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Article

Aging Collagen: Fostering Students' Motivation and Understanding through Meaningful Gamification

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Abstract

Although gamification has been used in education for many studies, the focus has primarily been on rewards-based gamification, with limited attention to meaningful gamification. This study represents the design and evaluation of a meaningfully gamified educational tool, Aging Collagen, aimed at enhancing intrinsic motivation and learning outcomes regarding collagen among lower secondary students. The design of Aging Collagen followed the guidelines from the RECIPE framework proposed by Nicholson (2015) and incorporated additional research findings that align with this framework. Nineteen students (aged 10-12) of an international school in the Netherlands participated in the study. Data was collected through focus-group interviews, surveys, and knowledge tests. The results indicated a high level of intrinsic motivation among students and an improvement in their understanding of collagen. This study identified five key factors that contributed to students' intrinsic motivation: sensory stimuli, simple language, interactive elements, minigames, and virtual characters. This study highlights the potential of meaningful gamification in educational contexts. Future research should address limitations of the current study, such as a lack of long-term assessment of outcomes, and further explore the RECIPE framework's applicability across various scientific topics to validate and enhance its effectiveness in other domains as well.

1. Introduction

In recent years, gamification has been widely used in science education aiming to enhance students' motivation and promote learning [1]. One of the advantages of gamification is enabling students to engage in enjoyable learning experiences without being afraid of failing [2]. Points, levels, leaderboards, and competition are the most used game elements in the educational context [1]. However, using those game elements has been criticized as rewards-based gamification. Focusing on these extrinsic rewards can promote short-term change but undermine intrinsic motivation in the long run [3, 4].

Meaningful gamification [3] has become a new trend, which aims to build intrinsic motivation and meaning in non-game settings. Nicholson [3] proposed the RECIPE framework for meaningful gamification design, comprising Reflection, Engagement, Choice, Information, Play, and Exposition. This player-centred approach aims for long-term and meaningful changes. While research on the application and effectiveness of meaningful gamification in education is limited, it showed promising results on students' engagement, motivation, and learning [5-7]. Since meaningful gamification is a relatively new concept, further studies are needed to examine its applicability and effectiveness.

The present study aimed to explore how an educational tool can be designed using meaningful gamification to support and motivate primary and lower secondary students in science education, or more specifically biology. Teaching biological concepts in primary education helps to enhance students' scientific literacy [8]. However, students have difficulty understanding abstract and complex biological concepts, such as cell theory and genetics [9, 10]. Also, decreased interest in biology was found in older students (grades 7 to 9) compared to younger students (grades 5 to 6) [11]. The decreased interest in turn negatively affects students' learning, as students are more motivated to learn biology by their interest and willingness [12]. These findings address the need to help students understand abstract biological concepts and increase motivation. Meaningful gamification seems to be a promising way of achieving this.

In the study presented in this paper, an educational tool, Aging Collagen, was designed using the RECIPE framework from Nicholson [3]. Aging Collagen teaches students about collagen in our human body. The decision to focus on teaching proteins is based on the idea that learning different types of proteins and their roles in the human body can help students reason about genetic phenomena in future learning [13], which is one of the most difficult topics in biology learning [10]. In this study, collagen was chosen specifically and thus Aging Collagen was built.

This paper presents a design-based research effort to meaningfully gamify Aging Collagen. First of all, this research contributes to the existing literature on meaningful gamification by connecting the RECIPE framework to related literature and using this to underpin the design of Aging Collagen. Next, a mixed-methods approach was chosen to study the effectiveness of meaningful gamification in Aging Collagen. Both qualitative and quantitative data were collected to evaluate this, including focus-group interviews, surveys, and knowledge tests.

The findings from this paper contribute to the limited body of existing academic research towards meaningful gamification and its effectiveness. However, the insights from this study transcend academics. With this research, design principles can be formulated to help teachers or educational content creators to design gamified learning experiences in a meaningful way. This study shows how educational tools can be created in a science-driven way, and how those tools can in turn be used to extend the scientific knowledge-base.

The rest of the paper is structured as follows: the remaining section provides an overview of the main topics of this study, including the theoretical framework of meaningful gamification and its implementation in previous studies. The second section describes the methodology used, including the approach, participants and data collection and analysis, and elaborates on the implementation of the RECIPE framework and other relevant theories in the design of Aging Collagen. Section 3 presents the results of students' intrinsic motivation and understanding. In Section 4, the results are interpreted in the context of the existing literature and point at possible limitations of the current study. The paper concludes with design principles derived from the findings that can enhance the existing RECIPE framework.

1.1 Background

This section introduces the main topics related to this study, including more on motivation and (meaningful) gamification. Moreover, some background information about the main topic of the game, collagen, is described.

1.1.1 Motivation

Motivation is an individual's choice of engagement in and effort put into an activity, including intrinsic and extrinsic motivation [14]. Intrinsic motivation is the motive to perform a task that is derived from the participation itself [14]. Learners can be intrinsically motivated by challenge, curiosity, or fantasy. Extrinsic motivation, on the other hand, is doing something to attain a separate outcome [15]. Some common extrinsic rewards include badges, points, and levels.

Research shows that intrinsic motivation is positively associated with school achievement because it reflects a sense of volition and personal interest rather than external pressure [16]. However, Taylor, et al. [16] also found that students' intrinsic motivation has repeatedly decreased as they move into higher grades. This trend is evident in biology, where decreased interest was observed in older students (grades 7 to 9) compared to younger students (grades 5 to 6) [11]. This decline in interest negatively affects students' learning, as their motivation to learn biology is closely tied to their interest and willingness [12]. Thus, as suggested by Taylor, et al. [16], it is beneficial to engage students in learning activities that are interesting and enjoyable, fostering their intrinsic motivation.

1.1.2 Gamification

Gamification, according to Kapp [17], is an approach to instruction "that facilitates learning and encourages motivation through the use of game elements, game mechanics and game-based thinking". Gamification is distinct from Game-Based Learning (GBL), which uses existing games to enhance the learning process [5]. However, Caponetto, et al. [18] found that a few studies used gamification as a synonym of GBL.

Game elements are elements that are characteristic of games [19]. The game elements are the central parts of gamification, including but not limited to points, leaderboards, progress bars, avatars, virtual goods, and time manipulation [20]. Game mechanics refers to the actions, behaviours, and control mechanisms within a game context [21]. For example, one of the game mechanics in Aging Collagen is completing quizzes in a limited time to gain virtual goods.

1.1.3 Meaningful gamification

In recent years, gamification has been widely used in science education [1]. Specifically, biology and health were the top content areas for most gamification applications [1]. The most used game elements in education include points, levels, leaderboards, and competition [1, 22]. Nicholson [23] referred to such gamification focusing on Badges, Levels, Achievements, and Points as BLAP gamification, also called rewards-based gamification. Kim [4] and Nicholson [3] argued that rewards-based gamification can promote short-term change but undermine intrinsic motivation in the long run. This argument has been supported by recent empirical studies. Toda, et al. [24] proposed a systematic mapping of the negative effects associated with gamification in educational contexts and found that leaderboards, points, and badges had a strong influence on the negative effects (e.g., indifference, loss of performance, undesired behaviour).

Contrary to rewards-based gamification, Nicholson (2012, 2015a) suggested an alternate way, *Meaningful gamification*, aiming at building intrinsic motivation and meaning in non-game settings. Nicholson developed a RECIPE framework for meaningful gamification, which is player-centred and aims for long-term change. RECIPE is composed of six elements: Reflection, Exposition, Choice, Information, Play, and Engagement (see a description of every

element in Table 1). In the application of RECIPE, Nicholson [3] suggested that each component should be considered in the design, and extrinsic rewards should be utilized sparingly and replaced with meaningful elements like narrative, choice, and playful content. In Section 2.3, the different elements are described in more detail using examples from the implementation of Aging Collagen.

Table 1. *RECIPE framework from Nicholson [3, 23].*

Elements	Description
Reflection	Assisting participants in finding other interests and past experiences that can deepen engagement and learning.
Exposition	Creating stories that are integrated with the real-world setting and allowing them to create their own.
Choice	Developing systems that put the power in the hands of the participants.
Information	Using game design and game display concepts allows participants to learn more about the real-world context.
Play	Facilitating the freedom to explore and fail within boundaries.
Engagement	Encouraging participants to discover and learn from others interested in the real-world setting.

The limited research on the application and effectiveness of meaningful gamification in education showed promising results on students' engagement, motivation, and learning. Stansbury and Earnest [6] designed a learning environment with meaningful gamification elements for an industrial organizational psychology course. They found students in the gamified environment had significantly higher perceptions of learning, engagement, and motivation than those in the traditional course. Ling [5] found that meaningful gamification helped to motivate students to read background material and grasp key concepts that facilitate a flipped classroom. Tsay, et al. [7] conducted a multiyear study and found that coherent, meaningful gamification can successfully drive sustained student engagement in virtual learning environments and can help overcome the novelty effect, which is a pattern of a drop in participation a few weeks after the gamified system's introduction. Kingsley and Grabner-Hagen [25] developed a gamified lesson planning unit for preservice teachers. Results showed that meaningful gamification incorporating mastery learning and leveled curriculum contributed to the intrinsic motivation of preservice teachers.

Meaningful gamification is a relatively new concept. A large portion of the preliminary research about meaningful gamification focused on higher education in a formal setting. There's no research investigating the applicability and impact of meaningful gamification within primary or lower secondary education. Furthermore, among these studies, only Stansbury and Earnest [6] and Tsay, et al. [7] applied the RECIPE framework for meaningful gamification. Other studies instead used self-determination theory as a guideline for achieving meaningful gamification [5, 25]. This revealed a lack of empirical studies of the application of the RECIPE framework in gamification systems.

1.1.4 The collagen protein

Teaching students about various types of proteins and their functions in the human body can help them reason about genetic phenomena in future learning [13]. In this study, collagen was chosen due to its fundamental role in the human body, specifically in skin ageing. This makes it a relevant and engaging topic for students. Collagen is the most abundant protein in the human body, contributing around 30% of the total protein mass [26]. Collagen can be found in

connective tissues such as skin, cartilage, bones, and tendons [26]. It is responsible for the strength and elasticity of the tissues and organs, helping them to withstand stretching. A collagen fiber has a characteristic coiled structure, comprised of bundles of smaller fibrils, while a collagen fibril is a bundle of triple-stranded collagen molecules [27]. It's like a rope weaving together, providing strength and elasticity.

Collagen is a key determinant of the preservation of skin firmness and elasticity [27]. With age, skin becomes less elastic, and wrinkles appear. The disorganization and reduction of the collagen network contribute to this change [28]. Some extrinsic factors like ultraviolet radiation, smoking, and alcohol use can stimulate the ageing process [28, 29].

2. Methods and Material

The purpose of this study was to explore how an educational tool can be designed using meaningful gamification to support and motivate primary and lower secondary students in learning proteins. Moreover, this study aims to advance the understanding of the RECIPE framework. In this study, a gamified tool called Aging Collagen was designed around the core elements of the RECIPE framework. The effectiveness of meaningful gamification on students' learning and intrinsic motivation was evaluated in a mixed-methods study. As such, the main research question is: How can meaningful gamification with RECIPE elements support children (aged 9-14) in their intrinsic motivation and understanding regarding collagen?

First, to answer this research question, Aging Collagen is designed by implementing the six RECIPE elements. To do so, Section 2.3 elaborates on the design of Aging Collagen and the theoretical underpinning of how this implements the elements of the RECIPE framework. This helps to better understand the RECIPE framework and other theories that align with the RECIPE elements.

Next, the effect of Aging Collagen on the motivation and knowledge of the students is studied. This research applied the design-based research approach, in which three phases can be distinguished: preliminary research, prototyping, and assessment [30]. The preliminary research includes needs and context analysis. Following this, the prototyping phase consists of iterations, each being a micro-cycle of research with a formative evaluation to improve and refine the intervention. Finally, the assessment phase includes summative evaluation to conclude whether the solution or intervention meets the pre-determined specifications. The preliminary research phase had already been completed before performing this study. The current study focused on the assessment phase, during which Aging Collagen was evaluated using a mixed-methods approach. No control group is used since the aim is to explore the potential of meaningful gamification and the applicability of RECIPE, rather than proving it works better than traditional teaching.

2.1 Participants

The research was conducted on 19 students (aged 10-12) from the International School Utrecht (ISU) in the Netherlands. ISU is a state-funded international school, offering a complete International Baccalaureate (IB) program for students from 4 to 18 years old and with over 45 nationalities. The participants were in the first year of the Middle Years Program (MYP). The selection of this school was based on convenience sampling. The participants were randomly chosen from two science classes of the same level, with 10 students from one class and 9 from another.

According to Piaget's theory of cognitive development, primary or lower secondary students are still at the concrete operational stage, indicating that they cannot grasp abstract scientific concepts [31]. However, this view was challenged by Metz [32], who concluded that the

research literature failed to support the assumption that elementary school children cannot understand abstract ideas. Metz's notion was supported by the result of the study that students falling into the concrete operational stage of Piaget's theory could solve the problems in learning general science up to some extent as well as in rural and urban contexts [33]. Furthermore, Metz [32] stressed the significant role domain-specific knowledge played in children's cognition rather than their developmental stage. It indicates that students who have limited domain-specific knowledge may have difficulty learning complex concepts.

According to the Science Guide [34], MYP sciences courses encompass biology, chemistry and physics, and sometimes include interdisciplinary science units that explore concepts, skills and processes from two or more science disciplines. Based on the syllabus and teachers' words, the participants have learned several types of proteins within the chapter on Cell Structure but have not yet covered collagen specifically. Therefore, this target group seemed suitable, following the findings of Metz [32].

2.2 Data collection

The intervention took place during a science lesson, with all the participants gathered in a separate meeting room. To minimize interference, each participant wore earphones. As shown in Figure 1, the participants completed a pre-test before starting to play the game individually (see Section 2.2.1). After the gameplay, the participants were required to take a post-test and an intrinsic motivation survey (see Section 2.2.2). This was followed by conducting semi-structured focus-group interviews (see Section 2.2.3). All participants completed the pre-test and attended the interview. However, a few participants were unable to complete the post-tests and motivation surveys. For the study, a mixed-methods approach was chosen. Both the quantitative and qualitative data were collected to gain insight into students' motivation and learning outcomes. Data collection includes pretest and post-test scores, responses from the motivational survey, students' written notes during the interviews and audio recordings of the interviews.

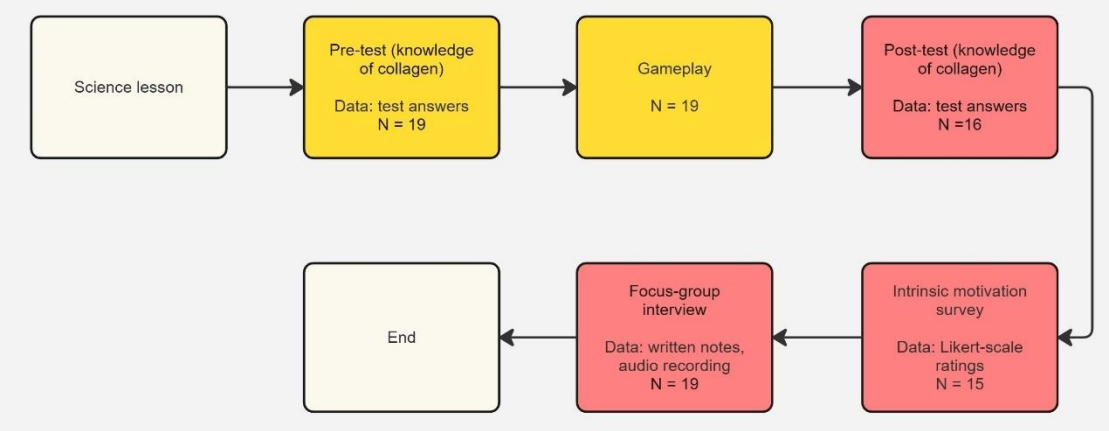

Figure 1. Data collection procedure

2.2.1 Pre-test and Post-test (knowledge of collagen)

To evaluate the difference in the participants' knowledge about collagen before and after the gameplay, pre-tests and post-tests were implemented. These assessments consisted of an identical set of 7 questions, ensuring a direct comparison of knowledge pre- and post-gameplay. These knowledge tests were developed based on the educational content in Aging Collagen. The questions can be found in Section 3.2 which discusses the results on the pre- and post-tests. The test format featured multiple-choice questions, including single-answer questions and multiple-answers questions. Additionally, the content of both the tests and the game were

validated by an expert on the topic, a PhD student at Zhejiang University School of Medicine, Hangzhou, Zhejiang, China.

2.2.2 Intrinsic motivation survey

A standardized motivational test, the Intrinsic Motivation Inventory (IMI) from Ryan [35], was used to evaluate participants' intrinsic motivational levels. IMI consists of six subscales used to assess participants' interest/enjoyment, perceived competence, perceived effort, perceived value/usefulness, perceived pressure/tension, and perceived choice. Each subscale contains 7-point Likert-scale items. Specifically, the subscale "interest/enjoyment" is the most direct measure of intrinsic motivation [36]. With this subscale, participants self-report their interests and inherent pleasure when doing a specific activity.

In this study, an adapted version of the subscale "interest/enjoyment" was utilized. The initial version contains seven items, while the adapted version only has six items. The item "while I was doing this activity, I was thinking about how much I enjoyed it" has been excluded, as it may confuse, as revealed by the pilot test with two students. Moreover, 'doing this activity' was replaced with 'playing Aging Collagen' in the items, as recommended in the IMI. The reliability of the adapted intrinsic motivation scale was checked by Cronbach's alpha using the software SPSS. The alpha coefficient for the six items in the scale is .827, suggesting that the six items have relatively high internal consistency.

2.2.3 Focus-group interview

To get further insights into students' learning outcomes and motivation, semi-structured focus-group interviews were conducted after the gameplay. These interviews, involving groups of four to five students each, utilized the advantages highlighted by Lewis [37] for focus-group interviews over individual interviews. In particular, group interviews can generate a wider range of responses than individual interviews and may enhance the reliability of children's responses by allowing them to challenge and extend one another's views. The interview scheme (see Appendix A) consisted of questions aimed at identifying which game elements contributed to the game's fun aspect and determining the effectiveness of Aging Collagen on students' learning. To ensure independent responses to the question, "What makes you think this game is fun?", all the interviewees needed to write down some keywords on the paper before sharing their thoughts. All the interviews were recorded and transcribed. The transcripts and written notes were coded in the software of NVIVO.

2.3 Aging Collagen

Aging Collagen is a gamified digital educational tool that introduces the distribution, function, and structure of collagen and its role in skin ageing. It was developed using Axure, software to create realistic and workable prototypes. Aging Collagen was designed to engage and guide players on an exploratory learning journey about collagen. It begins with avatar selection to show what the avatar will look like in fifty years, to attract players to discover the secret of ageing. Then a virtual character named Magic Mirror takes the players on a microscopic tour of the body and turns the player into a collagen molecule. To qualify as a collagen molecule, players must first learn the structure of collagen fibres and the distribution of collagen (phase one). Once they have completed a quiz, they are assigned to work on the skin, where they learn about the factors that can harm skin collagen (phase two).

The design of Aging Collagen not only followed Nicholson's (2015) guidelines from the RECIPE framework but also incorporated additional research findings that align with this strategy. To provide a more logical analysis of the game design, the analysis begins with the Play element rather than Reflection, changing the usual sequence of the RECIPE framework. Table 2 summarizes the six design elements of Aging Collagen as outlined in the RECIPE framework and their theoretical underpinnings. Following the table, a detailed discussion

elaborates on each element's application within Aging Collagen, demonstrating how theoretical insights were translated into practical game design decisions.

Table 2. *Implementations of Aging Collagen using the RECIPE framework*

RECIPE element	Implementation in Aging Collagen	Theoretical underpinnings
Play	Freedom of exploration of body parts with interactive elements; Five minigames.	[3, 23, 38, 39]
Engagement	The use of easy language; Sensory stimuli.	[3, 39-41]
Exposition	Real-world mirrored scenarios; Conversational style narratives.	[3, 42]
Choice	Avatar selection; Choice between quizzes and minigames; Decision-making in interactive scenarios.	[3, 39, 43]
Information	Focusing on educational content over rewards; Information is provided through interactions with Magic Mirror.	[3, 44]
Reflection	An online chat room for reflection on the learned content.	[3, 45, 46]

2.3.1 Play

According to the Self-Determination Theory, if the player finds fun in the activities, then there is no need for extrinsic rewards [39]. That is why the Play element distinguishes meaningful gamification from the BLAP gamification. As Nicholson [23] puts it, "a game without play is not a meaningful activity for many." His strategy to achieve meaningful gamification is to re-introduce play into the gamified activities. Further elaborating, Nicholson [3] highlights the necessity of voluntary play and exploration freedom.

In phase one of the game, the player is provided the freedom to explore the six body parts—eye, cartilage, tendon, bone, skin and artery—to uncover the role of collagen in the body. Instead of simply presenting the information, this phase is enriched with interactive elements to make it more playful. For example, within the eye section, the player can utilize a loupe to closely examine the cornea (Figure 2-left). In the skin section, the player needs to guess what percentage of dry-weight collagen takes up in the skin (Figure 2-right).

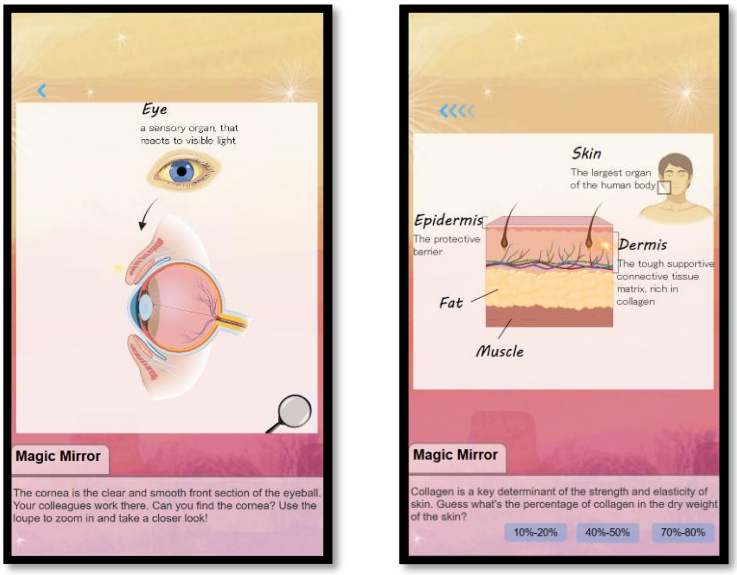

Figure 2. Screenshot of the eye (left) and skin (right) sections in Aging Collagen. Images in this figure are created in BioRender: https://BioRender.com/u97g101

To further elevate the playful experience, five minigames centred around the themes of collagen production, degradation, and ageing factors have been designed (Figure 3) in phase two of the game. For instance, the sunscreen minigame challenges players to identify the correct box containing sunscreen after a series of shuffles, highlighting the detrimental effects of sun exposure on skin collagen. Similarly, the smoking game encourages players to actively prevent smoking using the ban tool. These minigames, which are unlocked progressively, are optional, aligning with Nicholson's (2015) emphasis on voluntary play.

Figure 3. Choice screen for mini-games (left) and a screenshot of the sunscreen mini-game (right). Images in this figure are created using www.canva.com

2.3.2 Engagement

Nicholson [3] listed two types of engagement in meaningful gamification—social engagement and engagement with game mechanisms. The first type, social engagement resonates with the

concept of relatedness in Self-Determination Theory, suggesting that people feel more comfortable when they feel connected to the world around them [39]. The second type of engagement refers to the creation of an engaging gameplay experience, which can be enhanced through game mechanics [3]. Since Aging Collagen is designed as a single-player experience, it particularly focuses on the second type of engagement, engagement with game mechanisms, instead of social engagement. The idea of engagement with game mechanisms is underpinned by the theory of Flow, which suggests that a player who is in the state of flow is completely absorbed in an activity [40]. Beck [40] theorized that flow occurs when an activity represents a challenge to the person within the reach of their competence. In the context of gamification, Nicholson [3] supposed that gamification systems that do not get more challenging create boredom, while challenges presented that are too far above the player's skill level may create anxiety and frustration.

According to Bedwell, et al. [47], challenge refers to both the presentation of problems in a game as well as the difficulty of such problems. In Aging Collagen, the emphasis was on the presentation of the educational content. The educational content in Aging Collagen was crafted based on the existing literature on collagen, which may be challenging for children to comprehend. As Agrawal and Carpuat [48] suggested, shortening and rephrasing the text may be more suitable for children who have limited literacy skills. To make the content more comprehensible for children, Aging Collagen strategically reduced language complexity in terms of vocabulary and sentence structure without distorting its original intent and meaning [49].

To further enhance engagement, Aging Collagen followed the approach from Bedwell, et al. [47], who suggested that sensory stimuli can improve cognitive and emotional engagement. This approach is supported by Garris, et al. [14], who argue that dynamic graphics, sound effects, and other sensory stimuli can capture the attention and enhance engagement. Rieber [41] also found that students predominantly opt for activities with animated visuals. Incorporating these guidelines, Aging Collagen employed background music, dynamic graphics and videos to foster an engaging environment.

2.3.3 Exposition

Nicholson [3] defined Exposition as the process of presenting a narrative layer, emphasizing its importance of providing context, and enhancing engagement. The exposition element includes the development and presentation of the narratives. To connect the player to the real-world setting, Nicholson [3] provided one path—to create a narrative that mirrors the real world. In line with this, the narratives for the interactive scenarios in phase two were designed based on real-life events (Figure 4). For example, one scenario is "You're going on a vacation to Indonesia with your best friends to celebrate graduation!"

Figure 4. Examples of real-life scenarios used within Aging Collagen. Images in this figure are created using www.canva.com

Moreover, Aging Collagen employed a conversational style to present narratives. This approach is consistent with the study from Sorden [42], who found that people learn better from a multimedia presentation when the words are in conversational style (i.e., using first and second person as well as comments directed at the learner) rather than in formal style (i.e., using third person and no comments directed at the learner). To embody this approach, a virtual character named Magic Mirror was created to guide the player through the journey. This character serves as the player's mentor, transforming the learning experience into a shared adventure.

2.3.4 Choice

The concept of Choice comes from the Self-Determination Theory, which posits that if one has autonomy, one will have a more positive sense of self-being [39]. The element choice connects well with the element play. Voluntary play, as mentioned before, is a combination of the elements of choice and play. Nicholson [3] advocated giving the player a choice of which activities they want to undertake.

In line with this, Aging Collagen offers players a variety of choices throughout their journey to ensure a personalized experience. This begins with character selection (Figure 5-left), where players select an avatar and see their appearance 55 years into the future. This feature resonates with the findings of Ke and Abras [43], who observed that students enjoy having the ability to choose their characters.

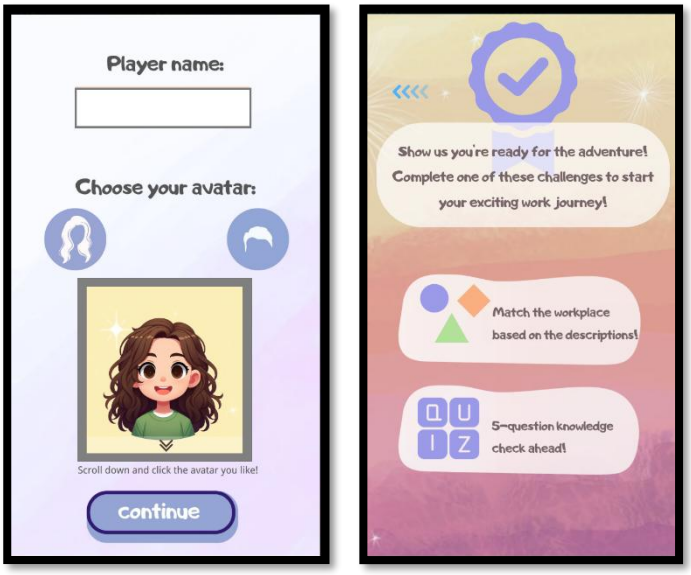

Figure 5. Menu for avatar choice (left) and menu for quizzes (right). Images in this figure are created using www.canva.com

In the first phase of the game, players are presented with an option to choose from two quizzes, allowing them to direct their learning path according to their preferences (Figure 5-right). The second phase of the game further amplifies this sense of autonomy by offering players the opportunity to engage in one or more of the five minigames. Additionally, the players are faced with decisions in interactive scenarios, When making these decisions, they can use tools they earned as rewards. Examples of these decisions are opting to refuse a cigarette from colleagues or choosing to consume vitamin A (earned as reward) to enhance collagen production.

2.3.5 Information

Nicholson [3] stated that the concept of providing information is based upon the idea of telling the player the "why" and the "how" behind the activities, instead of just the "what was done" and "how many points is it worth". Nicholson [3] suggested one way to provide information is to create a non-player character to offer guidance and assistance. This idea is supported by Abdul Jabbar and Felicia [44], who concluded that students became more motivated and felt immersed when interacting with virtual characters. In line with these principles, Aging Collagen utilizes Magic Mirror. The conversation with Magic Mirror has emphasized the educational content rather than the rewards they can get. For instance, in the minigame focusing on collagen degradation, the emphasis is placed on explaining the factors contributing to collagen loss rather than on scoring or external rewards.

2.3.6 Reflection

Nicholson [3] underscores the often-neglected aspect of gamification design: reflection, and highlights its importance in creating a meaningful gaming experience. Reflection enables players to step back and think about their game experiences. Without reflection after action, people do not find meaning in what they are doing [46]. Moreover, reflection is a good way to retrieve what we just learned from our memories, making the retrieved information more callable in the future [45].

Nicholson [3] suggested reflection can be done by having the player engage with a character that asks the player to recount their experiences, such as a reporter or an investigator. Following this recommendation, Aging Collagen incorporated a reflection section at the end of the game. The reflection section is designed as a virtual chat room "Collagen Corner Chat" where players

are encouraged to reflect on their journey through questions related to collagen and its role in the body (Figure 6). Players are presented with a choice at the end of the reflection section: they can indicate whether they feel they know all the answers, only some, or none. This decision point not only reinforces the game's emphasis on autonomy and choice but also encourages players to assess their learning outcomes critically.

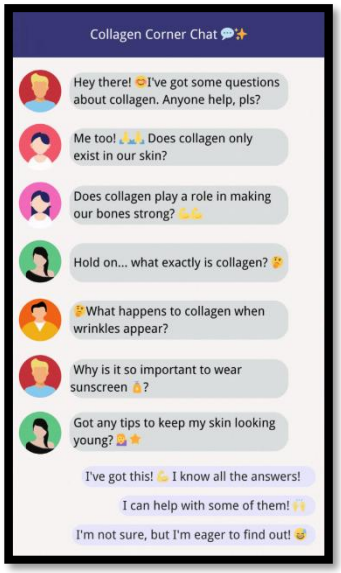

Figure 6. Screenshot of the chatroom that is used for reflection. Images in this figure are created using www.canva.com

3. Results

In this section, the results from the motivation survey and the pre- and post-knowledge tests are discussed.

3.1 Motivation

The evaluation of intrinsic motivation levels among students playing Aging Collagen, as measured by the adapted version of the Intrinsic Motivation Inventory, yielded highly positive outcomes. The overall mean score was 5.92 (SD = 0.84) on a 7-point Likert scale, indicating that Aging Collagen engaged their interest and enjoyment. It was further confirmed in the focus-group interview, with 17 students explicitly expressing that this game was fun. Specifically, 13 students wrote down the keyword "fun" on the notes. Comments such as "My eyes are glued to the screen," (Student 13) and "It was a very fun experience," (Student 10) underscore the fun aspect of the game. Moreover, when asked if they wanted to play another game that introduced a different type of protein, all students expressed enthusiasm. This shows that the RECIPE element play was successfully implemented in Aging Collagen/

To identify the key factors that motivate students, students were asked an open-ended question "What makes you think our game is fun?" in the interview. Table 3 shows the game elements that students highlighted as key motivators for their engagement and enjoyment.

Table 3. *Key Motivational Elements in Aging Collagen Identified Through Interview*

Themes	Codes	Number of students
Perception	Fun (play)	17
	Educational (information)	17

Game element	Sensory stimuli (engagement)	12
	Easy wording (engagement)	10
	Interactivity (choice)	7
	Minigame (play)	6
	Virtual character (information + exposition)	5
	Quiz (reflection)	2
	Rewards (choice)	2
	Avatar (choice)	1
	Reflection (reflection)	1

The most praised game element was the sensory stimuli (n=12). The rich animations and graphic designs were particularly appreciated, with five students expressing a specific fondness for the animations. Comments include "Cool imagery and animation" (Student 5), and "I also liked all the animations" (Student 15). The others like the overall graphic design, with one student specifying the colour (Student 16). The use of easy-to-understand language was the second critical motivator, as emphasized by 10 students. Many students remarked that "It's very easy to understand" (Student 3), and "They explain well" (Student 19). One student compared it with the information on Google, saying "It doesn't use that many complicated words, like for example in Google they use really complicated words" (Student 5). Both these motivators can be attributed to the implementation of the RECIPE element engagement in Aging Collagen.

The third game element praised was "interactivity" (n=7). Student 11 further explained "I liked it where we could click, and we got to learn more. I would like that and about like the eye there was like a magnifier and then when you looked with the magnifier you got to see the eye.. It is interactive." It indicates that students like to interact with the app rather than simply reading information. Student 4 also mentioned he liked the interactive scenarios: "I like that point because you need to choose, like how to protect yourself." This was the most mentioned implementation of the RECIPE element choice within Aging Collagen. Other choice game elements, like reward and choosing an avatar, were mentioned less. Though the rewards were not explicitly addressed, two students mentioned they loved the reward (n=2). Moreover, one student mentioned she liked choosing her avatar (n=1).

Six students specifically mentioned their enjoyment of the minigames. These minigames were recognized for their fun and educational value. One student explained why she thinks the game was fun by saying "Because you can do minigames and all, and it always relates back to main learning points, without even knowing you're learning facts" (Student 3). Moreover, one suggestion was made to extend the time allocated for minigames, indicating their popularity among the students. The game element minigames is related to the RECIPE element play.

The virtual character, Magic Mirror, was also noted by some students as an integral part of their gaming experience (n=5). Student 15 commented, "I also like the Magic Mirror part because that will keep everyone focused." Two students liked the Magic Mirror because it is "like someone is talking to you" (Student 7, 17). It suggests that they like the conversational style. The virtual character related to RECIPE elemeents information and exposition.

Additional elements like quizzes (n=2) and reflection (n=1) were also mentioned, though with less frequency. One student mentioned taking the quizzes can "see what you have learnt" (Student 18). Similarly, another student enjoyed the reflection section at the end because "you can say whether you understood it or not (Student 17). It indicates that these students like the game elements that help them reflect and examine what they have learned. This supports that, to some extend, the RECIPE element reflection was found to be a motivator in Aging Collagen.

3.2 Pre- and post-game knowledge levels

Beyond its entertainment value, Aging Collagen was also recognized for its educational value by 17 students (Table 3). To measure the impact of the game on students' comprehension of collagen, the pre-test and post-test data from 16 students were analyzed. The results shown in Table 4 suggested a notable increase in student knowledge about collagen across several aspects.

Table 4. *The number of correct answers in pre- and post-test.*

Question	Pre-test	Post-test
Q1: What is collagen?	11	13
Q2: Where can you find collagen in our human body? (Select all that apply)	0	14
Q3: What is the function of collagen?	6	15
Q4: What is the structure of collagen?	5	16
Q5: What factor can harm the collagen in our skin? (Select all that apply)	1	13
Q6: What happens to our skin when there's less collagen in it? (Select all that apply)	1	6
Q7: What can you do to help produce collagen in our body? (Select all that apply)	2	11

Initially, most students (n=11) already knew collagen is a type of protein (Q1), with three students choosing “I don’t know”, and two had the misconception that collagen is a type of sugar. After playing the game, the knowledge of this aspect slightly improved as two more students answered it correctly (n=13).

The analysis of responses to the multi-answer question on collagen distribution (Q2) indicated primary fragmented knowledge. Though no one answered it completely right, many students correctly recognized collagen’s presence in the skin (n=10) and bone (n=9). However, its existence was less acknowledged in the eye (n=3) and tendon (n=4). Post-game results showed marked improvement, with nearly all students (n=14) correctly identifying collagen in all body parts.

Students’ understanding of the function of collagen (Q3) saw improvement as well. Initially, only a few students (n=6) could correctly attribute elasticity and strength to collagen's functions. A segment of the group either did not know (n=4) or held misconceptions regarding its function (n=6). The post-test results revealed that nearly all students (n=15) gained the correct understanding after the gameplay.

A particularly impressive improvement was evident in students’ knowledge concerning the structure of collagen (Q4). Before playing the game, half of the students did not know the answer (n=8), and only a handful of students provided correct answers (n=5). However, a complete turnaround was noted in the post-test responses, where all students (n=16) demonstrated an accurate understanding of collagen's structure.

Students’ prior knowledge of factors detrimental to skin collagen (Q5) was notably deficient, with a majority choosing “I don’t know” (n=10). Though only one student answered it correctly, a few students correctly recognized one or two of the three factors, including sun exposure (n=6), smoking (n=5) and alcoholic use (n=4). This understanding improved markedly after gameplay, with most students (n=13) correctly choosing all three factors.

Understanding of the dermal changes associated with decreased collagen content (Q6) also improved. Many students (n=9) knew that wrinkles would appear, while six students knew that the skin would become less elastic. However, four students had the misconception that skin

colour may also change. After the gameplay, almost all students (n=14) knew wrinkles would appear. Still, five students thought the skin becomes stretchier.

Measures to help produce collagen (Q7) were assessed. Initially, only two students had it right. After the gameplay, all the students (n=16) acknowledged the importance of vitamin C on collagen production, and a majority (n=13) recognized the role of vitamin A as well.

4. Discussion

The purpose of this study is to explore how an educational tool can be designed towards meaningful gamification to support and motivate primary and lower secondary students in learning proteins. First, an educational tool named Aging Collagen exemplified meaningful gamification by incorporating the six RECIPE elements—Play, Engagement, Exposition, Choice, Information, and Reflection—into its design. Its entertainment and educational value have been proved by the results obtained from lower secondary school students. The high mean score of intrinsic motivation underscored the game's success in captivating students' interest, affirming that the RECIPE framework effectively guided the game's development towards meaningful gamification.

To study this in more detail, the intrinsic motivation of the students was assessed. The results identified the top five game elements as key motivators for the students: sensory stimuli, the use of easy language, interactivity, minigames, and the virtual character. The utilization of sensory stimuli contributed the most significantly to the game's fun aspect. This finding is consistent with Rieber's (1991) assertion that animated graphics enhance the motivational appeal of instructional activities. It also resonates with the findings from Rosas, et al. [50], who demonstrated the capacity of visuals to improve attention and concentration. Moreover, one student mentioned their fondness for colour. It aligned with the previous findings that game characters with round shapes and saturated warm colours (yellow, pink, and orange) lead to higher emotion induction and better learning outcomes [51, 52]. Children tend to connect bright colours with positive emotions and dark colours with negative ones [51].

The use of easy language ranked as the second most significant factor in enhancing students' intrinsic motivation. This finding aligns with the findings from Engelmann, et al. [49] that complex scientific texts pose challenges for non-expert readers for various reasons, among which are jargon, and abbreviation. Too many challenges may cause frustration and anxiety, according to Flow theory [40]. By using easy language, the students do not face great challenges when reading scientific text in the game, attributed to their motivation. As one of the students remarked, he liked it because "the description in Aging Collagen was easier to understand compared to information on Google". Both sensory stimuli as well as easy wording are related to using Engagement. The high number of students mentioning these aspects shows that Engagement was successfully achieved in Aging Collagen.

Interactivity emerged as another significant motivator, with many students expressing they liked the game because it was interactive. Interactive elements were embedded within the Play and Choice components of the game, aiming to provide exploration freedom (in body parts) and choices (in real-world scenarios). Both features were emphasized in the interview, and resonate with the claim that these children, as Digital Natives, crave interactivity—an immediate response to every action [53]. This finding showcased the value of integrating interactivity into educational tools to stimulate student interest and participation.

The utilization of Play in Aging Collagen, particularly through minigames effectively fostered intrinsic motivation among students, as evidenced by the results positioning minigames among the top five motivators. This preference for play underscores the inclination of children towards gameplay, aligning with Qureshi and Qureshi's assertion that children like to play, and for most of them, it is the only activity they enjoy throughout the day [54]. The results from this study revealed that the Play element was a crucial factor in fostering intrinsic

motivation among the majority of students. This finding validated Nicholson's (2012) approach of integrating Play into gamification design to make the gamified activities meaningful.

The use of the virtual character, Magic Mirror was another key motivator. Magic Mirror was crucial in the Exposition and Information components. Students' remarks were consistent with the findings from Sorden [42] that children liked such conversational style because they felt like talking to people.

The other elements, such as avatar and quiz were less emphasized by the students. These components contributed to the game's overall educational and engaging experience, albeit to a lesser extent compared to the primary elements identified above.

Additionally, the pre- and post-test data on students' understanding of collagen highlighted the educational efficacy of Aging Collagen. The pre-test data showed that students had limited knowledge about collagen. While they could successfully recognize collagen as a type of protein, they knew little about its function, structure, distribution, and its role in skin ageing. Post-gameplay improvements indicated that the game effectively filled knowledge gaps and corrected misconceptions, especially regarding collagen's structural aspects and environmental factors affecting it. However, the persistence of certain misconceptions, especially concerning the effects of collagen loss on skin elasticity, indicates a need for more precise instructional content within the game.

4.1 Limitations

While this study offered valuable insights into the immediate impact of meaningful gamification on learning about collagen among lower secondary students, it did not assess long-term learning outcomes. The research design lacked follow-up assessments weeks or months after the initial engagement with Aging Collagen. Consequently, although a positive effect on students' intrinsic motivation and understanding of collagen was observed, there is no evidence regarding the durability of these learning gains over time. The evaluation of long-term effects is crucial in gamification because students may forget what they have learned and their motivation may decline once the novelty wears off, as highlighted by Tsay, et al. [7]. This limitation points to the need for future research that incorporates follow-up evaluations to measure the enduring impact of gamified learning tools on student education.

Moreover, this study did not include a control group for comparison. It is important to note that this limitation is not unique to this study but is also prevalent in existing studies. Previous studies primarily focus on applications that use meaningful gamification without making comparisons with those that use reward-based gamification. Therefore, it remains uncertain to what extent meaningful gamification overcomes the drawbacks of reward-based gamification. Future studies can address this limitation by incorporating control groups to compare the effectiveness of meaningful gamification with that of rewards-based gamification, providing a clearer understanding of the relative impact of meaningful gamification.

Another limitation is the lack of diversity among the students in terms of age, educational background, and cultural perspectives. This homogeneity restricts the generalizability of the findings to a broader student population. Future studies should aim to include a more diverse participant pool to enhance the applicability of the findings across different student populations. Another aspect of the student population that was not explored in this research is their initial science interest, and the development of that interest after interacting with Aging Collagen. In future studies, it would be interested to take this aspect into account as it can both be used to describe the population in more detail as well as to explore the development of interest in addition to the development of knowledge, which was the focus of this study. For future research, it should be considered to add the instruments developed by Boeder, et al. [55] and Linnenbrink-Garcia, et al. [56] to the study. As a consequence, using the IMI should be reconsidered, to avoid survey fatigue.

Additionally, the study had a small sample size, which limits the generalizability of the results to a larger group. Future research should strive for a larger sample size to validate the results more robustly.

Lastly, while this research demonstrates the effectiveness of meaningful gamification for learning about collagen, it is uncertain whether similar results would be obtained with other scientific topics. The impact of meaningful gamification may vary across different subjects. Research exploring various subjects would help clarify the scope and limitations of meaningful gamification in different educational contexts.

5. Conclusions

In contrast to widely adopted rewards-based gamification, meaningful gamification gained less focus in academic research. With a focus on primary and lower secondary education, this study aimed to shed light on the implementation of meaningful gamification and its impact on students' understanding and intrinsic motivation. The findings revealed the educational tool Aging Collagen, designed following the RECIPE elements—Reflection, Exposition, Choice, Information, Play, and Engagement—was successful in enhancing students' intrinsic motivation and knowledge. This success was evidenced by the high mean score of self-reported intrinsic motivation levels among students and the remarkable improvement between pre- and post-test results.

This study identified sensory stimuli, easy language, interactivity, minigames, and the virtual character Magic Mirror, as key motivators, highlighting the importance of these elements in designing educational tools that appeal to young learners. Some of the design elements, such as sensory stimuli and easy language were insights from existing research by Beck [40], Ke and Abras [43], Abdul Jabbar and Felicia [44] and Rodgers [46], aligning well with the RECIPE framework. The result indicated integrating these elements can enrich the RECIPE framework, creating a more comprehensive and effective educational tool.

In summary, based on the findings of this study, it was possible to identify four key design principles that can improve the effectiveness of educational tools in terms of students' intrinsic motivation and understanding. These principles, which are based on existing literature, aim to further develop and enhance the RECIPE framework to make it more concrete and effective. These principles not only align with the core elements of the RECIPE framework but also improve its applicability and effectiveness:

- Use sensory stimuli to enhance engagement. When designing the component of Engagement, incorporate visuals, and animations to capture attention.
- Simplify language to achieve flow. Tailor complex scientific content into accessible language for the target audience, reducing jargon and utilizing clear explanations to make concepts approachable.
- Integrate play and interactive elements to enhance playfulness and provide autonomy: Embed these elements in the components of Play and Choice to allow students to explore content and make choices. This can be achieved through minigames.
- Use conversational style to present information: Design virtual characters to guide the learners through the journey and present educational content in a conversational style, making it feel personal and engaging.

While this study focused on the topic of collagen, it offered valuable insights for the development of educational tools across various scientific topics. Future studies could expand the application of the RECIPE framework to other areas of science education.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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Appendix A: Interview scheme

Table 5. Interview scheme

Time	Questions	Type
30''	Good morning/afternoon! Thanks for your participation in my study. My name is Ashley. I'm a science communication student at the university. I'm here because I'd like to hear more about your views on our game. I will treat your answers completely anonymously so feel free to share your thoughts. Our conversation will last about 5 minutes. And I'd like to record it. Will you agree to that?	Introduction
5'-10'	What do you like about this game most? / What makes you think our game is fun? Before sharing your views, could you please write down some key words on the paper? Probe for one or various combinations of game elements [1, 44]: • Sensory Stimuli: Animation, sound effects • Minigames/Puzzles/Quizzes/Challenges	Key question: Game elements that make the game more fun

	• Visual character (NPC) • Learner control/Choice: the ability to choose avatar and different quests • Badges • Narrative/Storyline	
5'-10'	Did you learn something from the game? Can you tell me about some cool or fun things you learned while playing the game? Follow-up question: Is there any other aspect of collagen you're curious about that is not covered in the game? According to the learning content, they may mention the topics: • Collagen distribution • Collagen function • Factors that can harm collagen • Ways to protect collagen/boost the production of collagen	Key question: The effectiveness of the game on learning collagen.
0'10	If we invite you to play one more game about different proteins next month, would you like to participate?	Motivation for continued participation