user experience (Hypothesis H5 corroborated).
- The AR application offers an excellent user experience (pragmatic and hedonic quality), supporting its use for autonomous learning and as an innovative patient-centered solution (Hypothesis H6 corroborated).

3. Publication 3:

- Both mobile AR and MR (with grayscale and color passthrough) are effective methods for increasing knowledge about carbohydrate choices in patients with Type 1 diabetes (5-36 years) (Hypothesis H7 corroborated).
- AR and color MR significantly outperforming the traditional method. Grayscale MR also showed better learning outcomes than the traditional method (Hypothesis H8 corroborated).
- MR with color passthrough (using Meta Quest 3) proved superior to both grayscale MR (Meta Quest 2) and mobile AR in terms of learning outcomes (Hypothesis H9 corroborated).
- AR and MR applications (both types) offer a user experience superior to the UEQ benchmark. Color MR and mobile AR offer a superior user experience compared to grayscale MR.
- MR with color passthrough has great potential to create engaging, contextually rich, and interactive learning environments that enhance both learning and user experience in TED.

6.3 Future work

Based on the discussion, conclusions, and limitations presented in this thesis, the following lines of future research are proposed:

- **Long-term learning:** Conduct longitudinal studies with extended follow-up periods (e.g., 1, 3, 6, 12 months) to evaluate the long-term retention of knowledge acquired through AR and MR, as well as the durability of learning effects.
- **Clinical and behavioral impact:** Conduct clinical trials measuring the real impact of these educational interventions not only on knowledge but also on self-management

behaviors (e.g., accuracy of carbohydrate counting in daily life, treatment adherence) and clinical outcomes such as glycemic control (HbA1c, time in range).

- **Expansion and diversification of samples:** Conduct new studies with larger samples and in more diverse patient populations (in terms of socioeconomic and geographical contexts, health systems, digital literacy levels) to support the obtained results.
- **Expansion of educational content:** Develop and evaluate AR/MR modules that address other crucial aspects of diabetes education beyond carbohydrate counting, such as insulin administration, hypo/hyperglycemia management, physical activity, and advanced nutrition.
- **Adaptive and personalized learning:** Explore the integration of artificial intelligence and machine learning techniques to create adaptive educational experiences that personalize content, pace, and difficulty according to each patient's individual needs and progress.
- **Real-world validation:** Evaluate the implementation, usability, feasibility, and effectiveness of these tools in clinical and home settings, outside controlled research environments, to better understand the barriers and facilitators for their adoption in practice.
- **Regional adaptability:** Standardize processes to efficiently adapt application content (foods, language, measurement units like carbohydrate choices) for different regions and cultures.

6.4 Scientific contributions

The publications derived from this thesis are the following:

6.4.1 Publications in journals indexed in JCR

1. **Title:** An augmented reality game to support therapeutic education for children with diabetes.
 - **Authors:** Andrés-Marcelo Calle-Bustos, M.-Carmen Juan, Inmaculada García-García, Francisco Abad.
 - **Publication:** *PLOS ONE*, 12(9), e0184645.
 - **Year:** 2017.
 - **DOI:** [10.1371/journal.pone.0184645](https://doi.org/10.1371/journal.pone.0184645).
 - **Ranking:**
 - Impact Factor: 2.766 (2017)
 - Category: Multidisciplinary Sciences. Rank 15 of 64 (Q1)
 - **Citations:**
 - 125 on Google Scholar (30/5/2025)

– 63 on Scopus (30/5/2025)

2. **Title:** Augmented reality for therapeutic education in patients with diabetes: Short- and Mid-Term Learning Benefits.

• **Authors:** Marcelo Calle, Francisco Abad, M.-Carmen Juan.

• **Publication:** *Sensors*, 25(4), 1017.

• **Year:** 2025 (February).

• **DOI:** [10.3390/s25041017](https://doi.org/10.3390/s25041017).

• **Ranking:**

– Impact Factor: 3.4 (2023)

– The categories in which the journal is listed in SCIE are:

* Engineering, Electrical Electronic. Rank 122 of 352 (Q2)

* Instruments Instrumentation. Rank 24 of 76 (Q2)

* Chemistry, analytical. Rank 34 of 106 (Q2)

3. **Title:** Mixed reality in therapeutic education for diabetes: Grayscale and color Passthrough Compared with Augmented Reality and Traditional Methods.

• **Authors:** Marcelo Calle, Francisco Abad, M.-Carmen Juan.

• **Publication:** *Applied Sciences*, 15(7), 4021.

• **Year:** 2025 (March).

• **DOI:** [10.3390/app15074021](https://doi.org/10.3390/app15074021).

• **Ranking:**

– Impact Factor: 2.5 (2023)

– The categories in which the journal is listed in SCIE are:

* Engineering, multicisciplinary. Rank 44 of 181 (Q1)

* Chemistry, multicisciplinary. Rank 115 of 231 (Q2)

* Physics, applied. Rank 87 of 179 (Q2)

* Material science, multicisciplinary. Rank 258 of 439 (Q3)

6.4.2 Conferences indexed in CORE

1. **Title:** An augmented reality app for therapeutic education and suitable for mobile devices with different features.
 - **Authors:** Andres-Marcelo Calle-Bustos, M.-Carmen Juan, Francisco Abad, Ramon Molla.
 - **Publication:** In *2019 IEEE 19th International Conference on Advanced Learning Technologies (ICALT)*, pages 413-417.
 - **Year:** 2019.
 - **DOI:** [10.1109/icalt.2019.00106](https://doi.org/10.1109/icalt.2019.00106).
 - **Conference Location:** Brazil.
 - **Ranking:**
 - Classified as “B” on the CORE list active at the time of publication, 2018
 - Classified as “Class 3” on the GII-GRIN-SCIE (GGS) list active at the time of publication, 2018
2. **Title:** Visual vs auditory augmented reality for indoor guidance.
 - **Authors:** Andrés-Marcelo Calle-Bustos, Jaime Juan, Francisco Abad, Paulo Dias, Magdalena Méndez-López, M.-Carmen Juan.
 - **Publication:** In *Proceedings of the 16th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications - Volume 1: HUCAPP (GRAPP)*, pages 85-95.
 - **Year:** 2021.
 - **DOI:** [10.5220/0010317500850095](https://doi.org/10.5220/0010317500850095).
 - **Conference Location:** Online.
 - **Ranking:**
 - Classified as “B” on the active CORE list at the time of publication, 2020

Bibliography

- [1] International Diabetes Federation, *IDF diabetes atlas, 11th edn.* Brussels, Belgium: International Diabetes Federation, 2025, Accessed: May 28, 2025. [Online]. Available: <https://diabetesatlas.org/es/resources/idf-diabetes-atlas-2025/>.
- [2] World Health Organization, *Diabetes*, Accessed: May 27, 2025. [Online]. Available: <https://www.who.int/news-room/fact-sheets/detail/diabetes>.
- [3] T. Dall, Y. Zhang, Y. Chen, W. Quick, W. Yang, and J. Fogli, “The economic burden of diabetes,” *Health Affairs*, vol. 29, pp. 297–303, 2010. DOI: [10.1377/hlthaff.2009.0155](https://doi.org/10.1377/hlthaff.2009.0155).
- [4] American Diabetes Association, “Economic costs of diabetes in the U.S. in 2017,” *Diabetes Care*, vol. 41, no. 5, pp. 917–928, 2018. DOI: [10.2337/dci18-0007](https://doi.org/10.2337/dci18-0007).
- [5] E. D. Parker, J. Lin, T. Mahoney, N. Ume, G. Yang, R. A. Gabbay, N. A. ElSayed, and R. R. Bannuru, “Economic costs of diabetes in the u.s. in 2022,” *Diabetes Care*, vol. 47, no. 1, pp. 26–43, 2024. DOI: [10.2337/dci23-0085](https://doi.org/10.2337/dci23-0085).
- [6] International Diabetes Federation, *Europe regional overview – IDF diabetes atlas, 11th edn.* Brussels, Belgium: International Diabetes Federation, 2025, Accessed: May 28, 2025. [Online]. Available: <https://diabetesatlas.org/data-by-location/region/europe/>.
- [7] International Diabetes Federation, *South and Central America regional overview – IDF diabetes atlas, 11th edn.* Brussels, Belgium: International Diabetes Federation, 2025, Accessed: May 28, 2025. [Online]. Available: <https://diabetesatlas.org/data-by-location/region/south-and-central-america/>.
- [8] World Health Organization. Regional Office for Europe, *Therapeutic patient education: continuing education programmes for health care providers in the field of prevention of chronic diseases: report of a WHO working group*. World Health Organization. Regional Office for Europe, 1998, Accessed: May 12, 2025. [Online]. Available: <https://iris.who.int/handle/10665/108151>.
- [9] K. Lange, P. Swift, E. Pańkowska, and T. Danne, “Diabetes education in children and adolescents,” *Pediatric Diabetes*, vol. 15, pp. 77–85, 2014. DOI: [10.1111/pedi.12187](https://doi.org/10.1111/pedi.12187).
- [10] M. Peyrot, K. K. Burns, M. Davies, A. Forbes, N. Hermanns, R. Holt, S. Kalra, A. Nicolucci, L. Siminerio, S. Skovlund, H. Stuckey, I. Viegas, J. Wens, I. Willaing, G. Kok, and F. J. Snoek, “Diabetes attitudes wishes and needs 2 (DAWN2): a multinational, multi-stakeholder study of psychosocial issues in diabetes and person-centred diabetes care,” *Diabetes Research and Clinical Practice*, vol. 99, no. 2, pp. 174–184, 2012. DOI: [10.1016/j.diabres.2012.11.016](https://doi.org/10.1016/j.diabres.2012.11.016).
- [11] V. Pais, B. P. Patel, S. Ghayoori, and J. K. Hamilton, “Counting carbs to be in charge: a comparison of an internet-based education module with in-class education

- in adolescents with Type 1 diabetes,” *Clinical Diabetes*, vol. 39, no. 1, pp. 80–87, 2021. DOI: [10.2337/cd20-0060](https://doi.org/10.2337/cd20-0060).
- [12] L. A. Nelson, S. E. Williamson, A. Nigg, and W. Martinez, “Implementation of technology-delivered diabetes self-care interventions in clinical care: a narrative review,” *Current diabetes reports*, vol. 20, Art. no. 71, 2020. DOI: [10.1007/s11892-020-01356-2](https://doi.org/10.1007/s11892-020-01356-2).
 - [13] D. Furió, M.-C. Juan, L. Seguí, and R. Vivó, “Mobile learning vs. traditional classroom lessons: a comparative study,” *Journal of Computer Assisted Learning*, vol. 31, pp. 189–201, 2015. DOI: [10.1111/jcal.12071](https://doi.org/10.1111/jcal.12071).
 - [14] M. Speicher, B. Hall, and M. Nebeling, “What is mixed reality?” In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, Glasgow, UK: Association for Computing Machinery, 2019, pp. 1–15. DOI: [10.1145/3290605.3300767](https://doi.org/10.1145/3290605.3300767).
 - [15] M. Kara and N. Çakıcı Alp, “Assessing the adoption of the yavuz battleship application in the mixed reality environment using the technology acceptance model,” *Multimedia Systems*, vol. 30, Art. no. 76, 2024. DOI: [10.1007/s00530-024-01277-0](https://doi.org/10.1007/s00530-024-01277-0).
 - [16] M.-C. Juan, C. Hidalgo, and D. Mifsut, “Mixed reality application for total hip arthroplasty,” *Virtual Reality*, vol. 28, Art. no. 39, 2024. DOI: [10.1007/s10055-024-00938-9](https://doi.org/10.1007/s10055-024-00938-9).
 - [17] A. Alhakamy, “Extended reality (XR) toward building immersive solutions: the key to unlocking industry 4.0,” *ACM Comput. Surv.*, vol. 56, no. 9, Art. no. 237, 2024. DOI: [10.1145/3652595](https://doi.org/10.1145/3652595).
 - [18] S. M. Kalaiarasan, A. Vafaei-Zadeh, H. Hanifah, and T. Ramayah, “Can we engage players with extended reality in gaming applications? A stimulus-organism-response framework,” *Entertainment Computing*, vol. 50, Art. no. 100651, 2024. DOI: [10.1016/j.entcom.2024.100651](https://doi.org/10.1016/j.entcom.2024.100651).
 - [19] S. Hindman, R. King, and A. Pereira, “Virtual reality based executive function training in schools: the impact of adaptivity on executive function and motivation,” *Computers Education*, vol. 234, Art. no. 105344, 2025. DOI: [10.1016/j.compedu.2025.105344](https://doi.org/10.1016/j.compedu.2025.105344).
 - [20] D. Furió, S. González-Gancedo, M.-C. Juan, I. Seguí, and N. Rando, “Evaluation of learning outcomes using an educational iPhone game vs. traditional game,” *Computers & Education*, vol. 64, pp. 1–23, 2013. DOI: [10.1016/j.compedu.2012.12.001](https://doi.org/10.1016/j.compedu.2012.12.001).
 - [21] M.-C. Juan, M. Loachamín-Valencia, I. García-García, J. M. Melchor, and J. Bedito, “ARCoins. An augmented reality app for learning about numismatics,” in *Proceedings of the 17th IEEE International Conference on Advanced Learning Technologies-ICALT2017*, IEEE Computer Society. Los Alamitos, CA: USA, 2017, pp. 466–468.
 - [22] M.-C. Juan, J. L. Charco, I. García-García, and R. Mollá, “An augmented reality app to learn to interpret the nutritional information on labels of real packaged foods,” *Frontiers in Computer Science*, vol. 1, Art. no. 1, 2019. DOI: [10.3389/fcomp.2019.00001](https://doi.org/10.3389/fcomp.2019.00001).
 - [23] M. Banquero, G. Valdeolivas, S. Trincado, N. García, and M.-C. Juan, “Passthrough mixed reality with Oculus Quest 2: a case study on learning piano,” *IEEE Multimedia*, vol. 30, no. 2, pp. 60–69, 2023. DOI: [10.1109/MMUL.2022.3232892](https://doi.org/10.1109/MMUL.2022.3232892).

- [24] M. Banquero, G. Valdeolivas, D. Ramón, and M.-C. Juan, “A color passthrough mixed reality application for learning piano,” *Virtual Reality*, vol. 28, Art. no. 67, 2024. DOI: [10.1007/s10055-024-00953-w](https://doi.org/10.1007/s10055-024-00953-w).
- [25] J. Hao, Z. Chen, Z. Yao, A. Remis, B. Huang, and Y. Li, “Effects of virtual reality on balance in people with diabetes: a systematic review and meta-analysis,” *Journal of Diabetes Metabolic Disorders*, vol. 23, pp. 417–425, 2024. DOI: [10.1007/s40200-024-01413-7](https://doi.org/10.1007/s40200-024-01413-7).
- [26] N. Vaughan, “Virtual reality meets diabetes,” *Journal of Diabetes Science and Technology*, vol. 19, no. 3, pp. 810–819, 2024. DOI: [10.1177/19322968231222022](https://doi.org/10.1177/19322968231222022).
- [27] J. Burkholz and S. von Mammen, “Empathy & information: ingredients for a children’s game on diabetes,” in *Proceedings of the 2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, Vienna, Austria, 4–6 September 2019, 2019, pp. 1–2. DOI: [10.1109/VS-Games.2019.8864537](https://doi.org/10.1109/VS-Games.2019.8864537).
- [28] M. Lanning, J. Shen, D. Wasser, S. Riddle, B. Agustin, K. Hood, and D. Naranjo, “Exposure to closed loop barriers using virtual reality,” *Journal of Diabetes Science and Technology*, vol. 14, no. 5, pp. 837–843, 2020. DOI: [10.1177/1932296820902771](https://doi.org/10.1177/1932296820902771).
- [29] L. Ruggiero, A. Moadsiri, L. Quinn, B. Riley, K. Danielson, C. Monahan, V. Bangs, and B. Gerber, “Diabetes island: preliminary impact of a virtual world self-care educational intervention for African Americans with Type 2 diabetes,” *JMIR Serious Games*, vol. 2, Art. no. e10, 2014. DOI: [10.2196/games.3260](https://doi.org/10.2196/games.3260).
- [30] K. Kempf and S. Martin, “Autonomous exercise game use improves metabolic control and quality of life in Type 2 diabetes patients—a randomized controlled trial,” *BMC Endocrine Disorders*, vol. 13, Art. no. 57, 2013. DOI: [10.1186/1472-6823-13-57](https://doi.org/10.1186/1472-6823-13-57).
- [31] S. Ghosal, E. Stanmore, J. Sturt, A. Bogosian, D. Woodcock, M. Zhang, N. Milne, W. Mubita, G. Robert, and S. O’Connor, “Using artificial intelligence-informed experience-based co-design (AI-EBCD) to create a virtual reality-based mindfulness application to reduce diabetes distress: protocol for a mixed-methods feasibility study,” *BMJ Open*, vol. 14, no. 2, Art. no. e088576, 2024. DOI: [10.1136/bmjopen-2024-088576](https://doi.org/10.1136/bmjopen-2024-088576).
- [32] Y. Lee, J. Hong, M. Hur, and E. Seo, “Effects of virtual reality exercise program on blood glucose, body composition, and exercise immersion in patients with Type 2 diabetes,” *International Journal of Environmental Research and Public Health*, vol. 20, no. 5, Art. no. 4178, 2023. DOI: [10.3390/ijerph20054178](https://doi.org/10.3390/ijerph20054178).
- [33] M. Mahmud, A. Cordova, and J. Quarles, “Auditory, vibrotactile, or visual? Investigating the effective feedback modalities to improve standing balance in immersive virtual reality for people with balance impairments due to Type 2 diabetes,” in *Proceedings of the 2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, Sydney, Australia, 16–20 October 2023, 2023, pp. 573–582. DOI: [10.1109/ISMAR59233.2023.00072](https://doi.org/10.1109/ISMAR59233.2023.00072).
- [34] E. Beverly, C. Love, M. Love, E. Williams, and J. Bowditch, “Using virtual reality to improve health care providers’ cultural self-efficacy and diabetes attitudes: pilot questionnaire study,” *JMIR Diabetes*, vol. 6, no. 1, Art. no. e23708, 2021. DOI: [10.2196/23708](https://doi.org/10.2196/23708).
- [35] M. Domhardt, M. Tiefengrabner, R. Dinic, U. Fötschl, G. Oostingh, T. Stütz, L. Stechemesser, R. Weitgasser, and S. Ginzinger, “Training of carbohydrate estimation for people with diabetes using mobile augmented reality,” *Journal of Diabetes Science and Technology*, vol. 9, no. 3, pp. 516–524, 2015. DOI: [10.1177/1932296815578880](https://doi.org/10.1177/1932296815578880).

- [36] A. Ahmadvand, J. Drennan, J. Burgess, M. Clark, D. Kavanagh, K. Burns, S. Howard, F. Kelly, C. Campbell, and L. Nissen, “Novel augmented reality solution for improving health literacy around antihypertensives in people living with Type 2 diabetes mellitus: protocol of a technology evaluation study,” *BMJ Open*, vol. 8, Art. no. e019422, 2018. DOI: [10.1136/bmjopen-2017-019422](https://doi.org/10.1136/bmjopen-2017-019422).
- [37] D. Ullman, E. Phillips, S. Aladia, P. Haas, H. Fowler, I. Iqbal, K. Mi, I. Riches, M. Omori, and B. Malle, “Evaluating psychosocial support provided by an augmented reality device for children with Type 1 diabetes,” *Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care*, vol. 10, no. 1, pp. 126–130, 2021. DOI: [10.1177/2327857921101117](https://doi.org/10.1177/2327857921101117).
- [38] A. Kurniawan, N. Puspita, Yusmaniar, and F. Rajendra, “The effectiveness of using digital applications for diabetes mellitus with augmented reality models as learning media in pharmacy education,” *Pharmacy Education*, vol. 23, no. 2, pp. 53–59, 2023. DOI: [10.46542/pe.2023.232.5359](https://doi.org/10.46542/pe.2023.232.5359).
- [39] N. Fajriyah, Susanti, and R. Kristiani, “Effectiveness of augmented reality-based therapeutic patient education on health locus of control in Type 2 diabetes mellitus patients,” *Nurse Health Journal Keperawatan*, vol. 13, no. 2, pp. 298–310, 2024. DOI: [10.36720/nhjk.v13i2.700](https://doi.org/10.36720/nhjk.v13i2.700).
- [40] J. Long, B. Masters, P. Sajjadi, C. Simons, and T. Masterson, “The development of an immersive mixed-reality application to improve the ecological validity of eating and sensory behavior research,” *Frontiers in Nutrition*, vol. 10, Art. no. 1170311, 2023. DOI: [10.3389/fnut.2023.1170311](https://doi.org/10.3389/fnut.2023.1170311).
- [41] A. D. Samala, L. Bojic, S. Rawas, N.-J. Howard, Y. M. Arif, D. Tsoy, and D. P. Coelho, “Extended reality for education: mapping current trends, challenges, and applications,” *Jurnal Pendidikan Teknologi Kejuruan*, vol. 7, no. 3, pp. 140–169, 2024. DOI: [10.24036/jptk.v7i3.37623](https://doi.org/10.24036/jptk.v7i3.37623).
- [42] K. Kovacs Burns, A. Nicolucci, R. I. Holt, I. Willaing, N. Hermanns, S. Kalra, J. Wens, F. Pouwer, S. E. Skovlund, M. Peyrot, and DAWN2 Study Group, “Diabetes attitudes, wishes and needs second study (DAWN2™): cross-national benchmarking indicators for family members living with people with diabetes,” *Diabetic Medicine*, vol. 30, no. 7, pp. 778–788, 2013. DOI: [10.1111/dme.12239](https://doi.org/10.1111/dme.12239).
- [43] W. Cefalu, M. Petersen, and R. Ratner, “The alarming and rising costs of diabetes and prediabetes: a call for action!” *Diabetes Care*, vol. 37, no. 12, pp. 3137–3138, 2014. DOI: [10.2337/dc14-2329](https://doi.org/10.2337/dc14-2329).
- [44] T. M. Dall, W. Yang, P. Halder, B. Pang, M. Massoudi, N. Wintfeld, A. P. Semilla, J. Franz, and P. F. Hogan, “The economic burden of elevated blood glucose levels in 2012: diagnosed and undiagnosed diabetes, gestational diabetes, and prediabetes,” *Diabetes Care*, vol. 37, no. 12, pp. 3172–3179, 2014. DOI: [10.2337/dc14-1036](https://doi.org/10.2337/dc14-1036).
- [45] C. Yoldi, “Formación en educación terapéutica en diabetes. ¿Qué tenemos y qué nos falta?” *Avances en Diabetología*, vol. 27, pp. 100–105, 2011.
- [46] J. C. Ferrer-García, J. A. Fornos, E. Menéndez, C. Ortega, I. Rica, J. J. Alemán, *et al.*, “Perfil profesional del educador de pacientes con diabetes,” *Avances en diabetología*, vol. 28, pp. 38–47, 2012.
- [47] J. A. Elliott, N. N. Abdulhadi, A. A. Al-Maniri, M. A. Al-Shafae, and R. Wahlström, “Diabetes self-management and education of people living with diabetes: a survey in primary health care in Muscat Oman,” *PLoS ONE*, vol. 8, no. 2, Art. no. e57400, 2013. DOI: [10.1371/journal.pone.0057400](https://doi.org/10.1371/journal.pone.0057400).

- [48] I. Schäfer, M. Pawels, C. Küver, N. J. Pohontsch, M. Scherer, H. van den Bussche, and H. Kaduszkiewicz, "Strategies for improving participation in diabetes education. A qualitative study," *PLoS ONE*, vol. 9, no. 4, Art. no. e95035, 2014. DOI: [10.1371/journal.pone.0095035](https://doi.org/10.1371/journal.pone.0095035).
- [49] D. B. Clark, B. C. Nelson, H. Chang, M. Martinez-Garza, K. Slack, and C. M. D'Angelo, "Exploring newtonian mechanics in a conceptually integrated digital game: comparison of learning and affective outcomes for students in Taiwan and the United States," *Computers & Education*, vol. 57, pp. 2178–2195, 2011.
- [50] J. Marti-Parreño, E. Méndez-Ibáñez, and A. Alonso-Arroyo, "The use of gamification in education: a bibliometric and text mining analysis," *Journal of Computer Assisted Learning*, vol. 32, pp. 663–676, 2016. DOI: [DOI:10.1111/jcal.12161](https://doi.org/10.1111/jcal.12161).
- [51] I. Glover, "Play as you learn: gamification as a technique for motivating learners," in *Proceedings of World Conference on Educational Multimedia, Hypermedia and Telecommunications Conference*, Jan. 2013, pp. 1999–2008.
- [52] D. Furió, S. González-Gancedo, M.-C. Juan, I. Seguí, and M. Costa, "The effects of the size and weight of a mobile device on an educational game," *Computers & Education*, vol. 64, pp. 24–41, 2013. DOI: [10.1016/j.compedu.2012.12.015](https://doi.org/10.1016/j.compedu.2012.12.015).
- [53] M. Akçayır and G. Akçayır, "Advantages and challenges associated with augmented Reality for education: a systematic review of the literature," *Educational Research Review*, vol. 20, pp. 1–11, 2017. DOI: [10.1016/j.edurev.2016.11.002](https://doi.org/10.1016/j.edurev.2016.11.002).
- [54] S. Deterding, D. Dixon, R. Khaled, and L. Nacke, "From game design elements to gamefulness: defining "gamification"," in *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments*, ACM New York, NY, USA, 2011, pp. 9–15.
- [55] J. L. Hung and K. Zhang, "Examining mobile learning trends 2003-2008: a categorical meta-trend analysis using text-mining techniques," *Journal of Computing in Higher Education*, vol. 24, pp. 1–17, 2012.
- [56] G. J. Hwang and P. H. Wu, "Applications, impacts and trends of mobile technology-enhanced learning: a review of 2008-2012 publications in selected SSCI journals," *International Journal of Mobile Learning and Organization*, vol. 8, pp. 83–95, 2014.
- [57] J. M. Zydney and Z. Warner, "Mobile apps for science learning: review of research," *Computers & Education*, vol. 94, pp. 1–17, 2016.
- [58] R. Shen, M. Wang, and X. Pan, "Increasing interactivity in blended classrooms through a cutting-edge mobile learning system," *British Journal of Educational Technology*, vol. 39, pp. 1073–1086, 2008.
- [59] N. D. Ward, R. J. Finley, R. G. Keil, and T. G. Clay, "Benefits and limitations of iPads in the high school science classroom and a trophic cascade lesson plan," *Journal of Geoscience Education*, vol. 61, no. 4, pp. 378–384, 2013. DOI: [10.5408/13-008.1](https://doi.org/10.5408/13-008.1).
- [60] H. C. Chu, G. J. Hwang, C. C. Tsai, and J. C. R. Tseng, "A two-tier test approach to developing location-aware mobile learning systems for natural science courses," *Computers & Education*, vol. 55, pp. 1618–1627, 2010.
- [61] K. Highfield and K. Goodwin, "Apps for mathematics learning: a review of 'educational' apps from the iTunes app store," in *The 36th Annual Conference of the Mathematic Education Research Group of Australasia*, Melbourne, VIC: MERGA, 2013, pp. 378–385.
- [62] J. DeShazo, L. Harris, and W. Pratt, "Effective intervention or child's play? A review of video games for diabetes education," *Diabetes Technology & Therapeutics*, vol. 12, pp. 815–822, 2010.

- [63] D. A. Lieberman, "Video games for diabetes self-management: examples and design strategies," *Journal of Diabetes Science and Technology*, vol. 6, no. 4, pp. 802–806, 2012. DOI: [10.1177/193229681200600410](https://doi.org/10.1177/193229681200600410).
- [64] S. J. Brown, D. A. Lieberman, B. A. Germeney, Y. C. Fan, D. M. Wilson, and D. J. Pasta, "Educational video game for juvenile diabetes: results of a controlled trial," *Medical Informatics (London)*, vol. 22, pp. 77–89, 1997.
- [65] N. Aoki, S. Ohta, H. Masuda, T. Naito, T. Sawai, K. Nishida, *et al.*, "Edutainment tools for initial education of Type-1 diabetes mellitus: initial diabetes education with fun," *Studies in Health Technology and Informatics*, vol. 107, pp. 855–859, 2004.
- [66] G. J. Klingensmith, J. Aisenberg, F. Kaufman, M. Halvorson, E. Cruz, M. E. Riordan, *et al.*, "Evaluation of a combined blood glucose monitoring and gaming system (Didget) for motivation in children, adolescents, and young adults with Type 1 diabetes," *Pediatric Diabetes*, vol. 14, pp. 350–357, 2013. DOI: [10.1111/j.1399-5448.2011.00791.x](https://doi.org/10.1111/j.1399-5448.2011.00791.x).
- [67] N. Aoki, S. Ohta, T. Okada, M. Oishi, and T. Fukui, "INSULOT: a cellular phone-based edutainment learning tool for children with Type 1 diabetes," *Diabetes Care*, vol. 28, pp. 760–760, 2005.
- [68] M. N. Kamel-Boulos, S. Gammon, M. C. Dixon, S. M. MacRury, M. J. Fergusson, F. Miranda-Rodrigues, *et al.*, "Digital games for Type 1 and Type 2 diabetes: underpinning theory with three illustrative examples," *JMIR Serious Games*, vol. 3, no. 1, Art. no. e3, 2015. DOI: [10.2196/games.3930](https://doi.org/10.2196/games.3930).
- [69] R. T. Azuma, "A survey of augmented reality," *Presence: teleoperators and virtual environments*, vol. 6, pp. 355–385, 1997.
- [70] M. C. Juan, M. Alcañiz, C. Monserrat, C. Botella, R. Baños, and B. Guerrero, "Using augmented reality to treat phobias," *IEEE Computer Graphics and Applications*, vol. 25, pp. 31–37, 2005. DOI: [10.1109/MCG.2005.143](https://doi.org/10.1109/MCG.2005.143).
- [71] J. Bacca, S. Baldiris, R. Fabregat, S. Graf, and Kinshuk, "Augmented reality trends in education: a systematic review of research and applications," *Educational Technology & Society*, vol. 17, pp. 133–149, 2014.
- [72] UNESCO Institute for Statistics, *International Standard Classification of Education ISCED 2011*, UNESCO Institute for Statistics. Montreal, Quebec, Accessed: May 12, 2025, 2012. [Online]. Available: <http://uis.unesco.org/sites/default/files/documents/international-standard-classification-of-education-isced-2011-en.pdf>.
- [73] M. B. Blake and J. D. Butcher-Green, "Agent-customized training for human learning performance enhancement," *Computers & Education*, vol. 53, pp. 966–976, 2009.
- [74] P. E. Liu and M. Tsai, "Using augmented-reality-based mobile learning material in EFL English composition: an exploratory case study," *British Journal of Educational Technology*, vol. 44, pp. E1–E4, 2013. DOI: [10.1111/j.1467-8535.2012.01302.x](https://doi.org/10.1111/j.1467-8535.2012.01302.x).
- [75] M.-C. Juan, L. Alexandrescu, F. Folguera, and I. García-García, "A mobile augmented reality system for the learning of dental morphology," *Digital Education Review*, vol. 30, pp. 234–247, 2016.
- [76] M.-C. Juan, M. Mendez-Lopez, E. Perez-Hernandez, and S. Albiol, "Augmented reality for the assessment of children's spatial memory in real settings," *PLoS ONE*, vol. 9, no. 12, Art. no. e113751, 2014. DOI: [10.1371/journal.pone.0113751](https://doi.org/10.1371/journal.pone.0113751).

- [77] S. Egenfeldt-Nielsen, *Beyond edutainment: exploring the educational potential of computer games*. Lulu Press, Inc., 2013.
- [78] T. Chiang, S. Yang, and G.-J. Hwang, “An augmented reality-based mobile learning system to improve students’ learning achievements and motivations in natural science inquiry activities,” *Journal of Educational Technology & Society*, vol. 17, pp. 352–365, 2014.
- [79] A. Jones, E. Scanlon, C. Tosunoglu, E. Morris, S. Ross, P. Butcher, *et al.*, “Contexts for evaluating educational software,” *Interacting with Computers*, vol. 11, pp. 499–516, 1999.
- [80] J. T. Mayes and C. J. Fowler, “Learning technology and usability: a framework for understanding courseware,” *Interacting with Computers*, vol. 11, pp. 485–497, 1999.
- [81] D. Squires and J. Preece, “Predicting quality in educational software: evaluating for learning, usability and the synergy between them,” *Interacting with Computers*, vol. 11, pp. 467–483, 1999. DOI: [10.1016/S0953-5438\(98\)00063-0](https://doi.org/10.1016/S0953-5438(98)00063-0).
- [82] P.-C. Sun, R. Tsai, G. Finger, Y.-Y. Chen, and D. Yeh, “What drives a successful e-learning? An empirical investigation of the critical factors influencing learner satisfaction,” *Computers & Education*, vol. 50, pp. 1183–1202, 2008. DOI: [10.1016/j.compedu.2006.11.007](https://doi.org/10.1016/j.compedu.2006.11.007).
- [83] O. A. Blanson-Henkemans, B. P. Bierman, J. Janssen, M. A. Neerincx, R. Looije, H. van der Bosch, *et al.*, “Using a robot to personalise health education for children with diabetes Type 1: a pilot study,” *Patient Education and Counseling*, vol. 92, pp. 174–181, 2013. DOI: [10.1016/j.pec.2013.04.012](https://doi.org/10.1016/j.pec.2013.04.012).
- [84] J. Garzón, J. Pavón, and S. Baldiris, “Systematic review and meta-analysis of augmented reality in educational settings,” *Virtual Reality*, vol. 23, pp. 447–459, 2019. DOI: [10.1007/s10055-019-00379-9](https://doi.org/10.1007/s10055-019-00379-9).
- [85] P. Milgram and F. Kishino, “A taxonomy of mixed reality visual displays,” *IEICE Transactions on Information and Systems*, vol. 77, pp. 1321–1329, 1994.
- [86] N. Özçelik, G. Ekşi, and M. Baturay, “Augmented reality (AR) in language learning: a principled review of 2017–2021,” *Participatory Educational Research*, vol. 9, pp. 131–152, 2022. DOI: [10.17275/per.22.83.9.4](https://doi.org/10.17275/per.22.83.9.4).
- [87] M. Bulut and R. Borromeo Ferri, “A systematic literature review on augmented reality in mathematics education,” *European Journal of Science and Mathematics Education*, vol. 11, pp. 556–572, 2023. DOI: [10.30935/scimath/13124](https://doi.org/10.30935/scimath/13124).
- [88] A. Mazzuco, A. Krassmann, E. Reategui, and R. Gomes, “A systematic review of augmented reality in chemistry education,” *Review of Education*, vol. 10, Art. no. e3325, 2022. DOI: [10.1002/rev3.3325](https://doi.org/10.1002/rev3.3325).
- [89] G. Lampropoulos, “Teaching and learning natural sciences using augmented reality in preschool and primary education: a literature review,” *Advances in Mobile Learning Educational Research*, vol. 4, pp. 1021–1037, 2024. DOI: [10.25082/AMLER.2024.01.013](https://doi.org/10.25082/AMLER.2024.01.013).
- [90] J. Fernández-Batanero, M. Montenegro-Rueda, and J. Fernández-Cerero, “Use of augmented reality for students with educational needs: a systematic review (2016–2021),” *Societies*, vol. 12, no. 2, Art. no. 36, 2022. DOI: [10.3390/soc12020036](https://doi.org/10.3390/soc12020036).
- [91] N. Fernandes, A. Leite Junior, E. Marçal, and W. Viana, “Augmented reality in education for people who are deaf or hard of hearing: a systematic literature review,” *Universal Access in the Information Society*, vol. 23, pp. 1483–1502, 2024. DOI: [10.1007/s10209-023-00994-z](https://doi.org/10.1007/s10209-023-00994-z).

- [92] I. Virca, G. Bârsan, R. Oancea, and C. Vesa, “Applications of augmented reality technology in the military educational field,” *Land Forces Academy Review*, vol. 26, no. 4, pp. 337–347, 2021. DOI: [10.2478/raft-2021-0044](https://doi.org/10.2478/raft-2021-0044).
- [93] M. Calle, M.-C. Juan, I. García, and F. Abad, “An augmented reality game to support therapeutic education for children with diabetes,” *PLOS ONE*, vol. 12, no. 9, Art. no. e0184645, 2017. DOI: [10.1371/journal.pone.0184645](https://doi.org/10.1371/journal.pone.0184645).
- [94] B. Laugwitz, T. Held, and M. Schrepp, “Construction and evaluation of a user experience questionnaire,” in *Proceedings of the 4th Symposium of the Workgroup Human-Computer Interaction and Usability Engineering of the Austrian Computer Society*, A. Holzinger, Ed., Graz, Austria: Springer Berlin Heidelberg, 2008, pp. 63–76. DOI: [10.1007/978-3-540-89350-9_6](https://doi.org/10.1007/978-3-540-89350-9_6).
- [95] D. Benjamin, J. Berger, M. Johannesson, B. Nosek, E.-J. Wagenmakers, R. Berk, K. Bollen, B. Brembs, L. Brown, C. Camerer, *et al.*, “Redefine statistical significance,” *Nature Human Behaviour*, vol. 2, pp. 6–10, 2018. DOI: [10.1038/s41562-017-0189-z](https://doi.org/10.1038/s41562-017-0189-z).
- [96] M. Schrepp, A. Hinderks, and J. Thomaschewski, “Construction of a benchmark for the user experience questionnaire (UEQ),” *International Journal of Interactive Multimedia and Artificial Intelligence*, vol. 4, pp. 40–44, 2017. DOI: [10.9781/ijimai.2017.445](https://doi.org/10.9781/ijimai.2017.445).
- [97] Grupo de Trabajo Guías Clínicas y Consensos de la Sociedad Española de Diabetes, “Perfil profesional del educador de pacientes con diabetes,” *Avances en Diabetología*, vol. 28, pp. 38–47, 2012. DOI: [10.1016/j.avdiab.2012.03.003](https://doi.org/10.1016/j.avdiab.2012.03.003).
- [98] A. Clerc, “Nutrition education to Type 1 diabetes patients: few changes over the time,” *Frontiers in Clinical Diabetes and Healthcare*, vol. 4, Art. no. 1243237, 2023. DOI: [10.3389/fcdhc.2023.1243237](https://doi.org/10.3389/fcdhc.2023.1243237).
- [99] P. Morales, S. Valero-Moreno, and M. Pérez-Marín, “New technologies in psychological intervention for adolescents with Type 1 diabetes: a systematic review,” *Current Psychology*, vol. 43, pp. 17 577–17 592, 2024. DOI: [10.1007/s12144-024-05694-2](https://doi.org/10.1007/s12144-024-05694-2).
- [100] B. Alhamad and S. Agha, “Comparing knowledge acquisition and retention between mobile learning and traditional learning in teaching respiratory therapy students: a randomized control trial,” *Advances in Medical Education and Practice*, vol. 14, pp. 333–342, 2023. DOI: [10.2147/AMEP.S390794](https://doi.org/10.2147/AMEP.S390794).
- [101] S. Gargrish, A. Mantri, and D. Kaur, “Evaluation of memory retention among students using augmented reality based geometry learning assistant,” *Education and Information Technologies*, vol. 27, pp. 12 891–12 912, 2022. DOI: [10.1007/s10639-022-11147-9](https://doi.org/10.1007/s10639-022-11147-9).
- [102] American Diabetes Association, “2. Classification and diagnosis of diabetes: standards of medical care in diabetes—2020,” *Diabetes Care*, vol. 43, pp. S14–S31, 2019. DOI: [10.2337/dc20-S002](https://doi.org/10.2337/dc20-S002).
- [103] A. Golay, G. Lagger, M. Chambouleyron, I. Carrard, and A. Lasserre-Moutet, “Therapeutic education of diabetic patients,” *Diabetes Metabolism Research and Reviews*, vol. 24, no. 3, pp. 192–196, 2008. DOI: [10.1002/dmrr.798](https://doi.org/10.1002/dmrr.798).
- [104] B. Ispir, A. Yildiz, and M. Ercoskun, “The use of augmented reality, virtual reality and mixed reality technologies in education: a bibliometric and systematic review,” *Journal of Quality Research in Education*, vol. 40, pp. 1–33, 2024. DOI: [10.14689/enad.40.1918](https://doi.org/10.14689/enad.40.1918).

- [105] H. Sung, M. Kim, J. Park, N. Shin, and Y. Han, “Effectiveness of virtual reality in healthcare education: systematic review and meta-analysis,” *Sustainability*, vol. 16, no. 19, Art. no. 8520, 2024. DOI: [10.3390/su16198520](https://doi.org/10.3390/su16198520).
- [106] M. Autelitano, N. Cattari, M. Carbone, F. Cutolo, N. Montemurro, E. Cigna, and V. Ferrari, “Augmented reality for rhinoplasty: 3D scanning and projected ar for intraoperative planning validation,” *Healthcare Technology Letters*, vol. 12, Art. no. e12116, 2025. DOI: [10.1049/ht12.12116](https://doi.org/10.1049/ht12.12116).
- [107] M. Calle, F. Abad, and M.-C. Juan, “Augmented reality for therapeutic education in patients with diabetes: short- and mid-term learning benefits,” *Sensors*, vol. 25, no. 4, Art. no. 1017, 2025. DOI: [10.3390/s25041017](https://doi.org/10.3390/s25041017).
- [108] H. Sulaiman, N. Ibrahim, R. Latif, and A. Yusof, “Students and teachers’ perception on future use of virtual reality (VR) in learning physics: a preliminary analysis,” in *Proceedings of the 2020 IEEE Conference on e-Learning, e-Management and e-Services (IC3e)*, Kota Kinabalu, Malaysia, 2020, pp. 1–6. DOI: [10.1109/IC3e50159.2020.9288464](https://doi.org/10.1109/IC3e50159.2020.9288464).
- [109] J. Madden, S. Pandita, J. Schuldt, B. Kim, A. Won, and N. Holmes, “Ready student one: exploring the predictors of student learning in virtual reality,” *PLoS ONE*, vol. 15, no. 3, Art. no. e0229788, 2020. DOI: [10.1371/journal.pone.0229788](https://doi.org/10.1371/journal.pone.0229788).
- [110] S. Habig, “Who can benefit from augmented reality in chemistry? Sex differences in solving stereochemistry problems using augmented reality,” *British Journal of Educational Technology*, vol. 51, pp. 629–644, 2020. DOI: [10.1111/bjet.12891](https://doi.org/10.1111/bjet.12891).
- [111] A. Dirin, A. Alamäki, and J. Suomala, “Gender differences in perceptions of conventional video, virtual reality and augmented reality,” *International Journal of Interactive Mobile Technologies*, vol. 13, pp. 93–103, 2019. DOI: [10.3991/ijim.v13i06.10487](https://doi.org/10.3991/ijim.v13i06.10487).
- [112] A. Álvarez-Marín, J. Velázquez-Iturbide, and M. Castillo-Vergara, “Intention to use an interactive AR app for engineering education,” in *Proceedings of the 2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, Recife, Brazil, 2020, pp. 70–73. DOI: [10.1109/ISMAR-Adjunct51615.2020.00033](https://doi.org/10.1109/ISMAR-Adjunct51615.2020.00033).
- [113] J.-C. Hong, M.-Y. Hwang, K.-H. Tai, and C.-R. Tsai, “Effects of gender and age on learning spatial concepts from a virtual reality game,” in *Proceedings of the BT-IEEE International Conference on Teaching, Assessment, and Learning for Engineering, TALE 2018*, Wollongong, Australia, 2018, pp. 1206–1207. DOI: [10.1109/TALE.2018.8615402](https://doi.org/10.1109/TALE.2018.8615402).
- [114] C. Hassenfeldt, J. Jacques, and I. Baggili, “Exploring the learning efficacy of digital forensics concepts and bagging & tagging of digital devices in immersive virtual reality,” *Forensic Science International: Digital Investigation*, vol. 33, Art. no. 301011, 2020. DOI: [10.1016/j.fsidi.2020.301011](https://doi.org/10.1016/j.fsidi.2020.301011).
- [115] D. Bangga-Modesto, “Examining student perception on mobile augmented reality integration, gender differences, learning styles, feedback, challenges, and opportunities in an online physics class,” *Science Education International*, vol. 35, pp. 2–12, 2024. DOI: [10.33828/sei.v35.i1.1](https://doi.org/10.33828/sei.v35.i1.1).
- [116] J. Cabero-Almenara, J. Fernández-Batanero, and J. Barroso-Osuna, “Adoption of augmented reality technology by university students,” *Heliyon*, vol. 5, no. 5, Art. no. e01597, 2019. DOI: [10.1016/j.heliyon.2019.e01597](https://doi.org/10.1016/j.heliyon.2019.e01597).

- [117] R. E. Petruse, V. Grecu, M.-B. Chiliban, and E.-T. Tâlván, “Comparative analysis of mixed reality and powerpoint in education: tailoring learning approaches to cognitive profiles,” *Sensors*, vol. 24, no. 16, Art. no. 5138, 2024. DOI: [10.3390/s24165138](https://doi.org/10.3390/s24165138).
- [118] Ericsson ConsumerLab, “Augmented tomorrow: AR experiences beyond smartphones and ar filters,” Ericsson, Tech. Rep., 2023, Accessed: May 13, 2025. [Online]. Available: <https://www.ericsson.com/4997c8/assets/local/reports-papers/consumerlab/reports/2024/augmented-tomorrow.pdf>.