

ChemTouch

A new way of seeing Chemistry

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Abstract

For the past decade, there has been a shift in the education system, from a more rigid and direct approach to teaching to a more fluid and engaging ambient. To that extent, games have been used as one of the most effective new methods to retain students' attention and interest. They are fun, challenging, and most importantly, they are a method of teaching different from what students are used to, which can lead to better retention of information by the students and better academic performance.

More recently, Virtual Reality has emerged as a new technology that promises an increase in students' engagement and immersion in the classroom and is being touted as a great complementary tool to be used in the education system.

In this thesis, we explore the development of "ChemTouch", an up-to-date version of "Touch On Chemistry" that focuses on improving the originals' concept. The game works on the Oculus Quest and is played with controllers. It consists of a series of mini-challenges where the player puts his knowledge of Organic Chemistry to the test.

To assess the game viability as an educational tool, two tests were conducted with students. The first one was done after the building mechanics of the molecules were complete to evaluate if the method was satisfactory to the majority of the player base. The second test was performed after the completion of the game to test all the challenges and get final feedback on the application.

Keywords— Organic Chemistry, Virtual Reality, Games, Learning

Resumo

Durante a última década, houve uma mudança no sistema educativo, de uma abordagem mais rígida e directa ao ensino para um ambiente mais fluido e envolvente. Na mesma medida, jogos têm sido utilizados como um dos novos métodos mais eficazes para reter a atenção e o interesse dos estudantes. São divertidos, desafiantes, e mais importante, são um método de ensino diferente daquilo a que eles estão habituados, levando a uma melhor retenção de informação por parte dos estudantes e a um melhor desempenho académico.

Mais recentemente, a Realidade Virtual surgiu como uma nova tecnologia que promete um aumento no envolvimento e imersão dos estudantes na sala de aula, sendo já considerada por muitos uma excelente ferramenta complementar ao sistema de ensino atual.

Nesta tese, exploramos o desenvolvimento de “ChemTouch”, uma versão actualizada de “Touch On Chemistry” que se centra na melhoria dos conceitos do jogo original. Funciona no Oculus Quest e é jogado com controladores. Consiste numa série de mini-desafios onde o jogador põe à prova os seus conhecimentos de Química Orgânica.

Para avaliar a viabilidade deste jogo como uma ferramenta educacional, foram realizados dois testes com estudantes. O primeiro foi feito após a implementação da mecânica de construção das moléculas, para avaliar se o método era satisfatório para a maioria dos estudantes. O segundo teste foi realizado após a conclusão do jogo para testar todos os desafios e obter um feedback final sobre a aplicação.

Keywords— Química Orgânica, Realidade Virtual, Jogos, Aprender

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Chapter 1

Introduction

In the current educational environment, games are gaining a notorious reputation as a great way to teach new subjects to students. Those who play them become more engaged and interested in learning, while also improving their retention of information.

However, making an educational game is a complex balancing act between fun and education. A game to focus on educating students will make them bored and disinterested in learning, nullifying the main advantages of using games as an educational tool. However, make the game fun, and the players will be too distracted with the mechanics of the game to get a meaningful learning experience.

Fortunately, the creation of an educational game can follow some rules to maximize its potential. Thanks to the many who made educational games before us, we can look to a vast selection of games and find the rules that work and those that do not in the development of an educational game.

In a more recent time, the interest in Virtual Reality has been steadily growing. For the past decade the cost of entry for Virtual Reality plummeted to a point where having an headset at home is not an exclusive luxury of the wealthy anymore. With this new technology, came new and engaging ways to learn, with several reports praising the effectiveness of VR in immersing the user in the virtual environment, leading to better understanding and focus in the subject that is being presented. The representation of 3D space in VR is also a major advantage of VR, especially in the context of subjects that require a deep understanding of complex structures in a three-dimensional space (like organic chemistry).

By mixing educational games with Virtual Reality Technology, a game can be created that can very effectively present new subjects to students, and that is exactly what the Game "Touch On Chemistry"¹ tried to achieve, an effective and fun way to learn Organic Chemistry.

With "ChemTouch", the solution developed in this work was to expand on the concepts and ideas brought forward by "Touch On Chemistry", by expanding on the challenges and mechanics of the game, while also bringing it to a more recent and affordable VR platform, the Oculus Quest.

1.1 Objectives

The main goal of this project is to improve on the game "Touch On Chemistry". By creating new challenges and changing some game mechanics, we expect to improve the users' engagement and subsequently improve "Touch On Chemistry" as an educational tool.

Another objective of this project was to port the game to a more up-to-date version of Unity while also updating the VR headset to be used with a more affordable alternative. This will hopefully help both students and developers to more easily pick the project up and improve on what is done.

Another objective of this project is to help the teachers more easily create new challenges with custom levels created by them, allowing for a more tailored experience in each class. By doing so, we expect to transform "Touch On Chemistry" into a regular tool to be used in class, instead of a one-time experience.

¹A video demo of Touch on Chemistry can be found here: www.facebook.com/LabJogosIST/videos/356169271623554

The final objective is to verify, both with the students and the teachers the new version of the game, by comparing the original and final versions of the game.

1.2 Document Structure

The document will start by presenting a brief background of the domain of study of the project (**Chapter 2**). This section tackles important topics such as Nomenclature and Structural Drawings in a concise but effective matter, so the reader can become acquainted with some terms that will be used throughout the thesis. We will then proceed to the literature review (**Chapter 3**), in order to better understand how to effectively create a good experience, learn of some projects that are currently available and analyse some of the core concepts of the original version of "Touch On Chemistry". After that, we tackle the approach that that was taken when developing this game to better understand what must be done to maximize this game's potential (**Chapter 4**).

We will then talk about the implementation, some of the problems and hurdles that were found along the way, as well as the feedback given (**Chapter 5**). We will follow up by presenting the results of the project as well as a small section discussing the results (**Chapter 6**).

Finally a conclusion will be added where some of the final thoughts and suggestions will be presented, followed by the appendix containing the references and forms used in the making of the project (**Chapter 7**).

Chapter 2

Background

Organic Chemistry is the field that studies the structure, properties, and reactions of organic compounds. More specifically, the study of molecules containing carbon atoms. While one may think that studying carbon-containing molecules would rule out many compounds, the truth is that this atom is present almost everywhere. It is also important to note that while the name Organic Chemistry would lead someone to think the studied compounds could only be produced in nature (organically), and while this was true until the XIX century, nowadays Organic Chemistry also includes the study of inorganic and man-made chemicals, such as plastics.

2.1 Nomenclature

Language can be a difficult obstacle in understanding things, especially difficult topics such as the names of a compound, but before 1930, there was no standard nomenclature for organic compounds. As knowledge of chemistry has developed and evolved in parallel with that of human languages, the similarities and differences between the chemical terms (words) used in different languages frequently reflected the geopolitics at the time that a class of chemical compounds was first discovered or synthesized (**Sayle 2009**). Compounds would be named without a specific structure, and difficulties in understanding the compounds by other countries would appear.

That is why, in 1930, the International Commission on Chemical Nomenclature, now known as the International Union of Pure and Applied Chemists (IUPAC) created the first standardized nomenclature to name chemical compounds. This standard consisted of several rules that were later revised and refined that allowed structures of chemical names to be easily recognized across the globe. To name a compound based on the IUPAC standard, there are five rules to follow:

- 1 Find the longest continuous carbon chain that contains the functional group. the number of carbon atoms in this chain will determine the prefix of the compounds' name.
- 2 Identify the highest priority functional group in the compound. This will determine the suffix of the name
- 3 Number the carbons in the longest carbon chain. Start with the carbon at the end closest to the functional group.
- 4 Look for any branched groups/halogen atoms and name them accordingly.
- 5 Combine the elements of the name into a single word in a specific order:
 - branched groups/halogen atoms in alphabetical order (ignoring prefixes)
 - prefix of the main chain
 - name ending according to the functional group and its position on the longest carbon chain.

Now that we know how to use the IUPAC nomenclature, let us have a practical example: let us try to name the compound in Fig 2.1 using this rules:

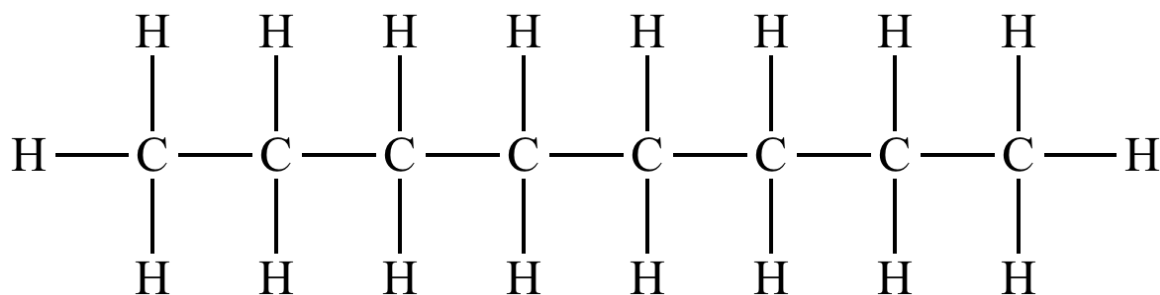


Figure 2.1: Organic compound following the Lewis Structure.

Table 2.1: Prefix used based on number of carbons

Number of Carbon Atoms	Prefix
1	meth-
2	eth-
3	prop-
4	but
5	pent-
6	hex-
7	hept-
8	oct-
9	non-
10	dec-

The first thing to do is to find the longest continuous carbon chain that contains the functional group. In this example, there is only one chain containing 8 carbon atoms, and so we can conclude the prefix will be oct- (see Table 2.1)

Now that we have the prefix, is now time to follow the next rule: identify the highest priority functional group in the compound. In organic chemistry, functional groups are specific substituents or moieties within molecules that may be responsible for the characteristic chemical reactions of those molecules (**Wikipedia 2021a**). Because we are only dealing with carbon and hydrogen in our example, we only need to look for Hydrocarbons, which are functional groups only containing the two atoms. By looking at the table 2.2 we can conclude that the chemical class of our molecule is an alkane and its suffix is -ane.

Because our molecule is an alkane, rules 3,4, and 5 were not needed in this exercise, and we reach the name of this compound: Octane.

Although very simple, this exercise still proves to be useful in showing that this system avoids problems related to arbitrary nomenclature. These rules allow one to be able to create a unique name for every different compound, allowing for a name of certain compound to be easily recognizable all around the world.

2.2 Structural Drawings

There are a few ways to represent a molecule in its structural form. One of these ways is by using the Lewis Structure. This Structure is a more general way of representing molecules for all Chemistry. It illustrates

Table 2.2: Suffix used based on hydrocarbons

Chemical Class	Number of Double Bonds	Suffix
Alkane	1	-ane
Alkene	2	-ene
Alkyne	3	-yne

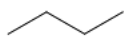
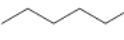
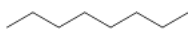

Substance	Condensed Structure	Skeletal Structure
Butane	$\text{CH}_3(\text{CH}_2)_2\text{CH}_3$	
Hexane	$\text{CH}_3(\text{CH}_2)_4\text{CH}_3$	
Octane	$\text{CH}_3(\text{CH}_2)_6\text{CH}_3$	
Decane	$\text{CH}_3(\text{CH}_2)_8\text{CH}_3$	

Figure 2.2: Molecule representation in both condensed and Skeletal Form.

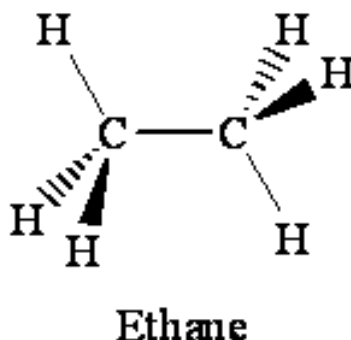


Figure 2.3: Ethane molecular representation in 3D space.

what atoms are connected, as well as all the bonds and lone pairs of electrons in the molecule. For example, in Fig 2.1 given previously, the molecule is being represented in the Lewis structure. We can see all the bonds, as well as all the lone pairs of electrons (atoms of hydrogen).

Another way to represent molecules is by using their molecular formula. Using Octane as an example, its molecular formula is C_8H_{18} .

In Organic Chemistry, we can further simplify the Lewis Structure of a molecule. By condensing the atoms of carbon and hydrogen together, we can create a simpler and easier structure to read. This is called a Condensed Structural Formula (see Fig 2.2)

Further simplification is possible by removing all the carbons and their attached hydrogen atoms from the drawing and then creating vertices to represent the bonds between the carbon atoms. This is called a skeletal structure of a molecule (see Fig 2.2)

Finally, it is also possible to represent the molecule structure in 3D Space, by using a different line representation, depending on where the atom should be in 3D Space (see Fig 2.3). In this view, a straight line represents a connection between two atoms in the Z-axis. To represent a connection where the atoms are in different Z-axis, we use a triangular shaped connection, where the atom that is connected to the base of the triangle is in front, or behind of the atom connected to the head of the triangle, depending if the triangle is filled or has a striped pattern.

2.3 Virtual Reality

Virtual Reality is a simulation of an experience (**Wikipedia 2021b**). This experience can be similar to the real world or something completely different. It is not a recent concept, with its original concept dating back to the 70s. However, until now, VR was never seen as a tool that could be used by everyone. In recent years, there was a breakthrough in progress in this sector thanks to the creation of more affordable and higher quality VR Headsets. These machines allow for a much more affordable way for the public to access these virtual experiences, opening the possibility for this technology to be used in education. Since the primordial days of VR headsets, the technology has evolved tremendously and there are now many different types of VR headsets (see Fig 2.4) with prices as low as 300€ as well as big improvements in haptics, motion tracking,



Figure 2.4: VR Headsets currently available.

and other aspects to achieve an unprecedented immersion in the virtual world.

Chapter 3

Related Work

In this chapter we will analyse all the relevant literature to complete the project. From the core fundamentals of learning to the analysis of the original project "Touch On Chemistry", this chapter aims to explain some of the decisions that were taken in the development stages of "ChemTouch", by presenting factual information regarding the topics explored.

3.1 Multimedia Learning

Since the days of public education, humans have used the same methods to teach students everything they needed to know. Teachers would stand in front of the class and spew information at a pace too quick for some or too slow for others. While this method served us well for some time, there is no doubt that it was not the ideal method for most of the students. It has been thoroughly studied and proved that this type of teaching method is demoralizing and inefficient and much better alternatives can be used in this day and age. One alternative that has been gaining traction and what most consider the new way of teaching is Multimedia Learning, a term that was somewhat obscure until the late 90s when Richard E. Mayer started to collect and reveal data on the topic. Mayer published several articles regarding multimedia learning such as one in 1997 (**R. Mayer 1997**), where he gives evidence that using both verbal and visual formats of learning leads to a significantly better understanding of a subject. In the research conducted, students consistently performed better when presented with a multimedia format compared to the more traditional methods of presenting the information. The article also reveals that students with low prior knowledge of the subject at hand benefited the most from this teaching method. This research and others alike were then used as the groundworks for his book published in 2003 (**R. E. Mayer 2003**) (**Fig 3.1**) where Mayer goes more in detail about his findings and provides more insight into how multimedia learning should be implemented. The author states that there are two separate channels for processing information, auditory and visual, and each of these channels has a limited and finite capacity to process information. By using both channels at the same time we can increase the capacity to process information more quickly while not overwhelming none of the channels, resulting in faster learning ability, and less fatigue while doing so.

It is now clear that multimedia learning is a superior method when it comes to teaching students new material. However, while now we know that using both audio and visual channels leads to better performance, we are still unsure how we can maximize this knowledge, or in other words, if using different types of media to teach students, such as using games and Virtual Reality would lead to the same performance as teaching using slides and videos in the classroom, and so a deeper investigation is necessary to try and answer this problem.

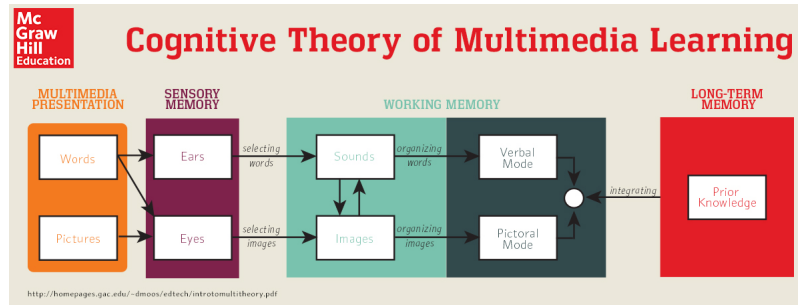


Figure 3.1: Cognitive Theory of Multimedia Learning

3.2 Digital Learning

Digital Learning presents itself as a great tool for Multimedia Learning, as the digital space provides numerous ways of acquiring information, both in an audio and visual way. With the increased digitalization of information, there is no doubt that the next way of teaching will be presented mostly in a digital fashion. Besides its ease of use, digital learning seems to increase the motivation and performance of students. In a study conducted in 2017 (M.-H. Lin 2017), 116 students were evenly split into two groups, one would only use digital learning, while the other would only use traditional methods for 32 weeks. The results show that the digital group performed significantly better than the traditional group both in terms of motivation and learning outcome (Fig 3.2).

Table 1. Variance analysis of digital learning on learning motivation

	Variable	F	P	Scheffe post-hoc
Digital learning	Intrinsic orientation	9.38	0.000*	digital learning (4.12)>traditional teaching (3.31)
	Extrinsic orientation	11.46	0.000*	digital learning (4.75)>traditional teaching (3.53)

* stands for $p < 0.05$

Table 2. Variance analysis of digital learning on learning outcome

	Variable	F	P	Scheffe post-hoc
Digital learning	Learning effect	13.42	0.000*	digital learning (3.95)>traditional teaching (3.15)
	Learning gain	15.16	0.000*	digital learning (4.27)>traditional teaching (3.38)

* stands for $p < 0.05$

Figure 3.2: Outcomes of digital learning

Digital Learning can also be responsible for the major shift we see in today's schools and Universities. By using these tools, learning shifted more towards an autonomous approach, as opposed to a more direct approach of teacher and student. Teachers are now a mentor, guiding the students towards the new information they acquire, instead of an expert on the field that is the sole bearer of information. This can be extremely beneficial, as it means many more students can get an excellent education, as it becomes cheaper for schools and universities to guide students to the best literature available, instead of needing to rely on paying to the best in their fields to teach their students. However, the benefits that these new technologies bring can also be a major drawback for the less fortunate. As the dependence on digital learning increases, it becomes fundamental more costly technologies for the student to keep up, and while most people can afford them and so it is a benefit for them, for those that can not, digital learning can lead to a worse outcome, as the information they need to acquire is now locked behind something they cannot access at home, which is fundamental on the autonomous approach of learning that has been gaining more and more followers. In a paper called "The paradoxical future of digital learning" (Warschauer 2007), the author critically analyses digital learning, exposing the problems mentioned above and concluding by stating that "Such approaches will not magically overcome educational inequity; that is a broader challenge involving much more than good

use of computers in schools. But simplistic views of digital learning, which pit new literacies against old, autonomy versus mentorship, or home versus school, will only serve to worsen educational divides". In conclusion, there is no doubt that digital learning revolutionized how the education system works. A way of giving students anywhere on the planet the best education and learning tools available at no extra cost for educational institutions is a breakthrough in education. However, it is also important not to forget the least fortunate who cannot afford the use of these systems and are being punished and left behind at no fault of their own. If we can conquer these problems, then it is clear that the advantages that digital learning provides are no doubt a welcome addition to our education system and something that will continue its stay for a long time.

3.3 Games and Learning

Games present themselves as a unique tool in education, the engaging and fun nature they provide seems like they are an ideal candidate to improve motivation among students and lead to better academic performance. And when looking at the literature regarding Games and Learning, this theory is proven true. A study conducted for almost 10 years analyzing the effect of educational games (**Backlund and Hendrix 2013**) present the results of 40 studies regarding serious games and found that of those, 29 showed positive effects, with 7 neutral and only 3 showing negative effects (**Fig 3.3**). These findings suggest that serious games can be used with positive effects in the classroom. However, the same results also show that not every serious game had a positive impact, leading us to conclude that, as with most educational methods, serious games must obey certain criteria for them to have positive effects in the class. To find said criteria, a good first place to look is what these games were and what they were trying to achieve. For this we can look at another article (**Cheng et al. 2015**) that is built upon most of the same studies the results found previously are based on. The article found some interesting key points, namely an increase in research regarding serious games during the years, meaning that the interest in the use of games in an educational environment seems to be gaining more and more support each year. The second key point is the genre and field of said games, where most were RPG/Adventure Games, followed by simulation games, and most were designed for science education. The final key point is the aim of the games, where most were aimed at knowledge construction, followed by problem-solving. To conclude, this study can help us better understand the current literature and knowledge regarding serious games, however, it is still not enough to come to a definite solution for what criteria one must have in mind when making a serious game.

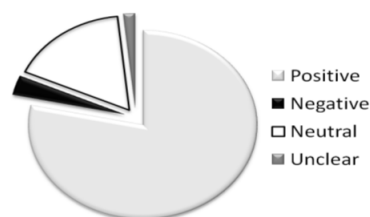


Figure 3.3: Evaluation results of identified empirical studies

Another approach is to directly analyze what games can provide and try to explore their qualities to try and apply them to an educational point of view. To do so, we can look at an article published in 2014 (**Oswald, Prorock, and Murphy 2014**), where we can find what qualities games can bring to the table. In the paper, the author finds that games primarily give players positive and fun emotions, both of which can be considered major benefits for an educational tool. Furthermore, games are great at getting someone involved and immersed, can be used with players with a wide variety of goals, and promote autonomy and competence, leading them to fit quite nicely in the current shift for a more independent learning environment.

3.4 A Framework for Serious Games

We now have a solid understanding of the benefits that serious games can bring us, as well as some of the research that was developed alongside them. But is still not enough evidence to gives us clear and exact criteria for developing a serious game and more like rough guidance in how to approach the challenge. And this uncertainty in finding answers is something that Pauline Rooney tries to answer in this article (**Rooney 2014**). In it, the author explores the use of a triadic theoretical framework for serious game design, outlining key literature and theories and point out some of the challenges and ideas each one presents.

The triadic theoretical framework has Pedagogy, Play, and Fidelity as its pillars, arguing that a good serious game must encompass the three in a careful balancing act to achieve a fun game that is both faithful to the original material, and providing a good learning outcome.

3.4.1 Pedagogy

On the Pedagogical front, most of the theories fall under the theoretical approaches of constructivism, which is “the assumption that knowledge and skills are constructed by learners as they attempt to make sense of their experiences” and authenticity being one of the more predominant themes, arguing that replicating ingame what the learner would face in real-life leads to a better learning outcome. We can further break down constructivism in several other theories, and one such theory is Situated Learning, which argues that for an effective learning outcome the learner must be embedded in an activity that makes use of its social and physical context, or, in other words, the learner must not only learn what something is but how to use it in the necessary context. Another theory is Problem-Based Learning, which shifts the focus from teaching to student learning by participating in problem-solving activities. Similar to Situated Learning, the use of authenticity and trying to replicate real-life experience is also predominant in Problem-Based Learning, with each problem the students complete translating directly into real-world knowledge. The final theory is Experiential Learning, which has its core ideas rooted in the notion that knowledge is created through the transformation of experiences. According to this theory, learning can be thought of as a cyclical process consisting of four stages. First, the learner starts with a concrete experience, then he observes and reflects upon it, and on this basis, he draws conclusions and generalizations as to how this knowledge can be used in other scenarios. In the last stage, the learner tests his hypothesis and conclusions through a new experience, leading to a new cycle of learning. This theory is based on a form of episodic learning, where students switch between learning new information and testing their new findings in short intervals. In conclusion, on the Pedagogical front, constructivism is its preferred theory, being the leading theory that all others are based upon. We can see that from the three theories explained in the previous section, all of them focus on presenting the student with material that translates directly to the real-life application and in the idea of small doses of learning followed by problems and materials for the students to test their newly acquired knowledge.

3.4.2 Play

The main goal of a game should be to entertain. The problem with this sentence is that with serious games, non-entertainment objectives of educating and informing are key aspects in the design process, this means that a careful balance between entertainment and pedagogical ideas must be set to create a successful serious game. As previously mentioned in the chapter, games bring Engagement, Motivation, Flow, and Immersion as no other medium can bring. Players can invest thousands of hours in one game trying to improve their skills and master the mechanics of the games, and it is this type of commitment that we try to bring to the classroom with the use of serious games. Many are the theories that surfaced through the years to help identify key game features that are crucial to player engagement (**Table 3.1**), but as games and technologies evolved so did the theories. However, there are key aspects that stood the test of time and are prevalent in most theories throughout the years. Challenges received the top mark, present in every proposal, followed by clear goals and feedback. This means that for creating a game that aims to fully utilize the capabilities of the medium, it has to present the player with a clear goal, that can be achieved by completing challenges as

well as providing constant feedback to the player as to how he is performing.

Study	Feature of Games
Malone (1981)	Fantasy (pleasurable content), control, challenge, curiosity, collaboration, competition
Bowman (1982)	Clear task, identifiable roles and responsibilities, player choice, balance between player skills and challenges
Prensky (2001)	Clear rules, continuous challenge and competition, clear goals and objectives, direct and instant feedback, immersive story line
Garris et al. (2002)	Fantasy, rules/goals, sensory stimuli, challenge, mystery, control
Sweetser and Wyeth (2005)	Concentration, challenge, skills, control, clear goals, feedback, immersion, social
Dumbleton (2007)	Engaging narrative, graduated challenge, consistent game, world, intuitive interface, player agency, clear feedback

Table 3.1: Summary of game features identified as key to player engagement

3.4.3 Fidelity

The last pillar of this framework is fidelity, and in this context, fidelity is conceptualized as both Physical fidelity, the degree to which a game sounds, looks, and feels like the real world, and Functional fidelity, the extent of how the game environment acts like the real world in terms of its response to player actions. For serious games in particular, while it would be intuitive to think that the higher both physical and functional fidelity is, the better the results, the literature suggests that may not always be the case. If the goal of the game is to teach a very specific skill that translates directly to the real world (i.e a game that teaches someone how to build a specific item), then physical fidelity is essential for the effectiveness of the game. However, if the main goal is to teach more abstract concepts, prioritizing the games' functional fidelity would be ideal.

In conclusion, there is no doubt games can help tremendously in our educational environment and the number of benefits they can have on students should not be overlooked. The use of serious games should become a staple in today's educational system, as they can provide new ways to acquire knowledge as well as improve students' motivation. However, creating serious games can be a complex task if not tackled correctly right from the start. It is important to keep in mind that a balance between pedagogy, play, and fidelity must be achieved to create an adequate experience that can achieve good results in the classroom. A serious game should focus on presenting the students with knowledge that can be directly applicable to real life, preferably in a short episodic fashion followed by the application of the newly acquired knowledge in the real world. It should present clear goals or tasks for the player to perform, constantly challenging him with new material and providing instant feedback about the players' performance. Finally, if the game aims to teach more abstract concepts of science and math, the game should be made with functional fidelity as its top priority.

3.5 VR and Learning

In recent years, VR has garnered a huge increase in popularity. Since the introduction of the Oculus Rift in 2010, there is been a steady year-to-year increase in the units sold worldwide. This means that each day, more and more people are adopting VR as a new technology in their homes and more interest is being shown in the capabilities of this technology in the field of education.

When compared to all the other mediums we use in education, VR shines when it comes to presence and immersion (Carroll, Osborne, and Yildirim 2019, Makransky, Andreassen, et al. 2020, Makransky, Terkildsen, and R. E. Mayer 2019), ranking better than its counterparts in every experience. However, when it comes to pedagogical results, the results can vary from study to study. For example, "in a study by Slavona and Mu (Slavova and Mu 2018)", a comparative study was conducted on students' performance in a standardized assessment when course content is delivered using VR and conventional lecture slides. Students using the lecture slides seem to perform better when it came to one-word answers, like a specific date or name. The authors believe the reason for this came from the fact that when using slides, students

would skim through the information and focus on keywords, remembering them more vividly, whereas, in the VR group, the important keywords were more difficult to catch, since the students had more things to be distracted with. Similar results were found in this study (**Makransky, Terkildsen, and R. E. Mayer 2019**), where students performed significantly worse in the VR group, despite reporting more presence due to the overload of information VR caused to the students.

One another study (**Parong and R. Mayer 2018**), VR was compared with slideshows in two experiments. On the first one, students would learn how the human body works, through a presentation in VR or slideshows. The results showed that students using the slideshows performed significantly better, but their motivation, engagement, and interest were lower than in the VR group. On the second experience, the test consisted in making the students have the lesson in its entirety in one go vs broken up in small segments followed by a resume of the segment. In this test, students' performance was significantly better in the segments group, and close to the same performance as the slideshow group, while their levels of motivation, engagement and interest did not suffer any changes when compared to the original VR group. In another study (**Makransky, Andreassen, et al. 2020**), similar results were found when VR was compared to the video. Students using VR reported significantly higher perceived enjoyment and presence than the video group but learned less than those using the video. However, when students were asked to engage in a generative learning strategy, the students in the VR group saw a significant improvement in their scores, while the video group did not see any significant changes. In conclusion, VR positions itself as an amazing technology that offers presence and immersion like no other medium to date. However, the same benefits can also become negatives when it comes to a learning environment, and this increase in immersion can result in worse performance by students due to the sensorial overload VR can cause. By applying generative learning and using a form of episodic learning as discussed in the section about Games and Learning, the sensorial overload does not happen, leading to students reporting all the benefits of VR, while also performing similarly to students using more traditional learning methods.

3.6 Chemistry Games

Chemistry Games have successfully managed to motivate students, and develop their skills to solve problems about the topic (**Stojanovska and Velevska 2018**). They can help to understand concepts better than traditional teaching models (**Wu et al. 2018**) and can lead to significant improvements in students capabilities (**Hou and Y.-C. Lin 2017**).

One example of a game that managed to do just so is Chemcaper (**Fig 3.4**) a "chemistry adventure game that teaches fundamental (with emphasis on the fun!) chemistry concepts" (**LLC 2016**). By playing this game, students can expect to learn about scientific apparatus, separation techniques, groups of elements, properties of elements and types of chemical bonding. The game also helped the retention of information for a longer time, with students reporting that they remembered 90% of the concepts taught in the game 6 months after playing it for the first time.

Another game with encouraging results is Elemen (**Paiboon Boonpotjanawetchakit 2020**). In this game, there are 118 elemental cards, one for each element in the periodic table. In the front of these cards, there is an image representing the element in a more day-to-day context, the name of the element, and a unique bar code (**Fig 3.5**). On the back, the player can see the element description together with some basic information including atomic number, group, symbol, period, melting and boiling points, the phase at STP, series, and density (**Fig 3.5**). There are also four additional cards representing player cards (**Fig 3.5**), these are used when playing with other people, up to a maximum of four players. To play this game, players must use an application on their phone that will ask questions based on the difficulty they have chosen. The game then starts and 20 questions are shown to the players. To get the right answer, players have to show the right element card and their player card to the camera. The faster the correct answer is submitted, the higher the score for the player. After the game ends, the player with the highest score will be declared the winner.

When compared with more traditional Elements Flashcards in terms of satisfaction score, Elemen outperform it in its enjoyment, encouraging self-learning and diversity of questions.

Finally, we have a game called React! (**R. Inc 2020**), "a game that can teach anyone the fundamentals



Figure 3.4: ChemCaper game and gameplay.

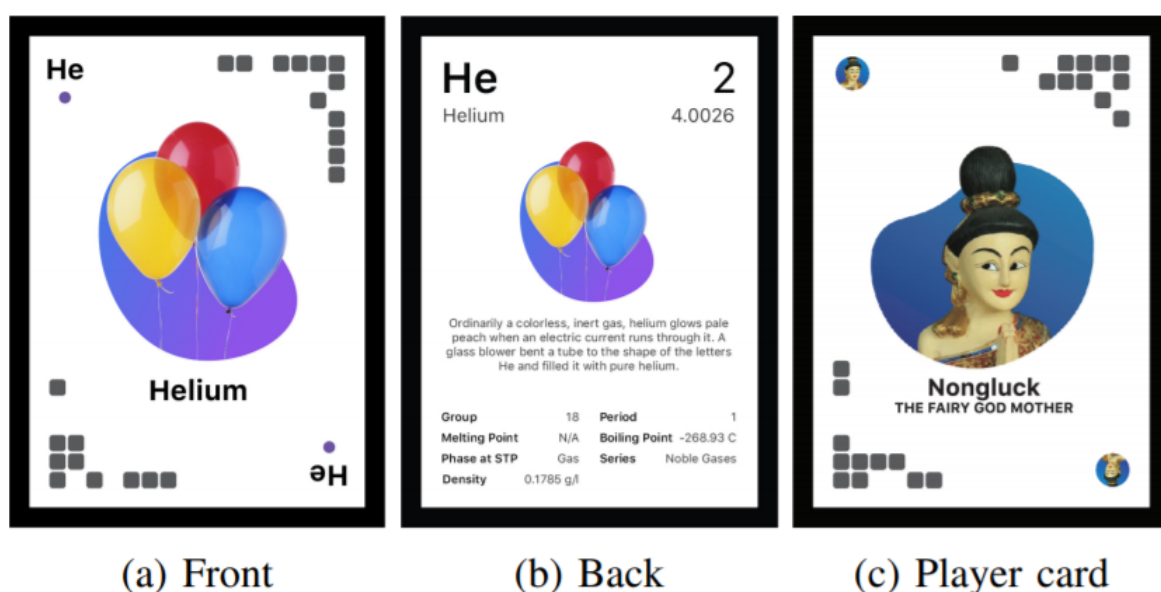


Figure 3.5: Elemen Cards

of organic chemistry”. In React!, each player is a scientist experimenting. To earn points, each player can discover and do chemistry reactions, compete for research funding and create unique molecules to reach the targeted functional group on their experiment and win the game. The game aims to teach material related to the first semester of college-level organic chemistry, with a focus on laboratory-based synthesis, and the feedback is very positive, with many students reporting a great experience in learning Organic Chemistry with the game.

3.6.1 Chemistry in VR

Besides more traditional board and card games, Chemistry Games can also be found in Virtual Reality. One such example is HoloLab Champions (**Games 2018**). In this game, the player has different tasks he must finish accurately to earn points and gain entrance into the Hall of Brains. A host guides the player through a series of mini-labs that lead up to an ultimate lab challenge.

Each mini-lab corresponds to an experiment the player must complete by scooping, pouring, burning, and mixing different elements to create the solutions’ chemical mix (**Fig 3.6**). The better the final mix is, the higher the player will score in that mini-lab session, and the further the player is with the mini-lab sessions, the harder each one will be, requiring a lot more materials and transformations than the first levels.

To create the perfect mix, the player must be very mindful of each activity he performs. When scooping and pouring, the user must ensure that the quantities of each element correspond exactly to the dose in the procedure. When burning an element, is fundamental to keep a watchful eye on the temperature it reaches, and when mixing, it is imperative that the elements blend according to the instructions.

The makers of the app described it has: "It's virtual lab practice with real lab mastery". The game won several awards and the overall feedback of the game is very positive.



Figure 3.6: Gameplay of HoloLab Champions

MEL Chemistry VR Lessons (**Science 2018**) is another example we can find in VR. Although more an application than a Game, MEL Chemistry Lessons aim to create a fun and engaging experience for the user to learn chemistry. Players can learn about solids and gases structure on the atomic and molecular level, construct any atom on their own and learn about electron configuration. The application offers multiple lessons that follow the basic school curriculum as well as tasks and tests that will help absorb more knowledge. The overall feedback of the app is very positive, with many praising the quality of the lessons offered and touting the app as a great entry point to learn Chemistry.

Nanome.ai (**N. Inc 2018**) is touted by its creators as the "Most Effective Tool for Drug Design Decision Making". Its a tool created to help in molecular design, by providing a collaborative space in Virtual Reality that can be used in general chemistry to pharmaceutical drug discovery. When using the app, users can build complex molecules in 3D space, by interacting with an interface hovering near them. This interface is very feature-complete, with many menus, but for Organic Chemistry and to this project, in particular, we will only focus on one of those menus and its sub-menus.

Pressing and holding the menu button (B button in the Oculus System) activates the tool selection menu (**Fig 3.7**), the user can then hover over the desired selection and then release the button. If no selection is made, the hand tool will be chosen by default.

- **Hand Tool:** The hand tool is the default state of the hand and allows basic interaction such as grabbing and clicking. The user can also hold down the joystick to make a laser pointer appear, which can be useful when explaining something of interest to other participants in the virtual room.
- **Measurement Tool:** When selected, allows the user to measure distances and angles between atoms and points of interest.
- **Selection Tool:** Works as a shortcut to select a specific type of structure in the workspace.
- **Torsion Tool:** allows the user to rotate bonds and changes the dihedral angles between atoms.

- MedChem Tool: Enables direct editing of atoms using the controllers. In this state, the user can add or remove atoms in specific places while also interacting with sub-menus that allow for an easier workflow. Of these sub-menus, the build menu provides most of the necessary tools for a comprehensive building experience. The user can select pre-existing molecular structures that are common to be found for a quick building experience, or make their molecule from scratch, by choosing each atom and connection at every stage of the process (**Fig 3.8**).
- Draw Tool: Provides a blank canvas where the user writes or sketches ideas and molecule structures in 2D space, additionally, it can also import PDFs or images.

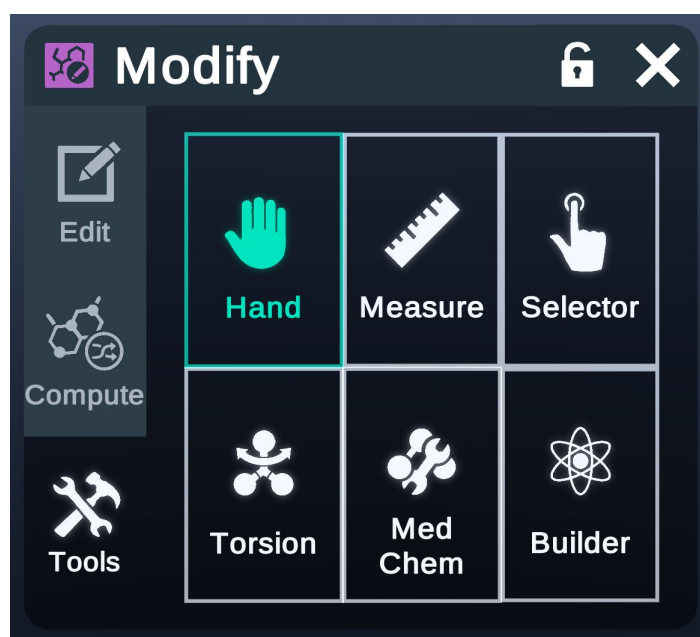


Figure 3.7: Tools Menu of Nanome.ai

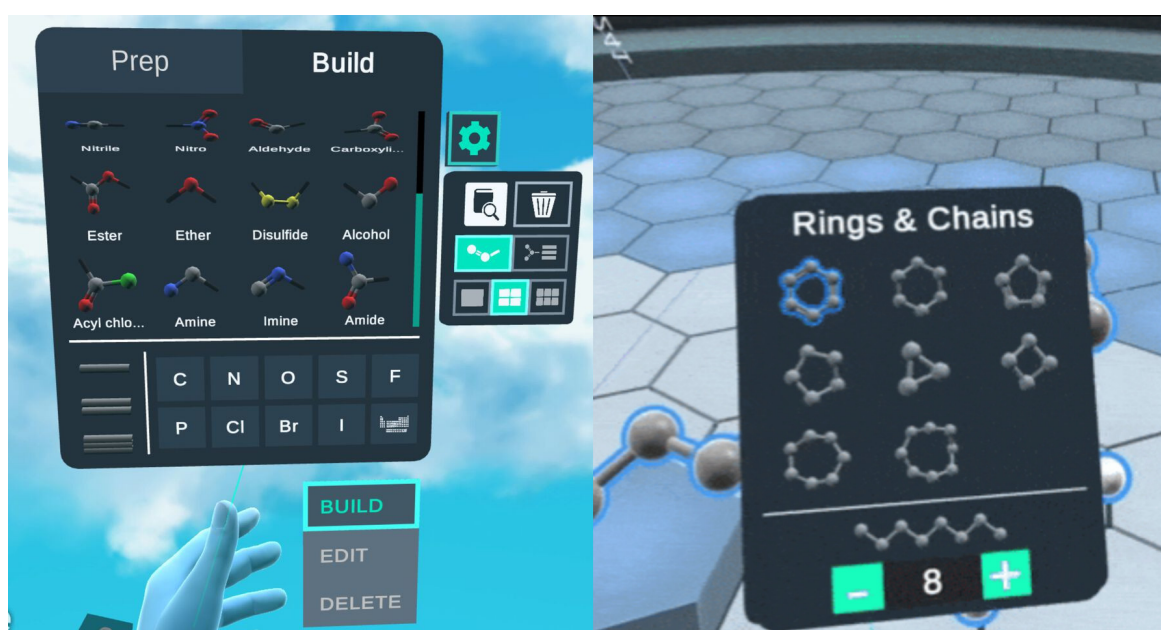


Figure 3.8: MedChem and Build Menu of Nanome.

Narupa is a framework created by Intangible Realities Lab, that focuses on providing rigorous real-time molecular simulation (O'Connor et al. 2019). It enables multiple participants in the same VR instance

while allowing for real-time complex simulations of molecular systems. However, the more interesting part of this application for this thesis is called Narupa Builder. Narupa Builder (**Fig 3.9**) is a sub-system of Narupa that allows the user to build, design, and edit molecules in VR. Its key features are its ability to build and export molecules in MOL2 Format, use the built-in library of common molecular fragments (rings, amino acids, etc.) for composing large structures quickly, or import custom fragments and Import reference images to aid the construction of complex structures.

While achieving similar results to the Narome.ai application, the process is slightly different in Narupa Builder. While in Narome, the menu is always in the same place, with Narupa, there are two menus, one in each controller. The left-hand deals with tools that activate instantly upon selection, and affect the structure in a global sense:

- Minimize structures energy
- Clear All
- Hide/Show Hydrogens
- Export
- Toggle Image
- Balance Hydrogens on Structure
- Undo/Redo

The right hand deals with the tools responsible to edit and modify the structure of the molecule:

- Build Atom: In this menu, the user can choose between several atoms to choose from
- Build Fragment: Similiar to Build Atom, but this time the user can select from an array of pre-composed molecular fragments
- Delete: This allows the user to delete a selected fragment or molecule
- Select: The user can select between fragments, molecules, or atoms which can then be used in various means, such as copy the selected fragment, delete, rotate...
- Copy structure/selection: Allows the copying of the selected fragment or molecule
- Move: Move the selection
- Rotate: rotate the selection
- Connect: creates a connection between the two selected atoms.

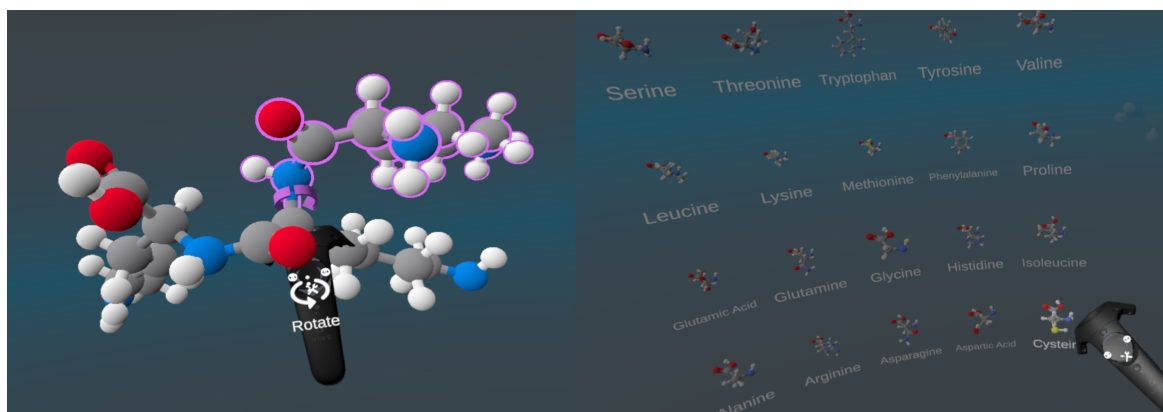


Figure 3.9: Narupa Builder Gameplay and UI

3.7 Past Version Analysis

The version of "Touch On Chemistry" we are going to analyze is the one made by Iris Rodrigues. This project was made in Unity Version 5.6.5f1 and used the HTC Vive with Leap Motion through SteamVR.

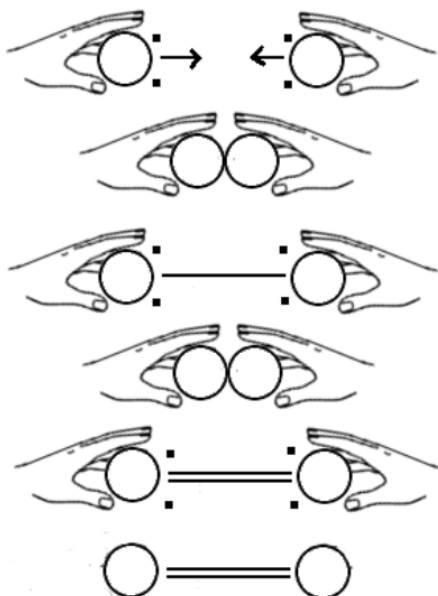


Figure 3.10: An example of how to connect atoms in "Touch on Chemistry"

3.7.1 Idea

The project "Touch On Chemistry" focuses on helping students acquire basic knowledge related to Organic Chemistry, namely nomenclature, structural drawings, and functional groups of organic molecules. The target audience is High School Students and its use should be within the class as a complement to the learning process.

The game presents the user with four different types of challenges: Build, Complete, Transform, and Multiple Choice, but the game mechanics for all the challenges remain the same, making it easier for the player to adapt to the game. In "Touch On Chemistry", the player can create molecules by connecting atoms to one another, as well as translating and rotating the molecules. To connect the atoms, the player must bring two of them together to create a bond (Fig 3.10). However, the player must keep in mind the rules of Chemistry for the bond to appear between two atoms, otherwise, nothing will happen.

The game is divided into several levels, each one can present one or more challenges, and depending on the challenge, the player may have to perform two different actions: One of them requires direct manipulation of the molecules to complete the challenge (Build, Complete and Transform), the other requires the player to press a button with the right answer (Multiple Choice). There are in total 50 levels, with increasing difficulty, and depending on the mode the user chose at the start of the game, a score is attributed to the player. There are also two modes of play. If the Normal Mode was selected, the lower number of moves a player makes, the better his score will be. In Speed Run Mode, the score will be higher the faster a player is to complete a challenge. The environment of the game is very simplistic, where all the game is played inside a virtual Lab.

3.7.2 Challenges

As mentioned previously, there are four types of challenges: Build, Complete, Transform, and Multiple Choice. Each presents the player with a different challenge to test his knowledge.

- **Build** - In this challenge the player receives a piece of information that describes a molecule and has to connect atoms to build the correct one. This information can be the structure, the name, the functional group it belongs to, or the formula;
- **Complete** - This challenge is similar to the Build challenge, but instead of starting from scratch, the player is given a partially built molecule to complete, considering the information given;
- **Transform** - In this challenge, the player is given a complete molecule and with information about the

molecule that he must achieve, has to transform the given molecule into one that corresponds to the described molecule. This information can be the structure, the name, the functional group it belongs to, or the formula;

- Multiple Choice - In this challenge, the player is presented with three possible choices and must look at the molecule given to assess the correct answer.

3.7.3 Results and Conclusions

The final game was tested with eight high school students and seventeen IST students. They were tasked with completing the tutorial and the Normal Mode. However, because the original Normal Mode was fifty levels, for this test only four levels were selected, one for each challenge type. The goals of this evaluation were mainly three:

- Students should be able to easily manipulate the atoms and perform the tasks with no frustration in the Virtual World;
- Students should have fun when playing the game, while also enhancing their knowledge of Organic Chemistry.
- The content presented to students should be accurate to what it is taught in schools.

To measure how well the system was working, the number of moves used to complete a challenge was recorded and a questionnaire was given to students at the end of the experience to assess their enjoyment of the game.

Overall, very positive results were found, with most students enjoying playing the game. However, some students showed difficulties to adapt to some mechanics of the game, namely how to create a bond between atoms. For a bond to be formed, students must let go of both atoms they are trying to create a connection, however, players kept trying to form bonds while holding one of the atoms all the time, resulting in several restarts to the challenge.

The results also showed that the game can be improved in areas like immersion and Challenge (see Fig 3.11) and overall positive experience with the game (see Fig 3.11). What is more, despite showing some promise and having positive feedback from Teachers, the results did not assess how good of an educational tool this game is. Despite finding that the game was fun, the results fail to give concrete evidence of the games' viability to be used with students to improve their academic performance in the long run.

We can also analyze another report of this game made by Diogo Ferreira to encounter yet another set of problems, namely that the hydrogen atoms should be smaller than the other atoms, the impossibility to create rings with the atoms, and that teachers did not have a proper way to use the application, as the game did not have a tool to read data from specific files used in Organic Chemistry. Finally, there is also the problem with the connections themselves. In the current build, the connections do not correctly depict certain rules in chemistry, namely the correct angles between connection and atoms. For example, in Touch On Chemistry is possible for an atom of carbon to be connected with four connections, all connecting to the atom in the same spot, resulting in a molecule that defies the laws of physics and can lead to extremely cumbersome molecules when we increase the complexity of the construction.

In Conclusion, despite "Touch On Chemistry" showing potential to be used in the classroom, this iteration still had areas where it could be improved. On the game side, players would often fail to connect atoms, all the atoms were the same size instead of having different sizes for hydrogen and halogens, it was impossible to create rings and teachers could not make their own levels. And when it came to results, "Touch On Chemistry" was not compared with other methods used in education, such as worksheets, leading to a conclusion that fails to answer if the game could and/or should be used in the classroom as a viable alternative.

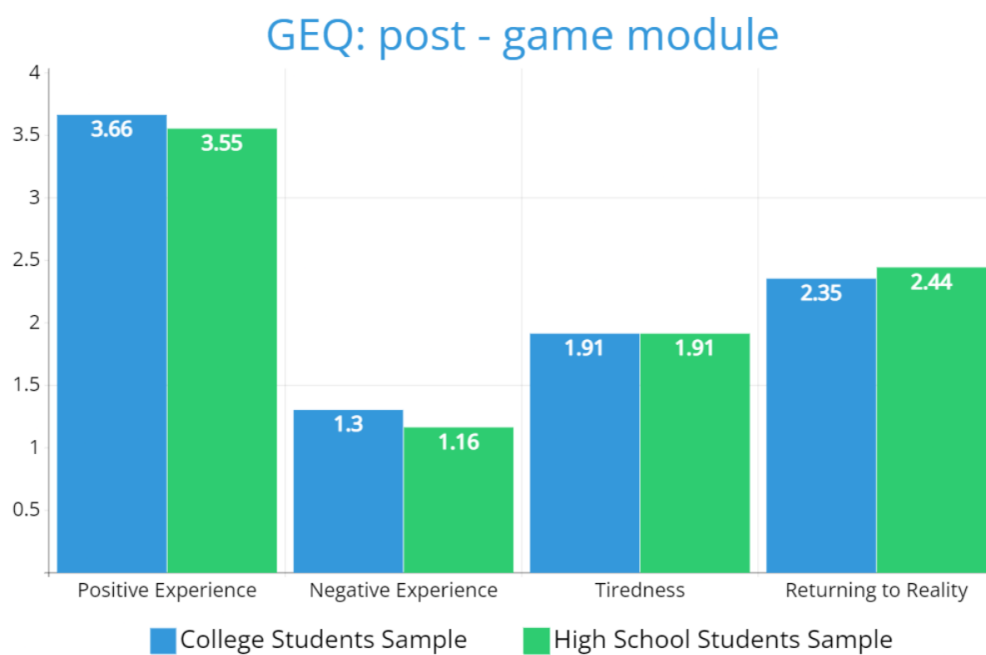
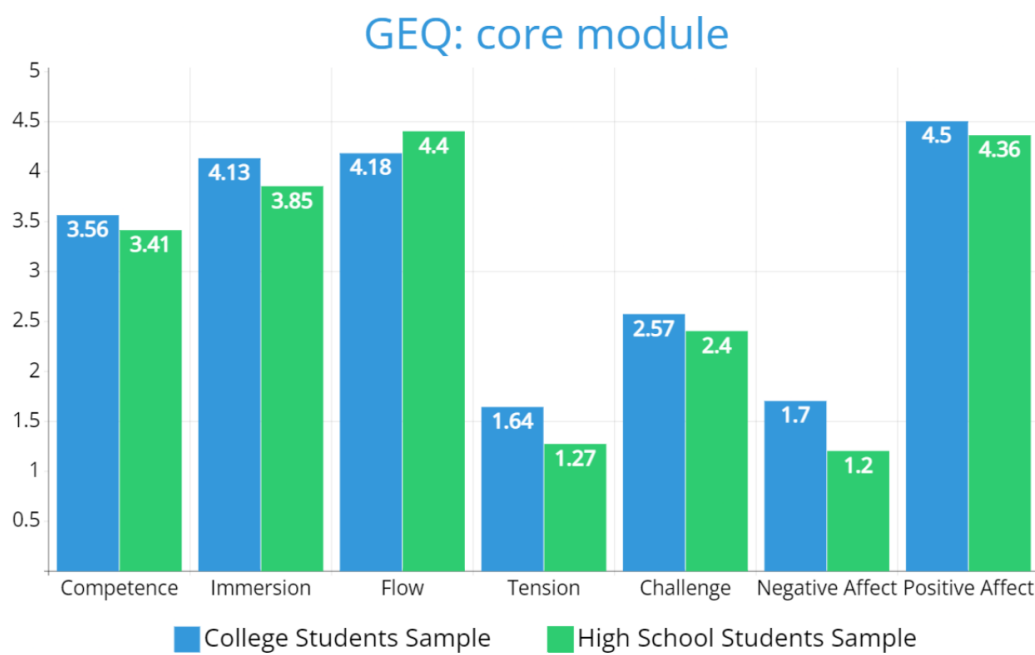


Figure 3.11: Results after testing the current version of "Touch On Chemistry"

Chapter 4

Approach

After gathering all the relevant information regarding the field of study, we can now proceed to make an informed decision on what is the best approach to making the application.

4.1 A Triadic Framework Desing

As we explored in the last chapter, making a serious game requires a careful balance between Pedagogy, Play, and Fidelity, meaning a game to achieve its goal of being a useful tool in education must respect the field of study, while also presenting to the student something new in the form of gameplay or mechanics that are engaging and promote the user excitement for the field. We also saw that using a game in an episodic fashion, especially in VR, is the best approach to maximize the games' effectiveness. To that end, "ChemTouch" must follow these rules if it wants to succeed as a serious game.

ChemTouch will be used to aid new students of Organic Chemistry with introductory concepts that can be hard to perceive in more traditional mediums. These introductory concepts include learning how to build simple molecules, transform molecules into other components, understanding the property differences between molecules with the same atoms and nomenclature, structural drawings, and functional groups of organic molecules.

To achieve this, the game is divided into levels. Each one contains a series of challenges regarding one or two concepts. This way, we prevent the student from being overwhelmed with several areas of study at the same time.

As it was with the previous iteration of "ChemTouch" called "Touch On Chemistry", the challenges will consist in: Build, Complete, Transform, and Multiple Choice. The reason for it is that these four challenges have been proven to be effective regarding player motivation and engagement and encapsulate the goals of this application. However, contrary to "Touch On Chemistry", each level is independent of one another and the game does not automatically advance to the next level. Instead, with "ChemTouch", our aim is for each session to last approximately 30 min. The student learns new material and then can choose the levels in "ChemTouch" regarding that material. After finishing those, the player can stop playing and only use the application again when he acquires new knowledge. Doing it this way, we aim for the application to be of use during the entirety of the course, instead of only being used once.

4.2 Pedagogical objectives

As this is a serious game, we must delineate what are the games' goals regarding its learning outcomes.

Fortunately, these goals were already defined in the previous iteration of the game:

- Recognize and name the major functional groups (hydrocarbons, carboxylic acids, haloalkanes, alcohols, aldehydes, and amines)

With “ChemTouch”, by building molecules and answering questions, students should improve their capacity to recognize the specific 3D structures that make a functional group, while also improving on naming that same group.

- Recognize the functional group a molecule belongs to
On a similar note to the explanation given in the bullet point above, by recognizing the 3D structures that form a functional group, students will be able to associate each molecule they build to the functional group it belongs to.
- Know the nomenclature of the molecules
- Correlate molecular structure with the nomenclature
In “ChemTouch”, several challenges ask the student to build a molecule from its nomenclature, while others will ask to identify the nomenclature of the 3D molecule presented to the player. The goal is to improve the students performance in all the aspects regarding nomenclature of a molecule.
- Correlate conventional drawings of molecular structures with their 3D structure
Due to the nature of “ChemTouch” as a 3D game, we can create challenges asking students to build molecules from their conventional drawing, which should allow students to more easily correlate the 3D and 2D structure of a molecule.

And with these objectives in mind, we can then start thinking about how the gameplay can be built to include this in its mechanics.

4.3 Play Objectives

The Game Part in a “Serious Game” cannot be understated, as it is the defining characteristic of this medium. However, as shown in the previous chapter, it should be carefully planned to work together with the pedagogical goals of the game, and not against it.

In “ChemTouch”, as stated previously, the players will advance in the level by completing a series of challenges. These challenges can be of four types and each type presents the player with different objectives. To aid in the students’ adaptation to the game, the mechanics of the game will remain very similar in all the challenges.

- Build – With this challenge, the player is presented with a piece of information regarding a certain molecule that he must build. This information can be the chemical structure of a molecule, the chemical name, or present the player with one molecule and ask him to build its enantiomer¹.
- Transform – Works similarly to the previous Challenge, but this time the player is given an already built molecule, and his objective is to take this molecule and transform it into another component.
- Complete – The goal in this challenge is for the player to complete a molecule given to him to the molecule that is asked of him.
- Multiple Choice – This challenge works similarly to the multiple-choice questions we are accustomed to, with the benefit that some questions could be asked regarding a 3D molecule presented to the player.

As these challenges are all quite flexible, the pedagogical objectives presented early can all be achieved in every one of these challenges, while also creating fun and engaging content for players to keep wanting to play more than once.

Furthermore, these challenges will also serve as a base for future developers to build upon, in order to create more engaging gameplay and mechanics. An example of this expansion could be in the development of a Role-Playing experience, where the student would go on an adventure conquering castles and fighting foes in a series of fun and engaging challenges (this example is further explored in **Chapter 7.3 - Future Work**).

¹Enantiomer - one of two molecules that are mirror images of each other

4.4 Fidelity Objectives

Finally, it is also important to achieve a high level of fidelity in this game. As this game is for Organic Chemistry, the game must be built with high physical fidelity in mind, meaning that building a model of a molecule in-game can be easily replicated in real life. To achieve this, we can look at the Chemistry Games and Applications previously studied and try to replicate some of its core ideas. What is more, we can look at how the students can build 3D molecules models in real life and use that knowledge to create a workflow that can be easily translated to the real world. The way we achieved this can better be understood in the Implementation Chapter.

4.5 Game Objectives and Environment

Because the game aims to be used in short bursts at a time, there are no concrete objectives in the game besides completing the levels regarding the concepts learned. Due to learning being the most important objective in this game, we felt that creating game modes with restrictions in time or movements the player could take, might challenge the player more, but would lead to an inferior learning outcome, as the user would be more focused on finishing the game as fast as possible instead of taking its time understanding its mistakes and the solutions to the work presented. And a similar conclusion can be presented for the environment the players will be put in Virtual Reality. While it would be possible for students to have levels in fantastic worlds, with beautiful scenarios, at the end of the day, it would take the student focus on the challenges at hand, leading to an unfavorable outcome. Instead, the game world will be as close as possible to the real world. The players will be in a laboratory with a board in front of them presenting the challenges.

Chapter 5

Implementation

We will now dedicate this chapter to the technical implementation of ChemTouch. We will go through each development milestone and explain the decisions that lead to each feature implemented in the game.

5.1 Touch On Chemistry

As previously mentioned, “ChemTouch” is a rewrite and improvement of “Touch on Chemistry”, originally developed by Iris Rodrigues. “Touch On Chemistry” was developed for the HTC Vive and used the Leap Motion Sensor and the Leap Motion Orion SDK.

While working as intended with the use of the HTC Vive and the Leap Motion, the application would not run in any other Headset, and with a combined price of around 880 dollars (or 760 euros), plus the need of a somewhat competent computer that was able to run VR applications and the difficulty to set up all the necessary materials to run the game, made it unthinkable to be considered a tool to be used in the classroom regularly. On the developer side, the use of the Leap Motion SDK meant that the game was specifically created to be used with Leap Motion Sensors, and would not work otherwise. Finally, there were also problems with the version of Unity the game was developed on.

“Touch On Chemistry” was developed in Version 5.6.5f1 of Unity, first released on 28 Dec 2017, which meant that we were going to be working with a version that is almost 4 years old. Add to that the fact that the application would not run on any of the developers PC, no matter the operating system (Windows or Mac), and the framework used was deprecated and newer versions no longer supported that version of Unity, meant that the continued development of the game was impossible.

The solution found was to start from scratch, with “Touch On Chemistry” being used as a reference point to what the overall game should look and play like, as the advantages of doing so far outweighed the cons. By starting anew, new technologies could be explored that would not only facilitate the use of the application with more affordable headsets but also facilitate the continue development of the game.

5.2 Oculus Quest and Unity XR

During the first stages of development, a lot of research was conducted to discover the best possible way of presenting “ChemTouch” to the most amount of people, while also creating a game that would have a solid foundation for future developers to work with. With these goals in mind, this application was created with the Oculus Quest in mind. This decision can be justified not only by the technology’s ease of use and affordability, but also to his accessibility in the University Campus. As mentioned in the multimedia learning section of the Related Work chapter, digital learning, while presenting tremendous advantages for those who can afford it, can have the opposite effect on those who cannot. This statement rings even more true with VR. Due to its somewhat recent development, Virtual Reality is still seen and priced as a luxury technology, only to be afforded by those with the means to splurge a lot of money. However, this perception is slowly

changing, thanks in part to the introduction of the Oculus Quest on May 21, 2019, in the market. This headset had an introductory price of 399 dollars (or about 357 euros based on the USD/EUR conversion rate at the time), which, despite still sounding expensive, was one of the most affordable VR headsets ever released. What is more, the Oculus Quest being a standalone device that could run games and software wirelessly, meant that there was no need for the user to have a powerful and expensive PC to run VR games smoothly. So, in one day, the price of entry to experience VR drastically decreased and could now be afforded by a lot more people. Nowadays, the trend to make VR affordable is not stopping, with new models of the Oculus Quest continuing to lower the entry price to experience VR. As for the framework used, the choice was more difficult. We could choose to use a game engine and a plug-in framework or code everything from scratch. Due to time constraints, the best option was to create "ChemTouch" with a game engine and a pre-built framework. More specifically, we would choose Unity as the game engine as it was the most familiar to the developer team. When it comes to frameworks, the decision was between the Oculus SDK and the Unity XR framework. Both had advantages and disadvantages, with the Oculus SDK having hand support and better integration with the Oculus Quest, while Unity XR is compatible with all the main VR headsets and as better integration with the Unity Pipeline. In the end, the desire to make a game that could be used as a foundation for future developers lead us to choose the Unity XR framework, the fact it supports multiple VR headsets allows future developers to more easily support another device if needed, assuring the continued development of "ChemTouch".

Unity XR is a framework created by the team at Unity. It is a unified plug-in framework that enables direct integration for multiple platforms, allowing for the same project to work with multiple VR headsets with little to no extra work needed for the developers of the application. Furthermore, due to being maintained by Unity, a developer does not need to rely on specific vendors to provide SDKs that may become obsolete in a couple of years.

Opened to the public in 2020, this technology is still in its infancy, but the backing of Unity and the stable environment it provides despite its years and with more features already planned to come out in feature updates, such as hand tracking support in the Oculus quest, make it the perfect choice as the framework to be used to build this project.

By combining both the Oculus Quest and the Unity XR, we aim to create a game that can be played today in one of the most affordable headsets in the market, while ensuring the future development of the application to be hassle-free and easily deployable in other headsets that will emerge in the future.

5.3 Development

Due to the difficulties found in the continued development of "Touch On Chemistry" and the decision to rewrite the code from scratch, the development was completely different from the original plan.

The development was divided into two different stages. In the first one, the objective was to build the core features of the game: atoms, connections, translation, build, and atom selection. After this stage, an informal test was conducted with some students of Organic Chemistry as well as their teacher to gather feedback on the current game development and discuss some ideas and challenges to be implemented in the next development cycle.

The second development cycle would focus on creating the environment and challenges that the students would face in the game, as well as adding some features that were asked during the feedback session. The first development cycle had a duration of 4 months (from the beginning of February till the end of May), with the testing session being performed on June 8 and the second development cycle beginning the day after and lasting another 4 months (from June 8 to the end of September).

5.4 Atoms

The first thing to tackle was how the atoms themselves would look like. To do so, we started by looking at their original design in "Touch On Chemistry". In that game, atoms were represented by 3D spheres.

Each sphere had different colors representing the different chemical elements as well as the chemical symbol imprinted on the atom surface. Each atom also had its respective valence electrons surrounding them (**Fig 5.1**, far left). This solution was a good start, each atom was represented and distinct enough from one another.

The inclusion of the valence electrons also seems like a good idea as it would provide some extra help to the player when trying to remember the characteristics of an atom. However, this solution might not be as good an idea as one initially might assume. One of the first problems with this implementation arises when scaling down the atoms. In the future, the application might be used for creating complex and massive molecule structures.

This type of construction could only be possible by scaling the atoms to a much smaller size. However, that would lead the imprint in the atom surface to become unreadable to the user and could worsen the clarity of each atoms' chemical element. Furthermore, the use of valence electrons could lead to a similar problem when the atoms are scaled-down, as they would be reduced to mere pixels in the screen of the user, and look more like artifacts than their intended goal. The permanent visibility of valence electrons would also clutter the environment, especially when molecules with a lot of atoms are created.

To combat these problems, some solutions were considered. To combat the readability problem, the easiest alternative was just to remove the imprint and each atom would just be differentiated by its color. However, during the testing phase, it was pointed out by one of the users that was red-green color blind how the Oxygen and Chlorine atom were the same color to him and it would be very difficult without more information to distinguish between the two.

With that new knowledge in mind, a final solution was created. Each atom would continue to be represented by its color with no imprint in the sphere. However, now the players could know the name of the chemical they wanted to grab by pointing their right-hand ray to the atom, and then the name of the compound would show up in its left hand (**Fig 5.2**).

A similar first solution was also tested to prevent the valence electrons problem. By removing them, the virtual environment would become a lot cleaner when many atoms were on screen. However, the usefulness of having a clear indication of the atoms' valence electrons was far too great to be eliminated.

To keep these indications while also decluttering the environment, the final solution tackled the problems in two different ways. The first way was to exchange the valence electrons for connection points. Connection points are the places in the atom where a new connection would be created when attached to another atom or molecule. The use of connection points was chosen instead of the original method as they would be a lot more useful when building molecules, by providing visual feedback to the player as to where exactly a connection would be created, with the bonus of doubling up as valence electrons when only one bond was to be created.

The second solution was to hide these connection points and only show them when a connection was to be formed. This way, when the molecule was not being built upon, all the connection points were hidden (**Fig 5.1**, center-left image).

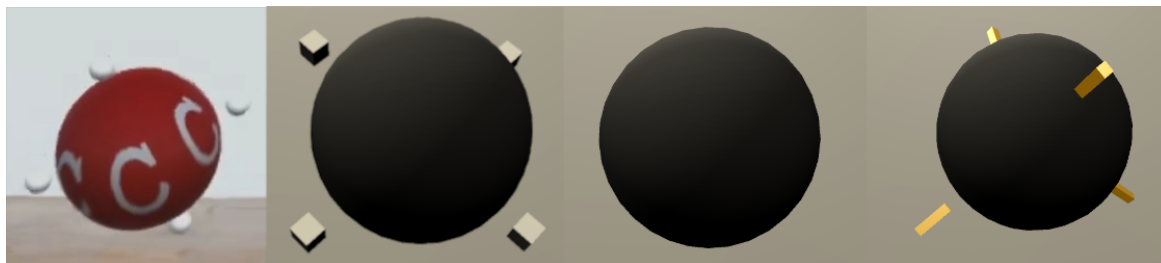


Figure 5.1: Evolution of the Atom in ChemTouch, from the original in Touch On Chemistry (far left), to the final version (far Right).



Figure 5.2: Atom Selection in-game

5.5 Connections

After atoms, it was the connections that needed some tweaking. In the original game, connections were simple 3D cubes that would connect each atom to another. This method worked well for simple connections of only one bond shared between the atoms. However, when the connections required a double or triple bond, the connection would just duplicate or triplicate and stack above the first connection (**Fig 5.3**). This method, while simple and easy to understand by the user, was not very faithful to the actual structure the connections form in the real world and a new approach needed to be implemented that would be both easy for the user to understand and more akin to real-life.

The solution found was to create individual 3D models for each connection type (**Fig 5.4**). These models were inspired by the shapes created when a double or triple bond is built using organic chemistry kits (**Fig 5.5**). Furthermore, now when building a molecule in Virtual Reality, instead of creating a connection each time a new bond is formed between two atoms, the connectable atom ¹ will just provide visual feedback to the user as to how many bonds the connection is currently on, and will only create the 3D model when the connecting atom ² is released (**Fig 5.6**).



Figure 5.3: Triple Connection in Touch On Chemistry

¹Connecting atom – the atom the user is currently holding in its hand

²Connectable atom – the atom the user wants to connect his atom to

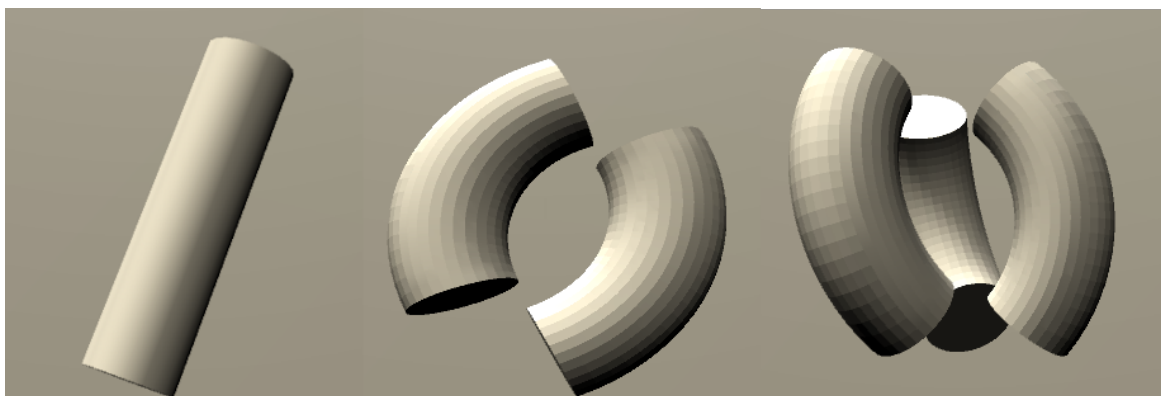


Figure 5.4: Every Connection Type in ChemTouch



Figure 5.5: Organic Chemistry Kit and connections

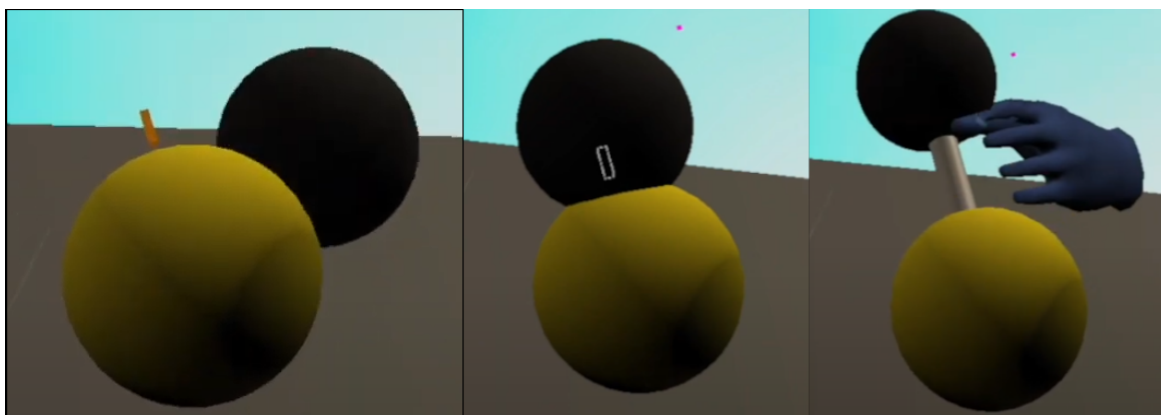


Figure 5.6: Process of creating a connection in ChemTouch

5.6 Build

After establishing how the atoms and connections would work in “ChemTouch”, we now had the fundamentals to start creating the building system.

In the original game, the building system worked by tapping atoms together. For example, if you wanted to connect a carbon and oxygen atom with a double bond, you would need to tap the atoms together twice to form the connection. Later in the development, a new method was implemented. This time the initial connection was formed in the same way, but the bonds were differentiated by the distance between the atoms. The closer the two atoms were, the stronger would be the connection between them.

This method ranked very favorably in the users’ test, so the same method was applied in the current game with slight tweaks. In the current iteration of the game, tapping atoms together will make the connection points appear in the free atom. By tapping again, these connection points change to better illustrate where the new connection will be formed. Finally by pulling the two atoms away from each other resets the connections (see example of pseudo-code below).

```
def changeConnection(atomInHand,atomToConnect)
{
  connectionType=0
  ...
  if(DistanceBetween(atomInHand, atomToConnect)<thresholdtoCreateConnection)
    connectionType=1
  else if(DistanceBetween(atomInHand, atomToConnect)<thresholdtoChangeConnectionType)
    connectionType++
  else if(DistanceBetween(atomInHand, atomToConnect)<thresholdtoRemoveConnection)
    connectionType=0
  atomToConnect.changeVisibleConnectionPoints(connectionType)
}

COMMENT - Function in Atom Class
def changeVisibleConnectionPoints(connectionType)
{
  AllconnectionPoints.setInactive
  switch (connectionType)
    case 0:
      return
    case 1:
      SimpleconnectionPoints.setActive
    case 2
      DoubleconnectionPoints.setActive
    case 3
      TripleconnectionPoints.setActive
}
```

Each connection point is represented by a different color and model. A simple connection point is represented by a single yellow parallelepiped, a double connection point is represented by two red parallelepipeds parallel to each other and a triple connection point is represented by three blue parallelepipeds also in parallel (**Fig 5.7**). Each connection point also provides additional feedback in the form of a white outline surrounding it to inform the player which connection point is currently selected to be used as the connection location (**Fig 5.6**, middle image) . This outline can appear in every available connection point of an atom, with the player only required to bring the connecting atom closer to his preferred point, and can change the connection point by hovering the connecting atom near another point.

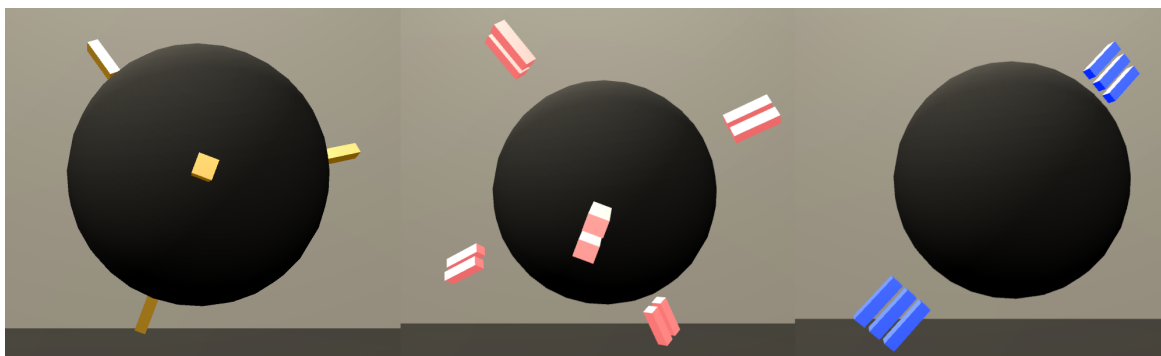


Figure 5.7: Simple, Double and Triple Connection Points represented in the Carbon Atom.

Another tweak made had to do with the connection point positions and structural fidelity of the molecular construction. In the original application, the user could create connections wherever he wanted in the atom if that connection would not exceed the number of connections permitted by the atom. That would make it possible for the user to create connections very close to each other or even inside one another, which is not very faithful to what happens in real life.

To solve this problem, our solution was once again inspired by the organic chemistry kits (**Fig 5.5**) students use to build molecules in the real world. In these kits, the atoms have predetermined connection points where a bond can be placed. These points are strategically placed throughout the atom to better represent his valence electrons position and ensure a more faithful rendition when complex molecules had to be built. The same principle was followed in “ChemTouch”, where the simple connection points represent the same exact points and locations of its counterpart in the chemistry kits, and the double and triple connection points were the location one would get by calculating the median location of the different simple connection points of the atom. Finally, when a connection was created between two atoms, the valence electrons that participated in that connection could not be used again as connection points. For example, if a user connects a nitrogen atom to carbon has a double bond and the connection uses the connection points one and two in the nitrogen, the atom has now lost two of its original connection points, and a new connection could only be created in the remaining connection points (see example of pseudo-code below).

```
def createConnection(atomInHand,atomToConnect)
{...
COMMENT - Want to get the closest connection point of the atom in the scene to the atom in my hand.
ConnectionPoint cp=GetClosestConnectionPointToHand(hand.position,atomToConnect)

COMMENT - Create the connection based on the type of the connectionPoint Used
Connection c= CreatePrefab(cp.type)

COMMENT - Move the connection center position to the middle point between the atom
in my hand and the connection point--
c.moveTo(GetMiddlePoint(atomInHand.position,cp.position)

COMMENT - rotate the connection to correctly point towards the atom we want to connect
c.rotateTowards(atomToConnect)

COMMENT - Move the atom we had in hand to the edge of the connection
atomInHand.moveTo(c.getEdgePointPosition)

COMMENT - Rotate the atom we had in hand to be correctly facing the other atom with the connection point cho
atomInHand.rotate(GetAngleBetweenPoints(atomInHand.getConnectionPointUsed.position,cp.position)
}
```

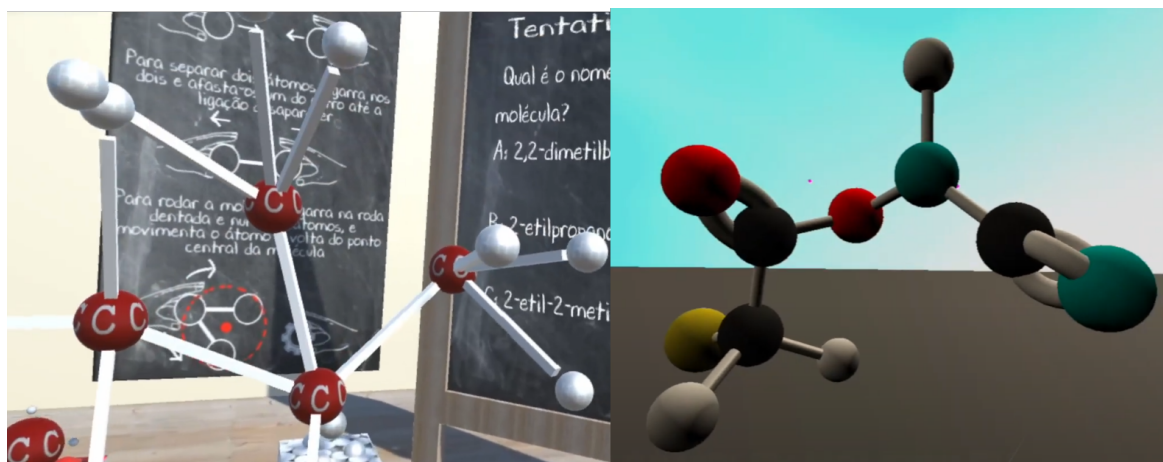


Figure 5.8: Complex build in Touch On Chemistry (left) vs Complex build in ChemTouch (right).

5.7 Move/Rotate

After building a molecule, the user may want to move or rotate it in the environment, so a method had to be implemented to do so.

Fortunately, this was thoroughly tested in the original game, with several concepts being presented to participants and a final method chosen to be implemented. In “Touch On Chemistry”, to move a molecule, the user could choose one of two ways. The first method was to grab one of the atoms and move it to a new location, with the rest of the molecule connected to said atom also being dragged along. The second method was to grab a pivot with the users’ left hand, which would make it possible to move the complete molecule.

After testing both methods, the results favored the first option. It was considered the easiest to use, the most intuitive, and preferred method by almost all the participants. However, this method had a flaw. Since in the original game it was possible to grab atoms of a specific molecule and move it around, with the connection moving along with it, when the user tried to move the molecule with this method, the original connection point would also move around which was not the intended goal of the user when trying to move the molecule of one place to another.

By taking the benefits and problems described into account when developing the current iteration of the game, a new method was created and later perfected that would eliminate the problems defined while maintaining the positive aspects. In the early stages of the development of “ChemTouch”, when a molecule was created, the user could translate it by grabbing the atom that is inside a semi-transparent white sphere (**Fig 5.9**), which would allow him to move the entire molecule while maintaining the original structural integrity of the same. This sphere would change every time to the same place where a new atom joined the molecule. Later in development, this was changed and now the molecule could be moved by simply grabbing any atom belonging to the molecule without the need of a pivot point.

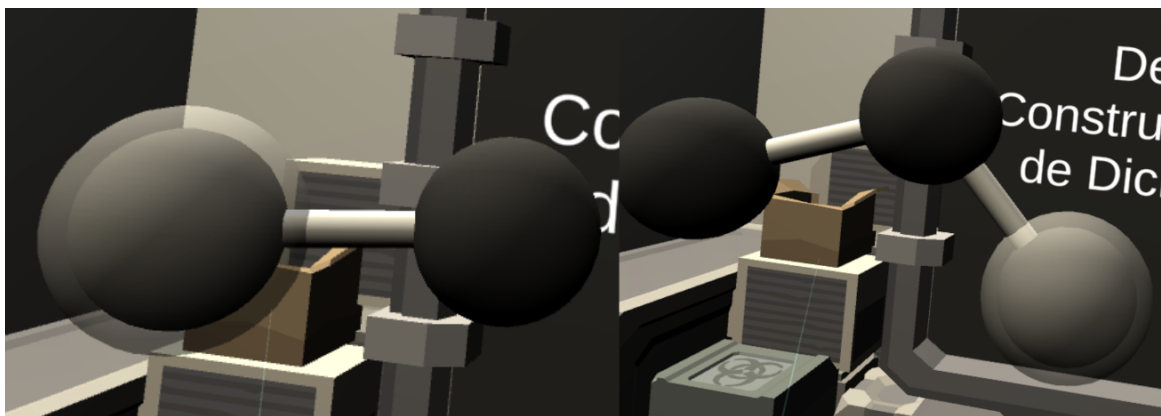


Figure 5.9: Early movement of molecules in ChemTouch

A similar approach was taken with the rotation of the molecule. The test in the previous implementation showed that the method of rotating the molecule around the pivot atom the users were grabbing produced better results in terms of performance and satisfaction, and so in “ChemTouch”, when a user grabs an atom connected to a molecule, not only allows him to move it to another location but also to rotate it around the grabbed atom in all 3 axis.

5.8 Atom Selection

In the original “Touch On Chemistry”, each stage the user participated in contained a different selection of atoms for the user to pick and build with. These atoms were presented above boxes corresponding to that atom element. Each time a user grabbed an atom from the box, a new one would pop up above it (**Fig 5.10**).

This concept, while simple and understandable, had two major problems regarding its goal. The first problem was the selection of atoms. Because in each stage the selection was limited to atoms that the correct solution contained, it would gift the user some knowledge that should not be given and make him correctly guess the answer that he may not have known otherwise. The second problem was the space required for the boxes when the user needed to build a very complex molecule with many different elements. For example, if the goal of a challenge was to build a molecule that contained 8 different elements, the amount of space required in the game for every box would make the experience of building a very tedious task of going back and forward picking atoms from different boxes, far away from each other.

To combat this problem, two methods were developed and tested. The first method was to get rid of the boxes and just put all the elements on a table. This table would always contain the same 8 elements regardless of the challenge the user had to complete (**Fig 5.11**). This way, the user did not have any unwanted help in completing the exercises. To prevent making the user go left and right picking up an element at the time, the elements could be grabbed by pointing the right controller to the desired element. By pressing the grip button, the atom would fly to the users’ hand, while also creating a new one in the same place on the table.

The second method developed was to put the elements in a menu that followed the left hand. With this method, the user would not need to point at a table or boxes to grab a new atom and instead would just need to look at his left hand, containing all the elements in a circular menu around it (**Fig 5.12**). Furthermore, hovering the right controller pointer inside one of these atoms would make his element name appear in the middle of the menu, making it easier for the user to distinguish between each atoms’ element.

After testing both solutions, the second method was chosen as the preferred method. The fact that atoms could be easily accessed by pointing at a menu in the players’ left hand made this method the easiest to use, most intuitive, and the preference of users.

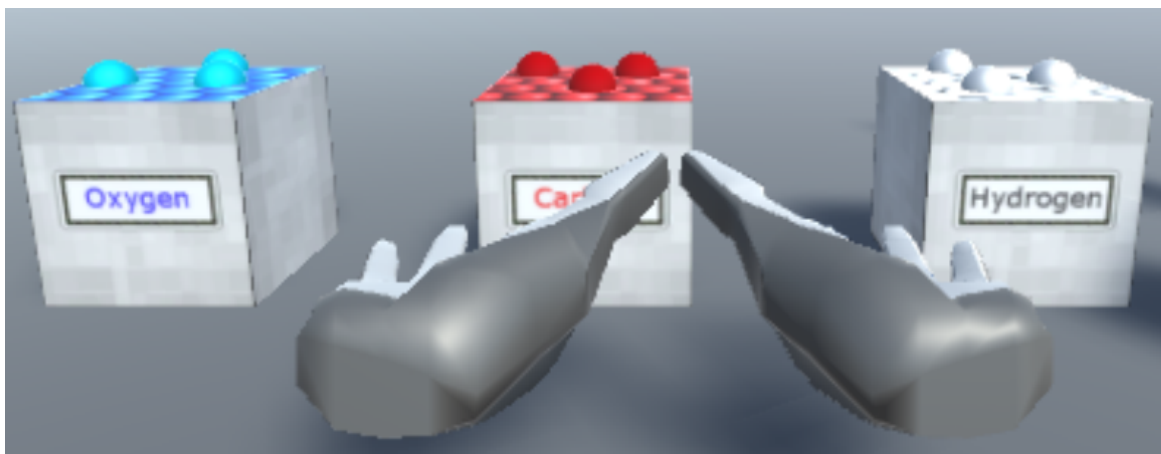


Figure 5.10: Atom Selector in Touch On Chemistry.

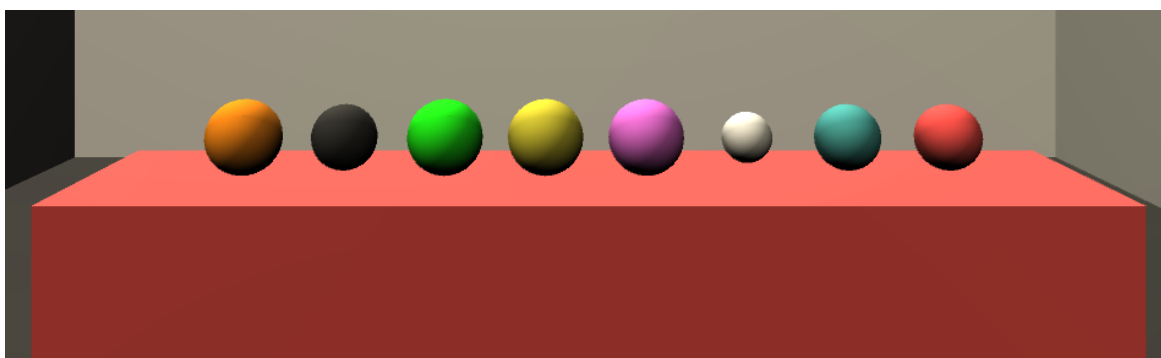


Figure 5.11: First prototype of an Atom Selector in ChemTouch.



Figure 5.12: Finalized Atom Selector in ChemTouch.

5.9 Removing connections, atoms and molecules

Once in a while, the users might make mistakes when building a molecule, so a system that would allow them to remove atoms or even whole molecules had to be implemented in the current game.

In the previous game, the users could remove an atom of a molecule by rapidly pulling the atom away

from it, making the connection between them disappear. To remove an atom or molecule from the scene, the user would drop them in the trash bin present in the game.

When implementing a similar approach in the current iteration of the game, we noticed a problem with the method described previously regarding the removal of connections. Because grabbing an atom also meant moving his molecule, this approach would sometimes make the molecule move unintentionally. We also noticed the risk this method would put the user and especially his surrounding in the real world. By making a fast movement to try and remove an atom, the user could inadvertently strike someone or something, not only hurting himself but causing damage around him in the process.

To fix this, the removal of the connections is now a toggleable menu button. When the player wants to remove a connection, he needs to change his current mode from building mode to erase mode. In erase mode the user can not grab atoms or molecules present in the scene, but he can remove some connections between atoms. When in this mode, some connections change color to red, representing the connections that can be erased, while others will not change color and can not be erased. To delete a certain connection, the user needs to hover his right hand above that connection, and, if it is a red connection, press the grip button in the controller (**Fig 5.13**).

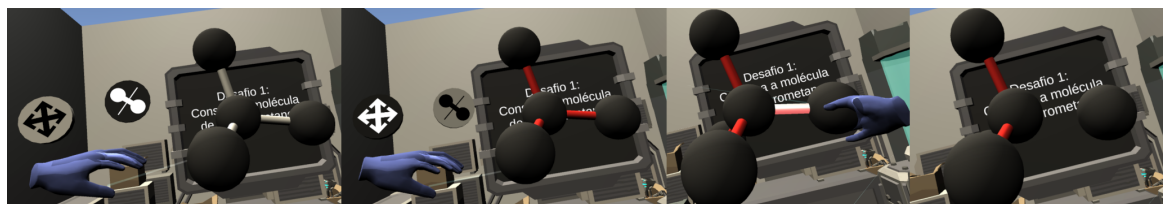


Figure 5.13: Process of deleting a connection in ChemTouch.

To remove an atom or molecule from the scene, the process is a lot simpler. When in building mode, the user just needs to grab with his right-hand controller the atom or molecule he wishes to delete and while grabbing it, press the trigger button on the controller. In erase mode, because the player can not grab molecules or atoms, it is not possible to erase them.

5.10 First Development Cycle Test

After implementing the building system, as well as all the other methods mentioned above, a test was conducted with students and their professors. It was organized by the developers of “ChemTouch”, with the goal of receiving feedback about the state of the current iteration of the game, as well as suggestions for its future development.

The test consisted of the users building a series of molecules with an increasing level of complexity. During each test, the developers would be monitoring what the user was doing in the Virtual World and writing down all the problems they would face in the game. After completion, the users would provide any additional feedback they had, and when all the students were done testing, an unstructured interview was conducted with all the students at the same time, to discuss concepts and possible challenges to be implemented during the second iteration of the game. The test was conducted with 8 students and 1 professor of Organic Chemistry and the feedback received regarded almost every aspect of the game implementation.

As mentioned previously, during the tests one of the students reported difficulties distinguishing between the oxygen and cloro atoms due to his red-green color blindness. Thanks to his feedback, the atoms were changed and now display their element name in the left hand every time the user hovers the right controller pointer on the atom. Another modification made in the project thanks to feedback during this test session was in the atom selector. During the test, several students reported some difficulties in grabbing the correct atom from the table, due to some of them being too far away and leading the users to grab other atoms unintentionally. To correct this, the atom selector was changed to the players’ left hand in a circular menu (**Fig 5.12**).

Besides feedback, by observing the users using the application, some other problems were found. During the test, most would occasionally make a wrong connection in a molecule. However, during this session, the functionality of only removing connections had not yet been considered, and so the users had to delete the whole molecule and start over again. To prevent this from happening again, a new toggleable button was created that would allow the users to delete specific connections instead of having to delete the entire molecule and restart again (**Fig 5.13**).

Finally, it was also noticed how the players had some difficulties in moving molecules. They would try to grab the closest atom of the molecule to them, instead of using the semi-transparent white sphere to move the molecule, and nothing would happen, leading to confusion and frustration. To fix this, the white sphere was removed and the players can now grab any atom in the molecule to move it around.

During this session, it was also discussed some aspects to be implemented in the second iteration cycle, namely the challenges. During the interview, students were presented with some of the concepts already thought of by the developers and asked their opinion about the challenges. The results showed that most would prefer a gaming focus approach to the game, with challenges that would involve using items or spells to complete ranking as the top choice of the students. However, it is also important to notice that the approach that was implemented in “Touch On chemistry” was also well received by the students.

5.11 Environment

When deciding the environment in which the game would take place, some considerations had to be taken into account to create something that would enhance the user experience and not the other way around.

As previously mentioned, when studying the effects of Virtual Reality in education, it was discovered that it can lead to an unfavorable learning outcome due to the capability of Virtual Reality to overwhelm the user with too much information at the same time. To prevent this from happening, the Environment should be as simple as possible, while also being faithful to a real-life scenario.

The scenario in “Touch On Chemistry” follows these rules, it is a very simple scenario containing a table where all the boxes with the atoms are presented and two blackboards in front of the user describing the current challenge (**Fig 5.14**).

In “ChemTouch”, the scenario takes some inspiration from the original environment, while also distinguishing himself from the original in some aspects.

In this version of the game, the scenario contains a lot more details and props filling the environment. The result, while making the scenario a bit more complex, feels a lot more faithful to a real-life laboratory where this type of experiment would take place. Similar to the previous iteration of the game, the use of a blackboard to describe the current challenge returns in this iteration, but this time, instead of two smaller blackboards, the scene only has one bigger blackboard right in front of the player (**Fig 5.15**).



Figure 5.14: The gameplay Environment in Touch On Chemistry.



Figure 5.15: The gameplay Environment in ChemTouch.

5.12 Solution Algorithm

After the student completes building a molecule to complete a stage, it must be analyzed to ensure that said molecule is the correct answer to the current challenge.

In “Touch On Chemistry”, the analysis happened whenever the user clicked on the button to verify the solution (**Fig 5.16**). This button would trigger the function responsible to check if the answer the student gave was the correct one, by analysing what was present in the scene and then checking if it corresponded to the solution.

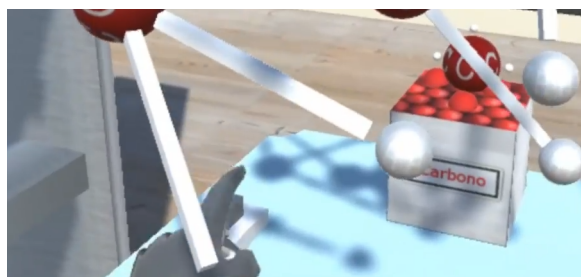


Figure 5.16: The solution process in “Touch On Chemistry”.

In “ChemTouch”, this process was simplified. Now, students just need to place the answer inside the verification machine that will automatically compare the answer to the solution (**Fig 5.17**).

The solution algorithm is present in both iterations of the game, but in “ChemTouch”, the algorithm received some tweaks that enable it to perform better than the older version and is easier to setup.

In the original game, the solution was verified through text files. When building a molecule in this game, a file would store all the bonds the molecule contained. This file would have several strings, each one identifying one bond. The string would contain two pieces of information: The type of bond (simple, double, or triple bond), and the pair of atoms that the bond was connected to. This file would then be compared to the solution file in two phases. The first phase would just check if the molecule and the solution had the same amount of bonds (strings). If they did not, then the verification would stop and the answer would be deemed incorrect. If they did, then each bond on the molecule file would be compared to the bonds in the solution file. If all the bonds on the molecule file were present in the solution file then the answer would be correct.

While this verification system was correct most of the time, there was one case where the verification would incorrectly assume the answer to be right. In the example shown here (**Fig 5.18**), the molecule on the

left is clearly different from the one on the right. However, because they have the same number of bonds and the same pairs of atoms, the solution algorithm would incorrectly assume both molecules to be the same.



Figure 5.17: Verification Machine in “ChemTouch”

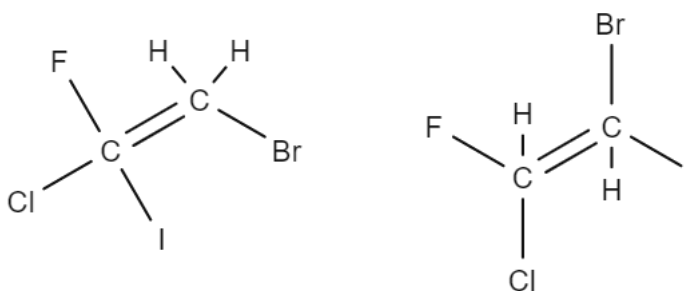


Figure 5.18: Algorithm incorrect case

In “ChemTouch”, a new stage in the verification process was added to tackle the problem described above. Instead of just verifying the number of bonds and the pair of atoms each was connected to, the correct solution algorithm also verifies the atom the bond is associated with. In other words, if the algorithm does not fail during the first two stages, it will iterate through each atom in the molecule and verify all the atoms it is connected with. It will then try to find the same atom in the solution and only when all the atoms are found to be the same in both cases, the molecule is deemed correct (see example of pseudo-code below).

```
def bool solutionChecker(molecule,solution)
{
    numberOfSameAtoms=0
    if(molecule.number_of_atoms==solution.number_of_atoms &&
    molecule.number_of_connections==solution.number_of_connections)
        COMMENT - Passed Test 1
        foreach(connection in molecule)
            if(connection.exists(solution))
                continue
            else return false
        COMMENT - Passed Test 2
```



```

        foreach(atom in molecule)
            if(atom.exists(solution))
                numberOfSameAtoms++;
            else return false
        if(numberOfSameAtoms==solution.number_of_Atoms)
            return true
        return false
    }

\\exists function in connection class
def bool exists(solution)
{
    foreach(solConnection in solution)
        if (this.typeOfConnection==solConnection.typeOfConnection &&
            this.leftAtom==solConnection.leftAtom &&
            this.rightAtom==solConnection.rightAtom)
            return true
    COMMENT - If iterates through all the solution and a connection is not found
    returns false
}

COMMENT - exists function in atom class
def bool exists(solution)
{
    foreach(solAtom in solution)
        if (this.typeOfAtom==solconnection.typeOfAtom &&
            this.connection1==solAtom.connection1 &&
            this.connection2==solAtom.connection2 &&
            this.connection3==solAtom.connection3 &&
            this.connection4==solAtom.connection4)
            return true
    COMMENT - If iterates through all the solution and an Atom is not found returns false
    return false
}

```

For example, in the molecule previously mentioned, after the verification succeeds in the first two stages, it will fail in the third one, as there is no carbon atom in the solution that has Chlorine, Bromine and Carbon has his bonds, nor there is a carbon atom with Hydrogen, Fluorine and Carbon has his bonds.

Besides the improvement in verification, how the verification works have also changed. In “ChemTouch”, the algorithm acts directly on the molecules instead of using text files. In other words, in “ChemTouch”, instead of having to create text files for every molecule a user creates and for every solution to each challenge, the Algorithm works directly in the 3D Structure of the molecule and the solution. By doing so, we allow for a more direct approach in the verification system while getting rid of unnecessary text files. This system also allows teachers to more easily create new challenges for the game. Because the verification is made to the 3D structure, teachers can create new challenges by simply building a molecule in-game. Then, by saving that new molecule as the solution for a new challenge, users can rapidly create several new objectives for students to complete.

5.13 Challenges

The final element to be added to the game was the challenges. As mentioned previously, the challenges present in the older version of the game are the same ones used in this iteration. Not only were they deemed engaging and fun by the users, but every one of them respects the core principles that must be present in a serious game.

The process to complete a Build, Transform or Complete challenge is very similar to the one found in “Touch on Chemistry”. The user is asked to complete the challenge presented on the blackboard, and after completion, he must place that molecule in the verification machine. This machine is the one responsible for running the solution algorithm described previously. The machine can then produce two results: Its insides can shine red, at which point in the blackboard a prompt will appear telling the player his answer is incorrect and to try again. This process does not eliminate the molecule, allowing the player to amend what is wrong with what he just built, instead of needing to retry again from scratch (**Fig 5.19**).

If the inside of the machine turns green, then the molecule built is the solution to the problem. A prompt will appear on the blackboard telling the player he got the answer correct and the molecule will disappear. After a few seconds, a new challenge will appear for the player to complete (**Fig 5.20**).

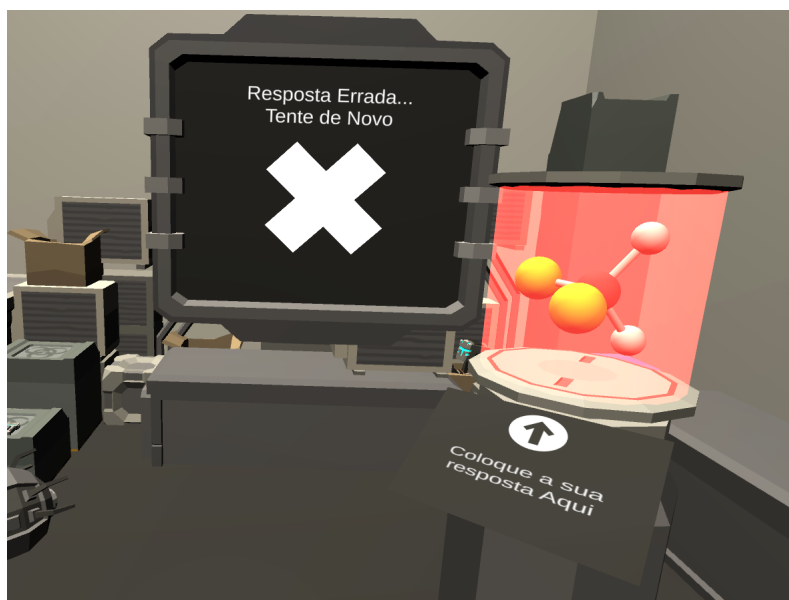


Figure 5.19: A Wrong Answer in ChemTouch.

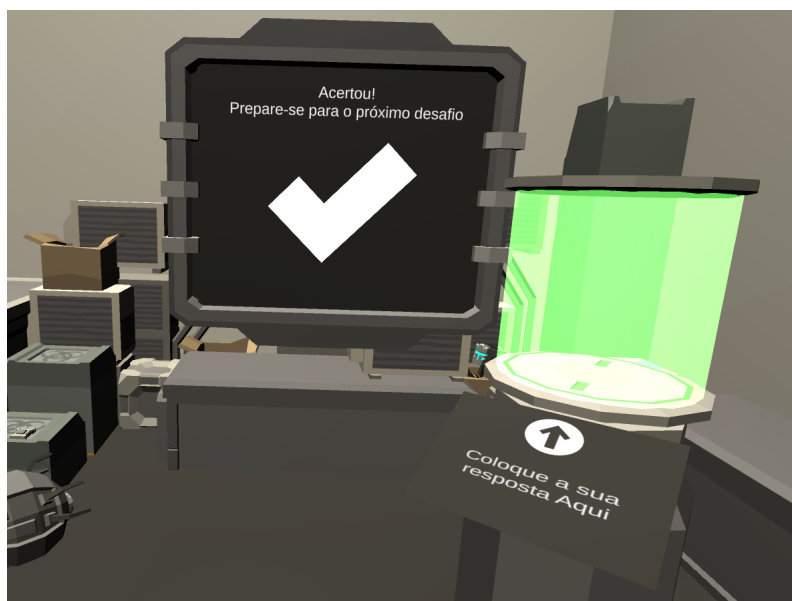


Figure 5.20: A Right Answer in ChemTouch.

To complete a multiple-choice challenge, the method is very different from the past version of the application. In “Touch On Chemistry”, when a multiple-choice challenge was given to the player, four buttons would also appear for him to choose from. Each button was associated with one of the answers and the player would complete the challenge by pressing the correct button.

In “ChemTouch”, the method to complete said challenge was “gamified”. When a Multiple Choice was prompt, a gun and Targets would appear (**Fig 5.21**). Each target would be associated with an answer and the objective of the player was to shoot at the correct one (**Fig 5.23**, **Fig 5.22**).

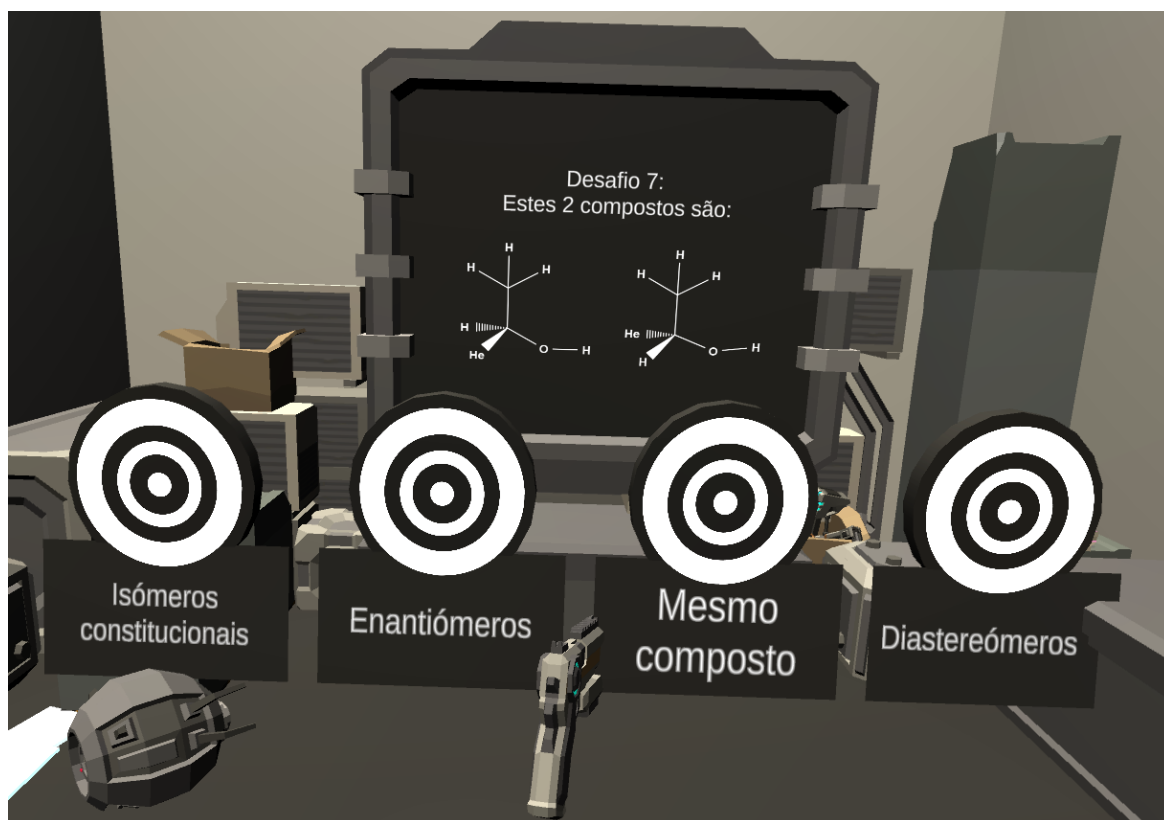


Figure 5.21: Multiple Choice Challenge In ChemTouch.

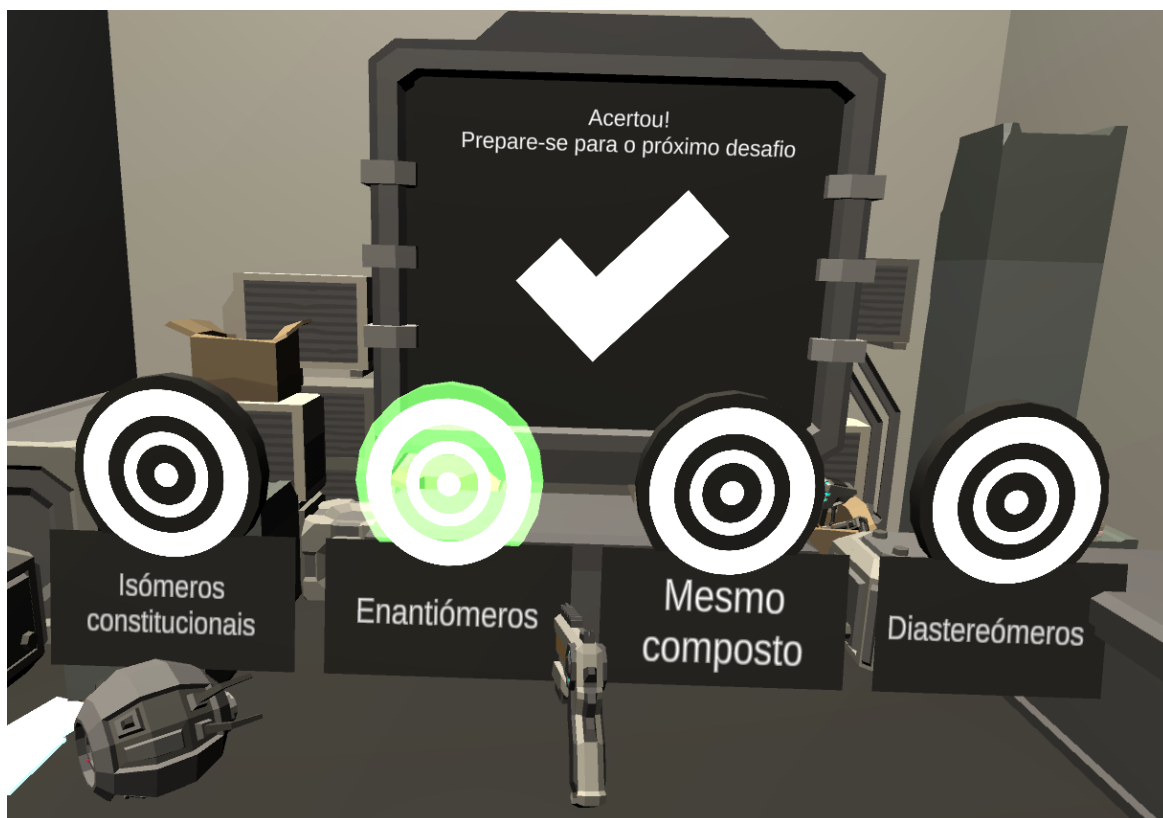


Figure 5.22: Right Answer to a Multiple Choice Question.

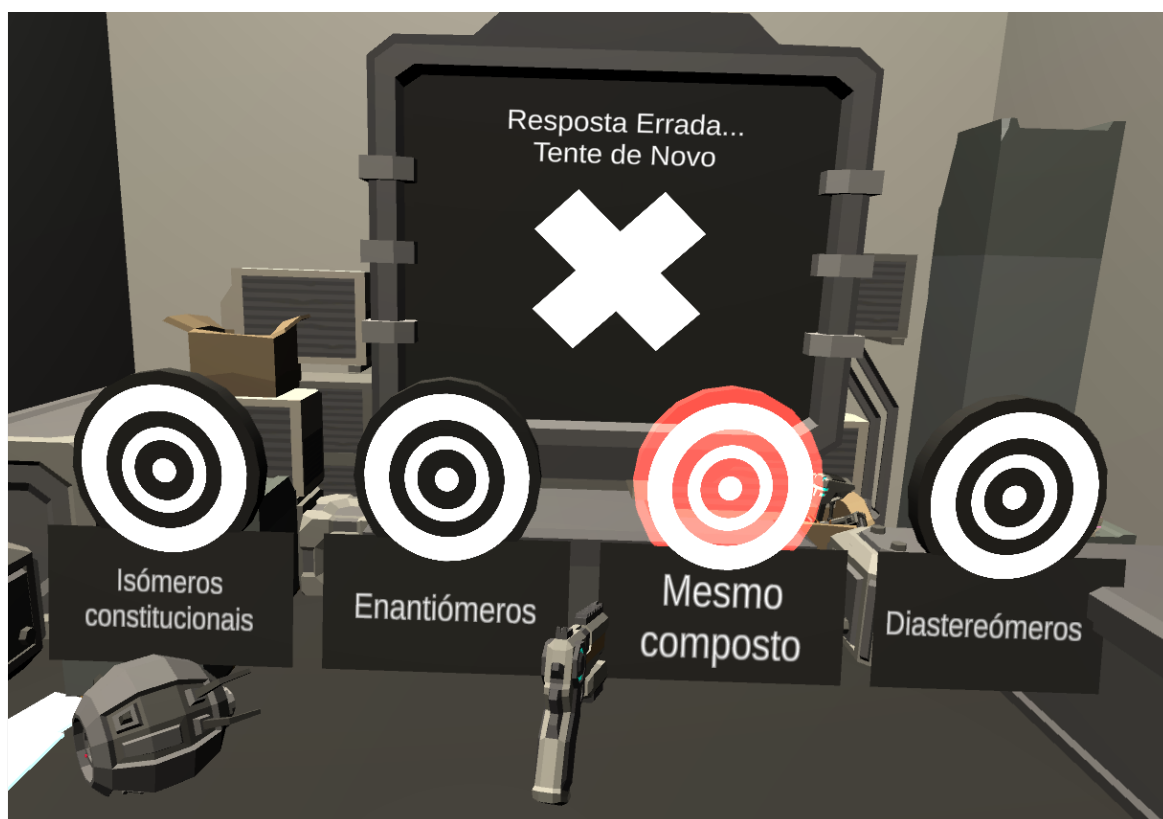


Figure 5.23: Wrong Answer to a Multiple Choice Question.

Chapter 6

Results

In this chapter, the results of this project are going to be presented. We will go over the testing done during the final stage of development, done in two exhibitions of the application, and after we will go over the goals and methodology used during the final testing session, as well as the results, both objective and subjective, of said session.

6.1 NEI/FIC.A Exhibitions

During the last month of development, the final game was tested, during two exhibits, to find problems and receive feedback from participants interested in the application.

The first exhibit was NEI (Noite Europeia dos Investigadores ¹), on the 24th of September. NEI is an exhibit that focuses on providing a place where students can showcase their games and applications to a wider audience, ranging from kids to adults. In this exhibit, each tent would provide the audience with different activities they could participate in and give feedback to the students.

The second exhibit was FIC.A (Festival Internacional de Ciência ², on the 12th of October. FIC.A had a similar objective to NEI, but with the focus on only presenting science projects. The goal of FIC.A was to celebrate science and knowledge within society by having a festival full of unique experiences in the fields of science, technology, culture and art.

The test consisted in completing eight challenges. The first four were building challenges, and the last ones were multiple choice. The building challenges would test the users' knowledge of nomenclature and structural drawings, while the multiple choices tested the users' capacity to distinguish between two molecules.

Due to the nature of the exhibits, most of the users that tested the application did not have prior knowledge of Organic Chemistry. As a result, most of the users could not complete all the challenges. Nonetheless, the goal of finding problems and receiving feedback was accomplished, and much was learned by observing the participants playing "ChemTouch".

6.1.1 Outcome

In NEI, "ChemTouch" was available for testing from 4:00 pm to 11:00 pm, during which ten individuals agreed to participate in the activity. The participants ranged from 13 to 38 years of age, and only two reported having some experience in the contents presented in the game. Of all the participants, only one completed the full test, with four of the participants giving up on the first level, four on the second level, and one on the fourth level.

In FIC.A, "ChemTouch" was available for testing during the same time period as in NEI, and eight individuals agreed to participate in the activity. The participants' age ranged from 14 to 25 years of age, with three participants reporting some experience in the contents presented in the game. Of all the participants,

¹More information about NEI can be found here: <https://noitedosinvestigadores.org/>

²More information about FIC.A can be found here: <https://www.fica.pt/>

two completed the full test, two stopped in the first level, four on the second level, one on the third level, and one on the fourth level.

To summarize, during both exhibitions, there were a total of 18 users that participated in this test. Of the 18, only 3 completed all the 8 challenges, with most stopping in the early levels. The ages of the participants were vastly different, ranging from 13 to 38 years old.

When looking at the average time and tries each challenge took to complete, as well as how many people completed each one, we noticed that the second challenge was the one most of the players failed to complete. When the participants were asked why they stopped at this challenge, the most prevalent reply was the complexity of the solution. Due to their lack of knowledge of Organic Chemistry, most players could not get past this level.

Another problem is the time players would take in completing the challenges. When looking at their times using game logs, we noticed that even the first-level completion time is a lot higher than it should be. By observing the participants using the game, it became quite obvious why this was the case. Before the users started using "ChemTouch" they would receive a short debrief by the developers on how the controls work in "ChemTouch". However, due to some complications during these sessions, most of the debriefs were made without a visual guideline of what would happen in-game when certain action was performed or button pressed. The result was that when most users started playing the game, it became very apparent how ineffective the debrief was, with players just pressing random buttons and showing no clue of how certain tasks were performed. On a more positive note, when the debrief was made in conjunction with in-game visual feedback, where the developers would explain the controls while the participants could see what the task being performed in-game, the users were much faster in adapting to the controls and consequently would be able to complete the first challenge, and were faster than the users that did not receive the debrief with in-game visuals.

The final problem found during these sessions had to do with the deletion of molecules. In the current version of "ChemTouch", when a user is grabbing an atom or molecule in the hand, he can delete it by pressing the trigger button in the controller. The problem with this is that many of the participants would inadvertently press the trigger button while building a molecule, and delete their entire work, resulting in having to restart the build. To fix this problem, just pressing the trigger button must not delete the currently held item. Instead, the user needs to hold the trigger button for a couple of seconds for the deletion to occur.

6.2 Goals

The objective of this test was to evaluate and compare the effectiveness of using Virtual Reality as a complementary tool in the learning of Chemistry. Namely, we wanted to explore how Virtual Reality could help students better understand concepts hard to conceptualize in a 2D space, by providing a 3D environment where the concepts can more easily be understood. A secondary objective of the test was to understand how people felt about using the application ChemTouch in the classroom, and how they perceived this tool when compared to a more traditional method.

6.3 Methodology

To properly test the effectiveness of Virtual Reality as a tool to be used in the classroom, the test aimed to evaluate how "ChemTouch" would fair against worksheets, both academically and subjectively. To do so, students were asked to complete a series of exercises in both mediums, while the developers would take observations regarding the time and tries each participant would take to complete each challenge.

The test would start with the developers explaining how "ChemTouch" works. Then, students would be given a number that would determine the order in which they could complete the test. Students that got odd numbers would begin by completing the worksheets followed by playing the game, while participants with even numbers would do the opposite. By doing this, we would eliminate any bias participants could develop by starting with one medium over the other. During each task, a developer would be observing the students

completing the tasks, measuring the time each participant would take to finish.

At the end of the test, each student completed a series of forms where they were asked to rank their experience in terms of enjoyment and perceived learning outcome in both mediums, as well as provide feedback with regards to “ChemTouch” features and concepts.

Finally, the worksheets were evaluated by the developers, and the academic performance of the students in each task was determined.

6.4 Testing Structure

Both the worksheets and the game challenges followed a similar structure. They were comprised of eight exercises divided into three separate sections. In the first section, students would have to create a molecule from its nomenclature. For “ChemTouch”, this section was comprised of three exercises, of increasing difficulty.

ChemTouch First Section Challenges:

1. Construa a molécula de Diclorometano.
2. Construa a molécula de 2-cloropropano
3. Construa o isómero R do 1,1- cloroflúoroetano

As for the worksheets, this section followed the same length and style of “ChemTouch”, but different questions.

Worksheets First Section Challenges:

1. Construa a molécula de Diclorometano.
2. Construa a molécula de Ácido 3-bromo-2-cloro-2-metilpropanóico
3. Construa o isómero R do 3- metilciclopenteno

In the second section, the objectives were the same, but the questions presented were in a Chemical Formula. “ChemTouch” had two exercises of this type:

ChemTouch Second Section Challenges:

4. Construa a seguinte molécula: CH3CClFCH3
5. Construa o enantiómero da seguinte molécula: CH3CClFCH3
6. Construa a seguinte molécula: CO2HCClCH3CH2Br

While the worksheets had three of these exercises:

Worksheets Second Section Challenges:

4. Construa a seguinte molécula: CH3CClFCH3
5. Construa a seguinte molécula: CH3CHFCH3
6. Construa a seguinte molécula: HOCH2CHCH3CH2CH3

In the final section, both the worksheets and the game were multiple choice questions and would present two molecules to the students while asking them to define the compounds’ relation.

ChemTouch Third Section Challenges:

7. Estes 2 compostos são: see Fig 6.1 a)

- a) Isómeros constitucionais
- b) Enantiômeros
- c) Mesmo composto
- d) Diastereómeros

8. Estes 2 compostos são: see Fig 6.1 b)

- a) Isómeros constitucionais
- b) Enantiômeros
- c) Mesmo composto
- d) Diastereómeros

Worksheets Third Section Challenges:

7. Estes 2 compostos são: see Fig 6.1 c)

- a) Isómeros constitucionais
- b) Enantiômeros
- c) Mesmo composto
- d) Diastereómeros

8. Estes 2 compostos são: see Fig 6.1 d)

- a) Isómeros constitucionais
- b) Enantiômeros
- c) Mesmo composto
- d) Diastereómeros

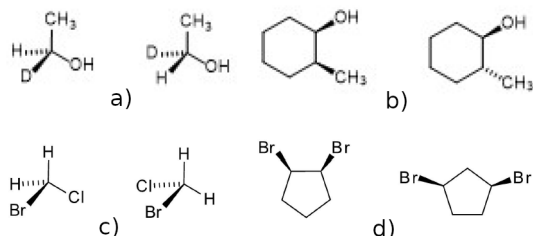


Figure 6.1: Multiple Choices Questions.

6.5 Users Demography

This test was performed by eight students of Biologic Engineering and Chemical Engineering of Instituto Superior Técnico. All of them had prior knowledge of the concepts presented in the evaluation, due to all the participants having had the subject of Organic Chemistry in the previous school year.

When it comes to their familiarity with Extended Reality, most of the participants already had some experience with the technology. Of the eight students, only two had never had any interaction with this medium, and the majority of this experience had to do with Virtual Reality. However, this experience had nothing to do with Organic Chemistry, with none of the participants reporting any experience with the use of VR as a medium to learn the subject.

Of the eight participants, only one reported using Virtual Reality frequently, mostly to play and not as a learning tool, with the rest of the students reporting not having access to the medium or not using it regularly. When asked if they would be interested in purchasing a Virtual Reality Headset soon, the results were split. Of the eight, only three showed an interest in buying a headset in the next one to three years.

Finally, as the building system of “ChemTouch” was heavily inspired by the chemistry kits students sometimes use in the classroom (**Fig 5.5**), they were asked if they had ever used these and how familiar they were with them. Of the eight participants, seven had never used the kits, with only one student using them once or twice before.

6.6 Results

6.6.1 Objective Performance Metrics Results

During the testing phase, there were key performance metrics measured for both mediums. For the worksheets, it was the time it took each participant to complete all the challenges and the final score each achieved. As for the game, we measured the time participants took to complete each challenge, as well as the number of tries they needed to complete a single challenge.

As previously mentioned, the participants were split into two groups, according to their number. To more easily explain the following results, the participants that were given an odd number will be called the WS-FIRST group, while the ones that received an even number will be called the CT-FIRST group. The WS-FIRST group were the ones that started with the worksheets and then moved on to the game, while the CT-FIRST group started by playing the game.

The results shown below reveal some interesting insights in the game viability as a learning tool. When talking about the time it took participants to complete each task (**Fig 6.2**), worksheets performed a lot better in this metric, with an average time of completion almost three times lower than the game. These results can partly be explained by the familiarity the students have with this method and the fact that in the worksheets students could only give one answer per challenge, but also due to the participants’ lack of experience with the game controllers. Despite the developers’ best attempts to explain to the participants how the game works, when looking more closely into the game completion time, it becomes clear that despite the efforts, the students still showed signs of struggling to understand the game mechanics in the early challenges. By observing the average students’ time in each challenge (**Fig 6.3**) we see that the first two challenges take a lot of time for participants to complete, despite being the easier ones in the test (see section **6.3 Testing Structure** to get more information about each challenge). Furthermore, if we compare the average time it took participants to finish each challenge with the time the developer takes to complete the same ones, we see how much time participants lost in the first two levels adapting to the controllers (**Fig 6.4**). Finally, when comparing the WS-FIRST and the CT-FIRST results, it does not look like any of the groups performed better than the other, with some challenges taking more time in one group and others taking more time in another group, but totaling a similar time of completion (**Fig 6.2**). However, when comparing each groups completion times, the results are a lot more promising. While the time it took for the CT-FIRST and WS-FIRST group to complete the challenges in the game was not significantly different, the same cannot be said for the time it took in completing the worksheets, with the CT-FIRST group performing much better than the WS-FIRST group. Because the exercises were similar in both cases and the CT-FIRST group could play the game first where it could retry the same exercise until it was correct, meant that the participants in the CT-FIRST group were better prepared and could more rapidly answer the questions in the worksheet.

Finally, when performing a significance test on the hypothesis: “Is there a significant difference between the performance of the CT-FIRST group when compared with the WS-FIRST group in the average completion time of a worksheet”, the results gave a P-value equal to 0.0016, meaning the difference is considered to be statistically significant.

However, it is important to note that because the CT-FIRST students performed the worksheets after some already being more than thirty minutes into the test, some of these results could be explained by the students wanting to finish the rest of the test quickly and not because “ChemTouch” made them faster at completing the worksheets.

WS-FIRST Group	CT-FIRST Group
10.51	7.28
12.35	8.21
13.32	9.02
13.3	6.61

Table 6.1: Time of completion of the worksheets by each student

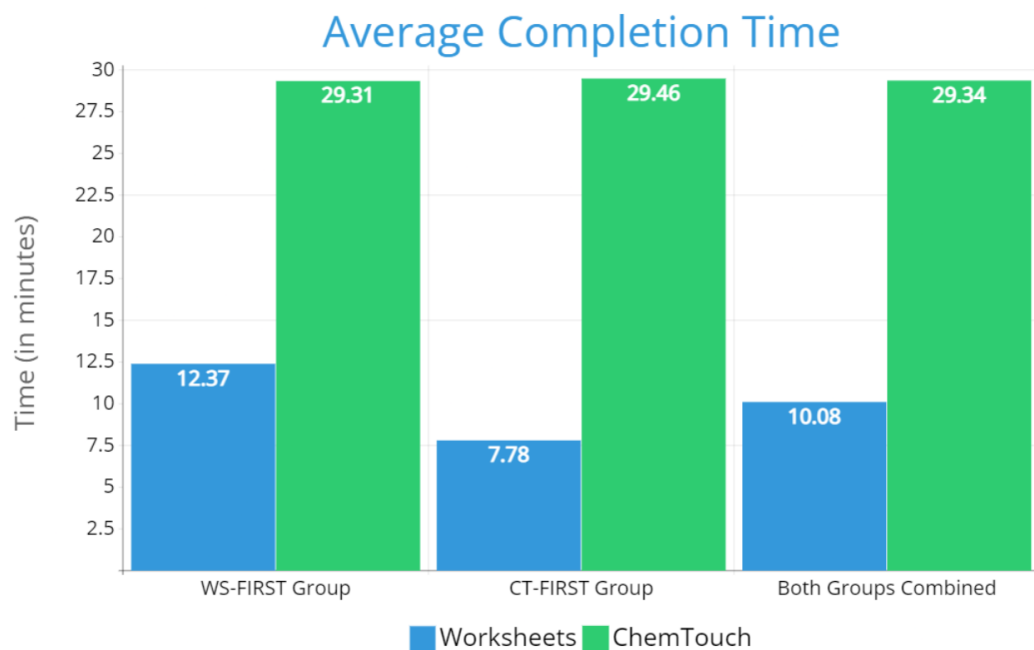


Figure 6.2: Average time of completion of each method.

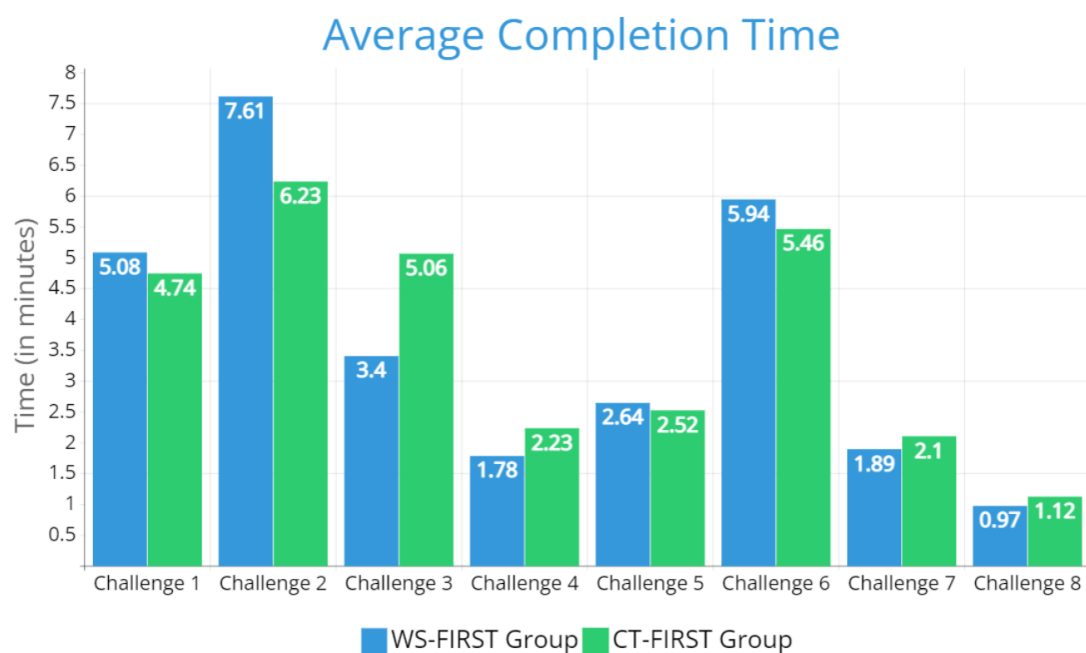


Figure 6.3: Average time of completion of each Challenge by Students in ChemTouch.

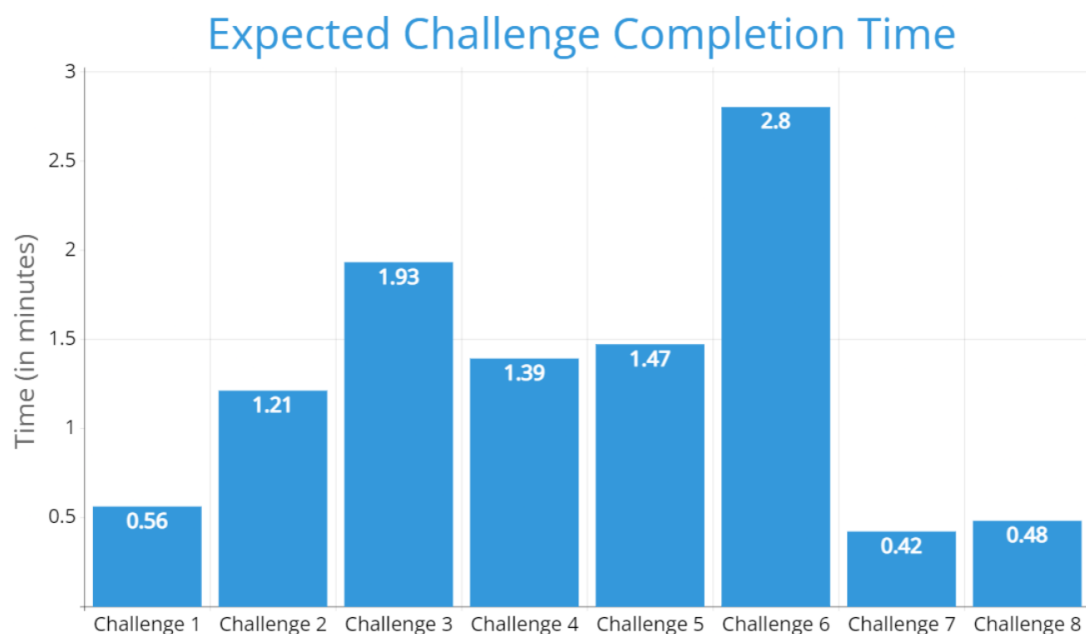


Figure 6.4: Completion time of each Challenge by the developer in ChemTouch.

And when it comes to the final score, the results echo a similar story. Students in the CT-FIRST group performed better than the ones in the WS-FIRST group (**Fig 6.5**). This can once again lead us to believe that using "ChemTouch" could have helped this group perform better in the worksheets.

However, when performing a significance test on the hypothesis: "Is there a significant difference between the performance of the CT-FIRST group when compared with the WS-FIRST group in the score of a worksheet", the results gave a P value equal to 0.3306, meaning the difference is not considered to be statistically significant (p less than 0.05).

Group	WS-FIRST	CT-FIRST
Participant 1	5/8	7/8
Participant 2	2/8	8/8
Participant 3	7/8	5/8
Participant 4	2/8	3/8

Table 6.2: The score of each participant in the Worksheets

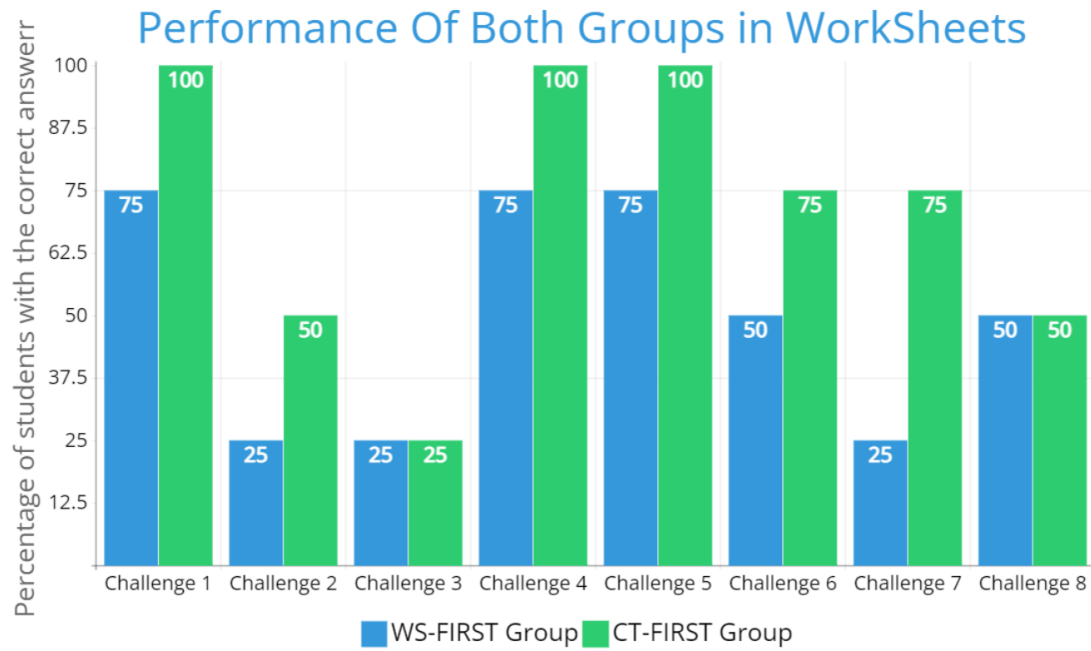


Figure 6.5: Average performance of each group in the worksheets.

When it comes to the number of tries each challenge took the students to complete, we have the same pattern as previously found, with some challenges being requiring less tries in one group than the other, while other challenges, the groups reverse position. However, when it comes to the first challenge, is interesting to see how many tries students needed to complete a challenge they scored quite highly in the worksheets (**Fig 6.6**). The reason for this is similar to the given for the time it took students to complete these same challenges. As the first challenge of the game, it served more as a tutorial for the participants to get a feel for the controllers, increasing the number of tries they took to complete. Therefore, these results are not representative of the difficulty of this challenge and more of the tries it took for the players to become familiar with the game.

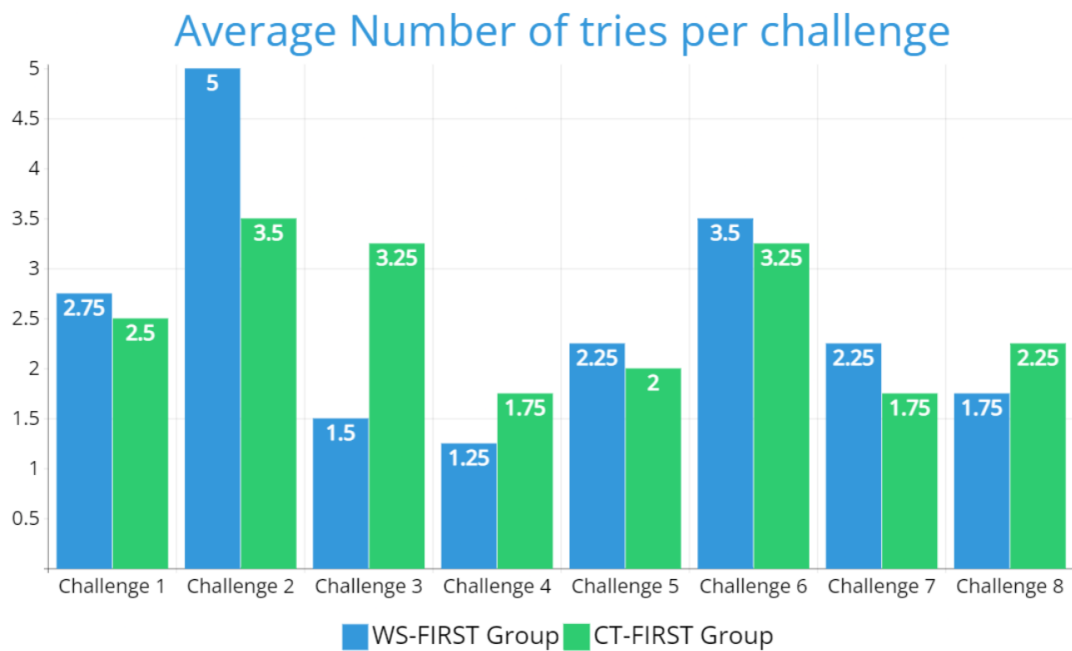


Figure 6.6: Number of tries per challenge by each group.

In conclusion, these performance results show the potential this application can have in improving the students academic achievements. While the time it takes students to complete challenges in the game must be reduced significantly, the participants in the CT-FIRST group were faster and score higher on the worksheets, hinting that “ChemTouch” could have had a real-world impact on the students’ performance.

6.6.2 Subjective Results

While the performance metrics were essential to appraise the game potential as an educational tool, the subjective opinion of the participants is also a fundamental component of this evaluation. There is no point in having an application showing great potential if nobody wants to use it. To that end, participants were asked to provide their opinion by filling three surveys: A System Usability Scale survey, the NASA Task Load Index survey, and a final satisfaction survey. With these three surveys, we aim to understand all the participants’ opinions of “ChemTouch”.

System Usability Scale

The System Usability Scale (SUS) provides a reliable tool for measuring a systems’ usability. It consists of a 10 item questionnaire with five response options that allow you to evaluate the effectiveness, efficiency, and satisfaction of the participant when using the system (**for the complete survey, see Appendix pages A2-A4**).

The first question asked the users if they would like to use “ChemTouch” more often, at which five replied with “Strongly Agree”, one with “Agree” and two with “Neither Agree nor Disagree”. Next, when asked about the system complexity, all the users gave good marks to the system, with five of the participants answering with “Strongly Disagree” and three with “Disagree” to the question “the system was unnecessarily complex”.

However, when it came to the ease of use of the system, the answers were a bit less consistent. When the participants were asked if they thought the system was easy to use, while most of the players gave it a positive score, one of the users gave it a negative one. And when asked if they would need the help of someone with technical knowledge to use the system, the answers were split between all the possible answers.

And this trend does not stop for the next two questions, where the users were asked if they thought the system was well integrated and functional and if they thought the system was inconsistent, most of the answers gave a positive score to the system, with one or two participants giving it a negative score.

Fortunately, this trend seems to stop for the next questions, all the participants thought the system was not difficult to use, and all but one thought he could learn how to use the system quickly.

Finally, the last two questions seem to follow the same trend as the ones connected with the applications’ ease of use. When asked if they felt confident using the system, most users gave a positive remark, while two give it a negative one. The last question asked if the user needed to learn several things before using the application at which most students responded that they did not with one answering that he did.

In conclusion, when it comes to the system usability, “ChemTouch” performed well, scoring an average 78.75 points out of 100, indicating that the system only needs minor improvements to the design.

NASA Task Load Index

The next questionnaire the participants were asked to fill was the NASA Task Load Index. This survey aims to rate the perceived workload in order to assess a task, system, or teams’ effectiveness or other aspects of performance (**for the complete survey, see Appendix pages A5-A6**).

The results showed promise at the start, with students giving positive remarks to how mentally exhausting it was to complete the exercises in “ChemTouch” and mostly positive at how physically exhausting it was, with one participant giving it a negative response. When asked how they felt about the pace of the experiment, the results were also positive, with no negative scores and most giving it a positive one.

However, this trend would not continue with the final three questions. When asked to rate their performance from “Horrible” to “Excellent”, three of the students rated themselves with the lowest ranking, with

two students ranking their performance as “Okay” and the other three ranking it as “Good”. When asked how hard the participants worked to achieve their level of performance, the results were very mixed. Two of the users thought they achieved their level of performance with low effort, three thought they achieved it with a “Decent” amount of effort, two with a “Good” amount, and one with a “Great” amount of effort. The final question asked how insecure, irritated, demotivated, stressed, and bored the players felt when completing the challenges in “ChemTouch”. This time the results were mostly positive, with half the participants answering they did not feel those emotions at all, and only one of the participants felt them a bit.

In conclusion, “ChemTouch” also performed quite well in this survey, scoring 73 points out of 100, indicating that the system still needs a few tweaks to reduce its perceived workload on the students.

Final Satisfaction Survey

The final survey was a comparison between the worksheets and the game. This comparison was done by asking the same questions to the students regarding both learning methods. In other words, when completing this survey, students were asked a series of questions about what they felt when completing the exercises using worksheets, and then they were asked the same questions, but this time regarding “ChemTouch” (**for the complete survey, see Appendix pages A7-A15**).

The results showed a very favorable view of “ChemTouch” when compared to the worksheets. Participants felt they did not need to try as hard to complete the tasks in the game, with three participants giving the application a positive score when compared to the worksheet single positive mark. All but one of the players gave the max possible score to the game in terms of how fun it was, compared to the worksheets six negative scores.

When asked if they wanted to use this game again during class, every student replied favorably, while the worksheets got mostly a neutral score. Users also felt that the exercises were overall easier to complete in the game when compared with the worksheets, thanks in small part to being able to try the challenge again if they failed compared to the worksheet one try policy. Students also felt more motivated to learn when using “ChemTouch”, compared to the use of worksheets where they actually felt less motivated.

The next question was the first where the worksheet could be thought of as the winner, when participants were asked how frustrated they felt when completing the exercises, two of the participants reported feeling this way when using the application, compared to zero in the worksheets. Despite this, the motivation of the users did not seem to be fazed by the frustration, with no users reporting feeling unmotivated when playing the game. For the next three questions, the answers to both methods were the same. Participants felt that the time given to perform the task was sufficient in both cases, understood what was asked for them to do, and felt both methods could be used in Organic Chemistry. Users also felt they would be more motivated and interested in Organic Chemistry if they could use this application more often in place of worksheets in the classroom, and the same sentiment was true for using the application at home.

When asked about their performance and using these methods as tools to aid in their preparation for exams, the worksheet seems to gain the upper hand. Students felt they performed better in the worksheet than in the game, and would also prefer to use them as their method of choice to prepare for the tests/exams. However, participants felt that they would have a better performance in Tests/Exams if they could use “ChemTouch” as a method of study. While this answer seems counter-intuitive at first, it does make sense for students wanting to use new methods of study to aid in their preparation for exams. Thanks to the superior capabilities of representing 3D, “ChemTouch” can be a tremendous help for those having difficulties understanding some concepts while only using worksheets.

Finally, it was asked if students thought if this method would be the future in education, to which all the students responded favorably to the game, while the worksheets mainly received a neutral score.

Results Conclusion

In conclusion, the results show a very promising future for “ChemTouch”. From the performance metrics to the subjective results, this game showed that an effective game to aid students learn Organic Chemistry is

possible to create. By using this application, users felt more motivated and interested in the topic, while also improving their performance in a real-world scenario.

However, despite the good results, there were also some problems participants encountered with the application, making some feel frustrated and unsure about its use as their choice to prepare for Tests/Exams. If in the future these problems can be solved, then there is no doubt that “ChemTouch” can become a serious tool in the arsenal of students of Organic Chemistry.

Chapter 7

Conclusion

The original plan for this thesis was to take the original version of “Touch On Chemistry” and improve its core mechanics and the “gamification” aspect of the game.

However, due to some unforeseen obstacles, the plan had to be changed. The main goal of this thesis was now to port the original game to an up-to-date version of Unity and create a foundation where future developers can easily pick up its development and improve the game as they deemed best.

In this chapter, we will analyze the process of creating this application, by exploring what we achieved, what we failed to achieve, and the future of “ChemTouch”.

7.1 Achievements

As mentioned previously, the critical goal of “ChemTouch” was to provide future developers with the groundwork of a Serious Game that aims to help understand Organic Chemistry. Fortunately, this goal was achieved. “ChemTouch” is now the successor of “Touch on Chemistry”, developed in newer software and hardware that not only simplify the continuation of the project development but significantly reduce the cost of entry to users interested in experiencing VR as an educational tool.

Another goal that we aimed to achieve in the development time was to improve on some concepts present in the original game, which we did. In “ChemTouch”, almost all the core concepts present in “Touch on Chemistry” were revised and reworked to be easier to use.

Finally, the results achieved during the testing phase of the finalized game are also worthy of attention. Most users that played “ChemTouch” enjoyed themselves, even the ones without prior experience with Organic Chemistry. These results can be seen as a testament to the positive experience any user can have when playing this game and the potential to use it as a tool to help attract more people to learn Organic Chemistry. The results also reveal the academic performance expected of students when using “ChemTouch” is similar to the use of worksheets, but with an increased engagement and motivation to complete the work. There were even cases where students reported having a much better time understanding concepts presented in the Virtual World, thanks to its capacity to display 3D structures.

7.2 Problems

During the development of “ChemTouch”, there were also some problems found. One of the first and most difficult challenges to overcome was creating the current building system. Due to the project using connection points as anchors for connections to form, meant that a lot of calculations had to be done before a single line of code was written. Not only the position but the rotation of each atom had to be taken into account for the structure of the molecule to be correct, making this feature the hardest one to implement into the game.

Another challenge found had to do with the SDK used when first implementing the basic features of a VR game. Due to his recent development, Unity XR does not yet have a big community of developers

ready to help when a bug is found, leading to some time wasted finding solutions to problems discovered at the beginning of the game creation. Fortunately, the documentation of XR was enough to fix most of the problems and the next developers will not need to worry about most of them.

Finally, there were also problems found during user testing. Because the final testing was done during a hole in the students' schedule, not many participants willingly showed up to use the application, with a total turnout of only 8 participants. This meant that the information collected during testing, although very important, could not be used to answer more complex questions requiring a bigger sample size. Another problem we had during the tests was the predominance of mistakes and "game-breaking" bugs the students found during the use of the application. This problem would occur a lot less frequently when the users would first watch a tutorial where they learned the controls and mechanics of the game, but it would still happen enough times to frustrate some users.

7.3 Future Work

Now that the groundwork for the game has been built, there are no shortages of possibilities when it comes to future work. From improving the gaming aspect of "ChemTouch" to adding new features to the application, the development of "ChemTouch" is just beginning. In this section, we will discuss some features that may be implemented in the future, as well as possible improvements to the already existing ones.

- **Tutorial:** The first and probably the most important new feature to be implemented in "ChemTouch" is a tutorial. During the testing phase, it became apparent that an explanation of some sort would be crucial for new users to experience the game the way it was intended. Users that were thrust directly into the world would make a lot of errors and be forced to restart the game multiple times, while ones that had previously learned the basics of the game would fair immensely better in completing the task at hand
- **Rotation of connections:** In the current game, the user cannot rotate connections already established in a molecule. While not a problem in smaller molecules, in complex molecules the connections would sometimes overlap one another. With this feature, the user could choose to rotate connections between atoms to help maintain a sound structure, even for very complex molecules.
- **Improved solution Algorithm:** The solution algorithm present in ChemTouch is already an upgrade from the original game. However, there are still cases where it could improve, mainly in the evaluation of enantiomers. Because they are a fundamental part of Organic Chemistry, the algorithm should be able to evaluate these cases when needed.
- **Hand Support:** The original game was built with hand tracking in mind. However, due to the early development of Unity XR, hand tracking is still not supported by the SDK. However, that support is scheduled to be added sometime next year, and migration to hand tracking could be possible to implement in a future version of the game.
- **Gamification of "ChemTouch":** Despite the change in this thesis goal, the gamification of "ChemTouch" is still a priority in the development. Future developers should focus on improving the game experience by modifying the challenges in a way that would promote player engagement and motivation while making sure the academic performance of the students would, at least, remain the same. For example, "ChemTouch" could implement some role-playing into the game. Instead of taking place in a laboratory, the game could follow a story where the player must conquer different castles to complete the game. Each castle would represent a level in the game, each one with a unique theme of Organic Chemistry:
 - **Nomenclature Castle** - In this castle, the player challenges their knowledge about molecules nomenclature.
 - **Functional Castle** - In this castle, the player challenges their knowledge about functional groups
 - **Structural Castle** - In this castle, the player needs to correlate the 2D and 3D structures of a molecule

With the use of different castles, the player would be able to tackle different learning objectives, one at a time, making the application viable to be used during the students' semester.

Each castle would be composed of challenges with similar mechanics to the challenges currently implemented, but with some twists:

- Build Challenge - Defeat the Horde: A series of monsters will rush at the player and the only way to stop them is to build the molecule each monster is weak to (**Fig 7.1-a**).
- Complete Challenge - Make a Path: In this challenge, the ground in front of the player has collapsed and he must rebuild it by completing the missing pieces in the molecules that constitute the ground (**Fig 7.1-b**).
- Transform Challenge - Destroy Obstacles: In this challenge, the player will face immovable obstacles, and by transforming the molecules that constitute that object, make them movable again (**Fig 7.1-c**).
- Multiple Choice - Shooting Range: In this challenge, the player will have to shoot at the right target to the question asked (similar to the same implementation in the current iteration (**Fig 5.21**)).

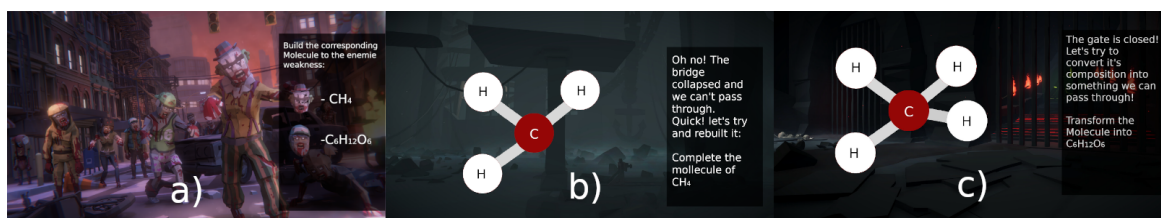


Figure 7.1: Possible gamification of “ChemTouch” challenges

- Level Creator: In the current iteration of “ChemTouch”, there is no way for users to create new challenges inside the game. To fix this, a level creator should be added to the game where users could easily and rapidly create new challenges.
- Creating benzenes and other closed molecules: At this stage in development, benzene rings and other closed structures cannot be created. As these are considered a fundamental part of Organic Chemistry, they must be supported in a future version of “ChemTouch”, whether by allowing the user to close molecules or giving the user a selection of pre-built molecules of this nature.
- Improve game stability: Finally, the last thing to improve is the stability of “ChemTouch”. During the user testing, some bugs were found that need fixing. These bugs range from mildly inconvenient to game-breaking, meaning that some bug-squashing is crucial for the future stability of “ChemTouch”.

Bibliography

- [1] P. Backlund and M. Hendrix. “Educational Games - Are They Worth the Effort? a Literature Survey of the Effectiveness of Serious Games”. In: Sept. 2013, pp. 1–8. DOI: 10.1109/VS-GAMES.2013.6624226.
- [2] M. Carroll, E. Osborne, and C. Yildirim. “Effects of VR Gaming and Game Genre on Player Experience”. In: *2019 IEEE Games, Entertainment, Media Conference (GEM)*. 2019, pp. 1–6. DOI: 10.1109/GEM.2019.8811554.
- [3] M.-T. Cheng et al. “The use of serious games in science education: a review of selected empirical research from 2002 to 2013”. In: *Journal of Computers in Education* 2 (July 2015). DOI: 10.1007/s40692-015-0039-9.
- [4] S. Games. *HoloLab Champions*. <https://www.schellgames.com/games/hololab-champions/>. 2018.
- [5] H.-T. Hou and Y.-C. Lin. “The Development and Evaluation of an Educational Game Integrated with Augmented Reality and Virtual Laboratory for Chemistry Experiment Learning”. In: *2017 6th IIAI International Congress on Advanced Applied Informatics (IIAI-AAI)*. 2017, pp. 1005–1006. DOI: 10.1109/IIAI-AAI.2017.14.
- [6] N. Inc. *Nanome.ai*. <https://nanome.ai/>. 2018.
- [7] R. Inc. *REACT! The Organic Chemistry Game*. <https://www.reactgame.com/>. 2020.
- [8] M.-H. Lin. “A Study of the Effects of Digital Learning on Learning Motivation and Learning Outcome”. In: *EURASIA Journal of Mathematics, Science and Technology Education* 13 (July 2017). DOI: 10.12973/eurasia.2017.00744a.
- [9] A. E. S. P. LLC. *Chemcaper*. ”<https://chemcaper.com/about-the-game/>”. 2016.
- [10] G. Makransky, N. K. Andreassen, et al. “Immersive Virtual Reality Increases Liking but Not Learning with a Science Simulation and Generative Learning Strategies Promote Learning in Immersive Virtual Reality”. In: *Journal of Educational Psychology* (Feb. 2020). DOI: 10.1037/edu0000473.
- [11] G. Makransky, T. S. Terkildsen, and R. E. Mayer. “Adding immersive virtual reality to a science lab simulation causes more presence but less learning”. In: *Learning and Instruction* 60 (2019), pp. 225–236. ISSN: 0959-4752. DOI: <https://doi.org/10.1016/j.learninstruc.2017.12.007>. URL: <https://www.sciencedirect.com/science/article/pii/S0959475217303274>.
- [12] R. Mayer. “Multimedia Learning: Are We Asking the Right Questions?” In: *Educational Psychologist* 32 (June 1997). DOI: 10.1207/s15326985ep3201_1.
- [13] R. E. Mayer. “Cognitive Theory of Multimedia Learning”. In: 2003, pp. 43–71. DOI: 10.1017/CB09781139547369.005.
- [14] M. O’Connor et al. *An open-source multi-person virtual reality framework for interactive molecular dynamics: from quantum chemistry to drug binding*. Feb. 2019.

- [15] C. Oswald, C. Prorock, and S. Murphy. "The perceived meaning of the video game experience: An exploratory study". In: *Psychology of Popular Media Culture* 3 (Apr. 2014), p. 110. DOI: 10.1037/a0033828.
- [16] S. V. Paiboon Boonpotjanawetchakit Kansinee Kaweerat. *Elemem: Interactive Digital Card Game for Chemistry*. The IEEE Global Engineering Education Conference (EDUCON) 2020. Porto, Portugal. 2020.
- [17] J. Parong and R. Mayer. "Learning Science in Immersive Virtual Reality". In: *Journal of Educational Psychology* 110 (Jan. 2018). DOI: 10.1037/edu0000241.
- [18] P. Rooney. "A Theoretical Framework for Serious Game Design". In: *International Journal of Game-Based Learning* 2 (Oct. 2014), pp. 41–60. DOI: 10.4018/ijgb1.2012100103.
- [19] R. Sayle. "Foreign Language Translation of Chemical Nomenclature by Computer". In: *Journal of Chemical Information and Modeling* 49.3 (2009). PMID: 19239237, pp. 519–530. DOI: 10.1021/ci800243w. eprint: <https://doi.org/10.1021/ci800243w>. URL: <https://doi.org/10.1021/ci800243w>.
- [20] M. Science. *MEL Chemistry VR Lessons*. <https://www.oculus.com/experiences/go/1457959427660729/>. 2018.
- [21] Y. Slavova and M. Mu. "A Comparative Study of the Learning Outcomes and Experience of VR in Education". In: *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 2018, pp. 685–686. DOI: 10.1109/VR.2018.8446486.
- [22] M. Stojanovska and B. Velevska. "Chemistry Games in the Classroom: A Pilot Study". In: *Journal of Research in Science Mathematics and Technology Education* 1 (May 2018), pp. 113–142. DOI: 10.31756/jrsmt.121.
- [23] M. Warschauer. "The paradoxical future of digital learning". In: *Learning Inquiry* 1 (Apr. 2007), pp. 41–49. DOI: 10.1007/s11519-007-0001-5.
- [24] Wikipedia. *Functional Group*. "https://en.wikipedia.org/wiki/Functional_group". "Last Edited: 2021-08-29". 2021.
- [25] Wikipedia. *Virtual Reality*. "https://en.wikipedia.org/wiki/Virtual_reality". "Last Edited: 2021-12-04". 2021.
- [26] C.-H. Wu et al. "The Design and Evaluation of a Gamification Teaching Activity Using Board Game and QR Code for Organic Chemical Structure and Functional Groups Learning". In: *2018 7th International Congress on Advanced Applied Informatics (IIAI-AAI)*. 2018, pp. 938–939. DOI: 10.1109/IIAI-AAI.2018.00190.

Chapter 8

Appendix

System Usability Scale (ChemTouch)

O System Usability Scale é um método simples de averiguar do nível de usabilidade de um sistema. Este formulário tem como objetivo avaliar a Efetividade, Eficiência e Satisfação do usuário no uso do aplicação ChemTouch.

1. Eu gostaria de usar este sistema com mais frequência.

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

2. Eu acho o sistema desnecessariamente complexo.

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

3. Eu acho o sistema fácil de usar.

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

4. Eu precisaria de ajuda de uma pessoa com conhecimentos técnicos para poder usar o sistema.

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

5. Eu acho o sistema bem integrado e bastante funcional.

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

6. Eu acho que o sistema é muito inconsistente

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

7. Eu acho que as pessoas aprenderiam rapidamente a usar o sistema.

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

8. Eu achei o sistema difícil de usar.

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

9. Eu senti-me confiante a usar o sistema

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

10. Eu precisei de aprender várias coisas novas antes de conseguir usar o sistema.

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

Este conteúdo não foi criado nem aprovado pela Google.

Google Formulários

NASA Task Load Index

O NASA Task Load Index é um método de averiguação do nível de carga de trabalho de um sistema. Este formulário tem como objetivo avaliar a dificuldade dos utilizadores no uso da aplicação ChemTouch.

1. O quão mentalmente desgastante foi completar os exercícios em ChemTouch

Marcar apenas uma oval.

	1	2	3	4	5	
Nada Desgastante	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Muito Desgastante

2. O quão fisicamente desgastante foi completar os exercícios em ChemTouch

Marcar apenas uma oval.

	1	2	3	4	5	
Nada Desgastante	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Muito Desgastante

3. O quão apressado foi o ritmo para completar a tarefa

Marcar apenas uma oval.

	1	2	3	4	5	
Nada Apressado	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Muito Apressado

4. Qual o nível de sucesso que atribuis à tua performance

Marcar apenas uma oval.

	1	2	3	4	5	
Horível	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Perfeito

5. Quão arduamente trabalhaste para atingir esse nível de performance

Marcar apenas uma oval.

	1	2	3	4	5	
Quase nada	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Muito

6. Quão inseguro, irritado, desmotivado, stressado e aborrecido te sentis-te durante a tarefa

Marcar apenas uma oval.

	1	2	3	4	5	
Quase nada	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Muito

Este conteúdo não foi criado nem aprovado pela Google.

Google Formulários

Questionário de satisfação final

***Obrigatório**

1. ID do Participante *

Ficha de
Trabalho

Por favor selecione abaixo as opções que melhor correspondem com a sua experiência ao completar as fichas de trabalho.

2. Senti que me esforcei muito para completar os exercícios *

Marcar apenas uma oval.

1 2 3 4 5

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

3. Achei divertido fazer os exercícios *

Marcar apenas uma oval.

1 2 3 4 5

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

4. Gostaria que este método de estudo fosse implementado mais vezes na sala de aula *

Marcar apenas uma oval.

1 2 3 4 5

Discordo Totalmente ☐ ☐ ☐ ☐ ☐ Concordo Totalmente

5. Achei fácil completar os exercícios *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

6. Sinto-me mais motivado a aprender com este método de estudo *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

7. Senti-me frustrado/a a fazer os exercícios *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

8. Senti-me desmotivado/a enquanto fazia os exercícios *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

9. Senti que o tempo dado para completar os exercícios foi suficiente *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

10. Percebi perfeitamente o que me era pedido em cada exercício *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

11. Sinto que este método de estudo pode ser usado na cadeira de Química Orgânica *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

12. Estaria mais motivado e interessado se pudesse utilizar este método de estudo mais vezes. *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

13. Se pudesse, usaria este método de estudo em casa mais vezes. *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

14. Senti que tive uma boa performance neste método de estudo *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

15. Sinto-me confortável a usar este método para estudar para Testes/Exames *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

16. Sinto que teria uma melhor performance em Testes/Exames ao estudar por este método. *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

17. Sinto que este método é o futuro na educação *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

ChemTouch

Por favor selecione abaixo as opções que melhor correspondem com a sua experiência ao completar os exercícios na aplicação em Realidade Virtual

18. Senti que me esforcei muito para completar os exercícios *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

19. Achei divertido fazer os exercícios *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

20. Gostaria que este método de estudo fosse implementado mais vezes na sala de aula *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

21. Achei fácil completar os exercícios *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

22. Sinto-me mais motivado a aprender com este método de estudo *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

23. Senti-me frustrado/a a fazer os exercícios *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

24. Senti-me desmotivado/a enquanto fazia os exercícios *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

25. Senti que o tempo dado para completar os exercícios foi suficiente *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

26. Percebi perfeitamente o que me era pedido em cada exercício *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

27. Sinto que este método de estudo pode ser usado na cadeira de Química Orgânica *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

28. Estaria mais motivado e interessado se pudesse utilizar este método de estudo mais vezes. *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

29. Se pudesse, usaria este método de estudo em casa mais vezes. *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

30. Senti que tive uma boa performance neste método de estudo *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

31. Sinto-me confortável a usar este método para estudar para Testes/Exames *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

32. Sinto que teria uma melhor performance em Testes/Exames ao estudar por este método. *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

33. Sinto que este método é o futuro na educação *

Marcar apenas uma oval.

	1	2	3	4	5	
Discordo Totalmente	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Concordo Totalmente

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