# MASTERARBEIT / MASTER'S THESIS

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„The Public's Knowledge on Radioactivity in Austria Affected by the Time Passed After Graduation and the Type of School Attended"

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Eva Susanna Holzinger, BEd

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| Mitbetreut von / Co-Supervisor: | Michael Malvern Hull, PhD |

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# 1. Introduction

The encounter with radiation emitted from a radioactive decay is unavoidable. Despite that, many believe that radioactivity is man-made, originating exclusively from medicine and power generation. Can this ignorance about radioactivity be quantified? What percentage of people are unaware that we are surrounded by radioactivity all the time? Does that number depend upon the type of school attended, the time since last attending school, and whether or not the person has seen the TV show “Chernobyl”? (cf. Morales & Tuzón, 2020, pp. 8–13; cf. Schecker et al., 2018, p. 231; cf. Sesen & Ince, 2010, p. 97)

In this master's thesis, I explore these questions with the help of an online questionnaire.

The second chapter of this thesis provides background theoretical information concerning radioactivity. In particular, I will explain how radiation is classified, and I will specify that this work is about the ionizing properties of alpha, beta, and gamma radiation.

The third chapter presents the theoretical, physical basis of radioactivity. This chapter starts with a brief historical overview, followed by the definition and different types of ionizing radiation (i.e., α, β, γ radiation). Subsequently, I present the properties of radioactivity. This includes the activity, the radioactive decay law, the decay constant λ and the half-life. One subsection of this chapter talks about the effects on human bodies and how to categorize the doses. Additionally, the effect and impact on the human body after irradiation and contamination is discussed. Other subsections introduce natural and artificial radioactivity and how to detect radiation. Finally, I present the measures recommended by the ICRP and ICRU concerning protection; in particular, I mention the ALARA principle.

The fourth chapter contains the definition of students’ conceptions and the theory of constructivism and conceptual change. Further students’ conceptions are discussed in more detail in Chapter 5, where I provide background information regarding the construction of the questionnaire.

Chapter 5 describes the development of the questionnaire, the process of the research and the analysis conducted. In addition, the research questions are stated

in this chapter, and the results are presented. The results are presented descriptively by diagrams and tables. Afterwards, an interference statistic is performed by means of a three-way ANOVA.

In the sixth chapter, the questionnaire's results are discussed and recapped. In addition, the limitations of this survey and possible further research in regard to this topic are listed. Among other things, this chapter also includes details concerning the implementation of the questionnaire, the results regarding the participants' emotions about radioactivity and the interpretations of the answers given to the individual questions. In addition, the observations are summarized at the end in reference to the individual survey questions.

The final chapters include references, appendix and the abstracts in German as well as in English.

# 2. Radiation in General

Radiation is everywhere, yet it is not visible to the naked eye. The human body does not have an integrated warning signal which alerts us when we are exposed to too much radiation. We will only notice an excessive radiation dose when our body is already affected by the damage caused by this very radiation. Hence, we do not know or feel whether we are exposed to high dangerous levels of radiation. But is every kind of radiation dangerous for the human organism?

In order to classify radiation, a scheme has been established. Radiation can be divided into corpuscular- and photon radiation. The photon radiation is also known as electromagnetic radiation and its restless quanta are photons, i.e., massless particles. An example of such a photon radiation are gamma (in short: γ) rays. Corpuscular radiation is a material transport in the form of particles with mass, which constitutes the difference to electromagnetic radiation. Types of this classification are alpha (in short: α) and beta (in short: β) particles. (cf. Krieger, 2019, p. 17)

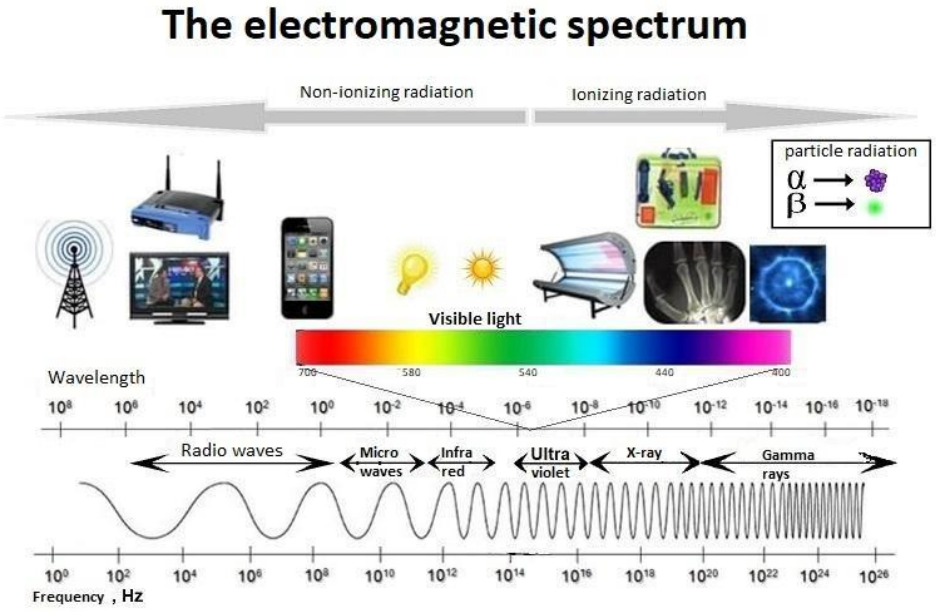


*Figure 1: How to Classify Electromagnetic Radiation; Source: (University of Bergen: 2020); https://www.uib.no/en/hms-portalen/75292/electromagnetic-spectrum*

Photon radiation, also called electromagnetic radiation, can be further divided in regard to its frequency or wavelength, and its energy. It includes micro waves, "*radio waves, infrared-, light- and ultraviolet radiation, X-rays, and gamma radiation*" (Krieger, 2019, p. 17). Figure 1 shows the individual sections according to wavelength and frequency. Electromagnetic waves do not require a medium for

propagation. In vacuum, they propagate with the speed of light. In a medium, the speed of propagation depends on the respective wavelength. (cf. Krieger, 2019, pp. 17, 31–32)

## 2.1. Ionizing Radiation

Figure 1 also presents a classification into non-ionizing radiation and ionizing radiation. This is not an additional classification of electromagnetic radiation but rather another system for classifying radiation. Ionizing radiation, unlike non-ionizing radiation, has enough energy to release electrons from the atomic shell. This energy is called ionizing energy. The border between ionizing and non-ionizing radiation is actually material-dependent and between 4 eV and 25 eV but the phrase “ionizing radiation” as it is commonly understood refers to DNA in human tissue, which requires approximately 30 eV (approximately 41 nm) for ionization. When an atom is ionized via radiation, an electron is ejected from the atom by the radiation’s impact. As a result, a hole remains where the electron has been removed. If the atom prior to the radiation impact was an electrically neutral atom, it is now charged and called an “ion”. An ion has an unequal number of protons and electrons. If there are more protons than electrons, the ion is positively charged and vice versa. Due to this ionization property, it is possible to measure different types of radiation with the help of devices, for instance, a Geiger-Müller counter. The mechanism to measure ionizing radiation is presented in Chapter 3.7. (cf. Krieger, 2019, pp. 17, 36, 65–66; cf. Schmiermund, 2019, p. 312)

All kinds of radiation which result from a radioactive decay have enough energy to ionize an atom. Thus, ions can be produced by nuclear processes. In contrast to visible light, ultra-violet radiation has a higher potential for ionization. (cf. Krieger, 2019, pp. 17, 65–66; cf. Schmiermund, 2019, p. 312)

X-rays have even more energy than ultraviolet light and, consequently, belong to the category of ionizing radiation. X-ray tubes are used to produce X-rays. Inside the tube there is a vacuum, and an anode and a cathode plate are placed vis-á-vis. They are oppositely charged which induces an electric field. Inside the electric field, an electron is accelerated. “*When the electrons strike and enter the anode, two processes lead to the production of photons: bremsstrahlung and vacancy filling*” (Grupen & Rodgers, 2016, p. 50), also called characteristic X-rays. A large portion of

the energy is lost as heat. Only a small portion of the energy is transformed into X-rays. (cf. Grupen & Rodgers, 2016, pp. 49–50)

The first possibility to produce X-rays mentioned by Grupen and Rodgers (2016, pp. 50-51) is “Bremsstrahlung”. In its production, the accelerated electron is forced to slow down at the anode, and the excess energy is emitted in the form of photons. These photons are then called “Bremsstrahlung” and their energy spectrum is continuous. The second possibility to produce X-rays, mentioned by Grupen and Rodgers (2016), is realized when “*electrons (…) fall from higher states to replace the electron that has been removed*” (Grupen & Rodgers, 2016, p. 51). For an electron to be removed, the accelerated electron has to hit an electron within an atom and ionize it: an electron hole appears. Electrons always strive towards the lowest energy level available. Hence, an electron from an outer shell replaces the electron in a lower energy level. While moving from a higher state to a lower state, the electron emits energy in the form of X-rays. It is also possible that the newly produced electron hole is replaced by another electron from an even higher level of energy. The amount of energy that is released corresponds to the difference between the two electron shells. Depending on the element of the hit atom, characteristic energy is produced. This kind of X-ray production is only possible for elements with a high atomic number.

In this thesis, the focus lies on ionizing properties of alpha, beta, and gamma radiation. Thus, X-rays and ultra-violet radiation are no longer mentioned.

# 3. Radiation from Radioactive Substances

## 3.1. Historical Overview

### 3.1.1. Henri Becquerel

Initially, the discovery of radioactivity was an accident which quickly turned out to be a revolutionary incident. Henri Becquerel was listening to a presentation on X-rays by the inventor Wilhelm Röntgen in 1895. The origin of X-rays was not clear at that time. Henri Becquerel was very enthusiastic about the presentation, and he was sure that there must be a connection between X-rays and the behavior of uranium salt. Uranium salt showed luminous phenomena. According to his estimations that X-rays were a concomitant of fluorescence, he planned experiments to see if uranium salt emits X-rays after sun irradiation. More specifically, he had an experimental setup consisting of uranyl salt and a photographic plate which was impermeable to light. The salt was a combination of uranium and potassium which shows fluorescent behavior. He believed that the uranyl salt will have fluorescent appearance after irradiation of the sun and thus, X-rays will be formed. To begin with, he put the salt on the photographic plate and put it in the sun. As a result of the sun's irradiation, the plate blackened which served as an indication for X-rays. To be certain, he repeated his experiment on the 26th of February in 1896. On this day, the weather was not sunny enough to conduct said experiment, so he postponed his investigation and put the plate with the uranyl compound in a drawer. In this drawer, the uranyl did not experience light excitation. Three days later, he wanted to continue the project and when opening the drawer, he was astonished. After developing the plate, even though the photographic plate was lightproof-sealed, a distinct blackening appeared on the plate where the uranium compound was located. Due to the lack of irradiation from the sun, the salt must have emitted something by itself which led to the blackening of the photographic plate. Becquerel's conclusion was that there must be a connection between the uranyl salt and an unknown radiation. This constitutes the first discovery of radioactivity. (cf. Grupen, 2008, p. 2; cf. Rutherford et al., 2010, pp. 4–5; cf. Schmiermund, 2019, pp. 315–316)

### 3.1.2. Marie and Pierre Curie

Two years later, Marie and Pierre Curie made further discoveries regarding radioactive material. Marie Curie wanted to know if the activity of a radioactive

element is a universal property or if her activity measurements depend on the respective material. She utilized uranium ore, also known as a “Pitchblende”, to investigate its activity and showed that the mineral had a much higher activity than uranium itself. When she measured the activity of uranium metals, she found a correlation between the amount of uranium present and the amount of activity measured. Hence, the activity is a property of the respective element, whether in a mixture or not, and its amount. Based on her observations, she made the hypothesis that there must be other substances in the mineral which are also radioactive. In this context, the radioactive elements polonium and radium were found. The high activity in the pitchblende, which was a million times higher than uranium, was caused by radium. The found radium was named after radioactivity itself, and the element polonium was named in honor of Marie Curie’s homeland Poland. Additionally, Marie and Pierre Curie found out that thorium is radioactive. (cf. Fischer, 2013, p. 176; cf. Rutherford et al., 2010, pp. 5–6; cf. Schmiermund, 2019, p. 316)

Based on these experiments and their results, Marie and Pierre Curie and Henri Becquerel have been awarded with the Nobel prize. Marie Curie was the first woman who won such an award. (cf. Fischer, 2013, p. 176)

> “*The Nobel Prize in Physics 1903 was divided, one half awarded to Antoine Henri Becquerel ‘in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity’, the other half jointly to Pierre Curie and Marie Curie, née Sklodowska ‘in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel.*’” (*The Nobel Prize in Physics 1903*, 1903).

### 3.1.3. Ernest Rutherford

After Marie Curie and Henri Becquerel, Rutherford discovered that not every element emits the same radiation during its radioactive decay. He found that there are three different types of radiation which he named according to “*the first three letters of the Greek alphabet*” (Grupen & Rodgers, 2016, p. 3). “*The emission of the energetic α particle, the swift β ray and the penetrating γ ray gave us new types of radiation to study […]*”(Rutherford et al., 2010, pp. 2–3). With the aid of a magnetic field and since radiation is always emitted straightforward, the individual types of radiation can be distinguished from another. This is possible because of the different charges of α

and β particles which are consequently deflected in different directions. γ rays are not diverted at all since they have no charge. At that time, the emission of the different types of radiation was declared to happen randomly. (cf. Rutherford et al., 2010, pp. 2–3; cf. Schmiermund, 2019, pp. 316–317)

### 3.1.4. Otto Hahn

Apart from the physicists mentioned so far, Otto Hahn also started to work with radioactive elements in England and his assignment was to separate the substances from a mixture of barium and radium salt. He separated the salts following the method established by Marie Curie and found out that there remained activity caused by an unknown substance. In addition to barium and radium, he was also detecting the activity of thorium. Afterwards, he drove with the steamer to Canada to tell Rutherford about his observations. (cf. Hahn, 1948, pp. 67–68)

In 1903, Rutherford and his pupil Frederick Soddy made assumptions about radioactive elements which change their chemical and physical properties after a spontaneous decay. They assumed that the parent nuclide has other properties after decaying with the emission of α and β particles than the daughter nuclide. The parent nuclide is a radioactive nuclide and after decay, the newly emerged nuclide is called daughter nuclide. Additionally, they believed that an atom could undergo more than one transformation in the form of changing the chemical element. Otto Hahn also believed that there is more than one transformation between the parent nuclide and the observed daughter nuclide. Hahn’s opinion was that some of the elements have the same chemical properties after their decay, but he was not certain enough to publish his thoughts. In 1907, Lise Meitner worked very closely with Otto Hahn in Berlin and shared his opinion. During this time, Lise Meitner was an unpaid worker because women were not very welcome in the halls of physics. (cf. Hahn, 1948, pp. 69–73; cf. Rutherford et al., 2010, p. 8)

There were various opinions regarding the chemical properties after decay. On the one hand, there were elements which have different chemical and physical properties after decaying. On the other hand, there were elements which have the same chemical, but different physical properties after decaying. (cf. Hahn, 1948, pp. 69–73; cf. Rutherford et al., 2010, p. 8)

> "*Erst Soddy hat dann mehrere Jahre später (1913) den aus all diesen Beobachtungen sich ergebenden wichtigen Schluß gezogen, daß es chemische Elemente gibt, die bei verschiedenen radioaktiven Eigenschaften und bei verschiedenem Atomgewicht gleiche chemische Eigenschaften besitzen, also im Periodischen System an die gleiche Stelle zu setzen sind. Soddy nannte solche Elemente „isotope" Elemente und wandte diesen Begriff auch auf die gewöhnlichen chemischen Elemente an. So verschwanden die bekannten Schönheitsfehler im Periodischen System, und die starken Abweichungen der Atomgewichte von der Ganzzahligkeit (z. B. Chlorisotope) fanden bald ihre plausible Erklärung*" (Hahn, 1948, p. 71).
>
> "*It was not until several years later (1913) that Soddy drew the important conclusion from all these observations that there are chemical elements which have the same chemical properties with different radioactive properties and different atomic weights, i.e., which can be placed in the same position in the periodic system. Soddy called such elements 'isotopic' elements and applied this term to the ordinary chemical elements as well. Thus, the well-known blemishes in the periodic system disappeared, and the strong deviations of the atomic weights from the integer (e.g., chlorine isotopes) soon found their plausible explanation*" (Hahn, 1948, p. 71).

After observations and assumptions that some elements have the same chemical but different physical properties (as a result of having a different mass number), Soddy drew his conclusion: the assumptions about the same chemical properties were correct. There are elements which can be placed on the same spot in the periodic table based on their chemical properties. Soddy called them isotopes. (cf. Hahn, 1948, p. 71)

In 1913, the law of radioactive displacements was developed. With the help of this law, it is possible to predict how an element will transform into another depending on the type of radiation. (cf. Hahn, 1948, pp. 69–73; cf. Rutherford et al., 2010, p. 8)

1919 was the year that significantly changed nuclear research. Ernest Rutherford succeeded in conducting the first artificial transformation by hitting nitrogen with alpha particles: After successfully hitting the shelling, the nitrogen transformed into oxygen. (cf. Hahn, 1948, p. 74; cf. Schmiermund, 2019, p. 317)

### 3.1.5. Enrico Fermi

In 1934, Fermi tried to find an element with a higher atomic mass by shooting uranium with neutrons to inducing a $\beta^-$ decay. He was searching for the heavier elements which were later called transuranic elements. What he did not know at that time was that uranium was already the heaviest element to be found in nature. In the same year, the daughter of Marie Curie, Irène Joliot-Curie, and her husband Frédéric, discovered artificially induced radioactivity with the help of alpha particles shot at aluminum. This shows that many different physicists were working on the same unsolved problems at the same time which led to overlaps. (cf. Schmiermund, 2019, p. 317; cf. Sime, 2000, pp. 50–51)

### 3.1.6. Otto Hahn, Lise Meitner and Fritz Straßmann

Approximately at the same time, Otto Hahn, Lise Meitner, and Fritz Straßmann repeated Fermi's experiment in Berlin. Otto Hahn was certain that Fermi's theory is the correct one. In 1938, shortly before the second world war, Lise Meitner had to flee because of her Jewish ancestry. She settled down in Stockholm, where she stayed in close contact with Otto Hahn. Otto Hahn and Fritz Straßmann continued to work on investigating whether elements could be created which are heavier than uranium. After successfully conducting an experiment, the researchers were optimistic that they had created a transuranic element. However, when they measured the activity of what they had supposedly created and continued to find it to be the same as the uranium they had begun with, they declared their first idea of having obtained a transuranic element as a misinterpretation. With the help of Lise Meitner, who continuously wrote letters to Berlin, they found out that the uranium nucleus breaks into lighter elements and some neutrons after being shot by a neutron. Based upon this observation, they came up with a new hypothesis: by shooting a neutron on a nucleus, they had facilitated the production of radium, which is a naturally occurring nuclide in the uranium decay chain. However, this belief of having facilitated the creation of radium was also a misconception. In fact, by shooting a neutron on a nucleus, they had found neither a transuranic element nor an element that arose from a natural decay. They had found Barium. Otto Hahn and Fritz Straßmann induced the first verified nuclear fission, which constitutes a milestone in the history of science. In the meantime, with the support of her nephew Otto Frisch, Lise Meitner managed to theoretically illustrate the nuclear fission and

was even able to estimate the energy released in this process. (cf. Grupen & Rodgers, 2016, p. 115; cf. Schmiermund, 2019, p. 317; cf. Sime, 2000, pp. 59–60)

Otto Hahn won the Nobel prize in chemistry for the discovery of the nuclear fission in 1944. No other person involved in this cutting-edge research was honored with the Nobel Prize, despite the fact that Lise Meitner cooperated closely for many years with Otto Hahn. (cf. Sime, 2000, p. 60)

## 3.2. What is Radioactivity?

Radioactivity is the spontaneous decay of an atom core, also called nucleus. The decay of the atom is accompanied by the emission of radiation which carries energy. Additionally, depending on the type of radiation, the number of neutrons and protons in the nucleus can change. As a result of a decay, it is possible that the atomic number changes (in other words, the element has changed). But why does this happen and what are the consequences? (cf. Krieger, 2019, p. 91)

A total of 3992 distinct nuclides have been discovered to date. A nucleus consists of a certain number of neutrons and protons. Isotones have the same number of neutrons but a different number of protons. Isotones with the same number of neutrons differ in their chemical properties by changing its element whereas isotopes from a given element do not differ in their chemical properties. 284 of the nuclides have a natural origin and the others have been produced artificially. An overview of all nuclides is presented in the table of nuclides. This table contains, among other things, all nuclides with the respective number of neutrons $N$, protons $Z$ (also called atomic number) and mass number $A$, which is the sum of an atom's neutrons and protons. The table of nuclides consists of a grid with the number of neutrons on the x-axis and the number of protons on the y-axis. In the middle of this table, there is a diagonal area where the nucleus is in the ground state and is therefore stable. This area is called the "*valley of stability*" (Grupen & Rodgers, 2016, p. 11). All the atoms above the stability curve are proton rich and will emit $\beta^+$ particles. Atoms beneath the stability curve are neutron rich and will emit $\beta^-$ particles. The process of β decays is found in Chapter 3.3.2. An atom is stable if the right neutron-proton balance is given, which is specific to every element and is listed in the table of nuclides. It is noteworthy that atoms with a higher atomic number, i.e., heavier atoms, must have a neutron surplus to be stable. Otherwise, the positive charge of the protons is too high which would cause an instability of the core. If the nucleus is unstable, the table of

nuclides shows the possibilities of how an atom will decay based on the type of radiation. How an atom is going to decay is marked by the background color and the respective symbol of the type of radiation of each individual atom. How the atomic number and the mass number of the resulting core change can be easily found with the help of the law of radioactive displacements. (cf. Grupen, 2008, p. 290; cf. Grupen & Rodgers, 2016, pp. 11–12; cf. Krieger, 2019, pp. 91–95)

## 3.3. Types of Radiation Released in Radioactivity

In this master's thesis, the types of radiation listed are the ones that students usually learn at school. These types of radiation presented in physics course books are alpha decay, beta decay and gamma rays. (cf. Apolin, 2008, pp. 58–60; cf. Sexl et al., 2013, p. 85)

Depending on the radioactive decay, radioactive transmutations can be classified into three groups:

- "*decays due to strong interaction*" (Krieger, 2019, p. 97) → reducing the mass number, e.g., alpha decay (cf. Krieger, 2019, p. 97),
- "*decays due to weak interaction*" (Krieger, 2019, p. 97) → conversions of nucleons without mass number change, e.g., beta decay (cf. Krieger, 2019, p. 97),
- "*decays due to electromagnetic interaction*" → "*Changes in the energy content of atomic nuclei due to rearrangement of nucleon configurations outside the ground state*" e.g., "*emission of gamma quanta*" (Krieger, 2019, p. 97).

### 3.3.1. Alpha Decay

Alpha decay happens when the nucleus of the atom is very heavy, i.e., the mass number is high. This kind of decay has the consequence that the parent core $X$ emits one helium core ${}^{4}_{2}He$ with 2 protons and 2 neutrons. The alpha decay is not accompanied by particle conversions. This ${}^{4}_{2}He$ is also known as a α particle. As a result, the mass number decreases by 4 in the daughter core $Y$. The energy of an alpha particle after a decay is between 4 and 9 MeV. (cf. Krieger, 2019, pp. 97–100; cf. Rybach, 2019, p. 314)

(1) $${}^{A}_{Z}X_{N} \rightarrow {}^{A-4}_{Z-2}Y_{N-2} + \alpha + Energy$$ (Krieger, 2019, p. 97)

Equation (1) shows the heavy parent nuclide $X$, which becomes a daughter nuclide $Y$ by emitting an α particle. In addition, the excess energy resulting from the decay is released. (cf. Krieger, 2019, p. 97)

How is it possible that an α particle escapes the core? The kinetic energy of an α particle is lower than the potential energy of the nucleus. Hence, the particle has not enough energy to equal the Coulombic potential energy and leave the potential well. The potential well results from the combination of the strong interaction, also called nuclear force, and the Coulomb force. By reaching enough energy to equal the Coulombic potential energy, the alpha particle overcomes the strong interaction which holds the atomic nucleus together and could leave the core. In addition, the α particle has a very high binding energy which increases the difficulty to leave the core. In classical physics, the particle would never be able to leave the potential well due to its low energy. In quantum physics however, it could be possible to find the particle beyond the well without the energy necessary to overcome the well. In this case, the alpha particle has tunneled through the potential barrier which is known as the tunnel effect. The higher the energy required to tunnel through, the longer the half-life of the isotope in question. The half-life of an isotope will be explained in chapter 3.4.2. (cf. Krieger, 2019, pp. 98–99; cf. Rybach, 2019, p. 315)

### 3.3.2. Beta Decay

"*If a radionuclide has an isobaric neighbour with lower energy, a β-conversion usually takes place. In this process, nucleons in the nucleus of the parent nuclide convert into each other under charge emission*" (Krieger, 2019, p. 102). β decays are induced by an unfavorable neutron-proton distribution. Two different kinds of beta conversions exist. On the one hand, there is the $\beta^+$ decay where one proton $p$ turns into one neutron $n$, a positive charge $\beta^+$, and a neutrino $\nu_e$. This decay equation is presented in equation (2). The positive charge is called $\beta^+$ particle or positron. (cf. Krieger, 2019, p. 102)

$$p \rightarrow n + \beta^+ + \nu_e + Energy \quad \text{(Krieger, 2019, p. 102)} \tag{2}$$

On the other hand, there is the $\beta^-$ decay where one neutron $n$ turns into one proton $p$, a negative charge $\beta^-$, and an antineutrino $\bar{\nu}_e$. This decay equation is presented in

equation (3). The negative charge is called $\beta^-$ particle or electron. (cf. Krieger, 2019, p. 102)

$$n \rightarrow p + \beta^- + \bar{\nu}_e + Energy \quad \text{(Krieger, 2019, p. 102)} \tag{3}$$

Due to the conservation law of the number of leptons, the decay equations (2) and (3) contain an electron neutrino or electron antineutrino. An electron or positron must build an antiparticle with almost zero resting mass to obey the conservation law. These particles hardly ever interact with matter and are therefore difficult to detect. Another property of the β decay is that the atomic mass number $A$ remains the same during one β decay since a proton changes into a neutron with almost equal mass and vice versa. Hence, only the ratio of neutrons and protons changes. Because of this, β decays are also called isobaric decays. In the nuclide map the β decays follow a 45° angled path. As a result, a nuclide which is produced by β decay is isobar for which only $Z$ and $N$ has changed. The energy of a beta particle is a maximum of about 2 MeV but is usually around 1 MeV. (cf. Krieger, 2019, pp. 88, 92, 102–103, 126; cf. Rybach, 2019, p. 314; cf. Schmiermund, 2019, p. 341)

### 3.3.3. Gamma Radiation

It may happen that the corpuscular emission of the alpha or beta radioactive decays was not sufficient to release all of a nuclide's excitation energy. Consequently, the nucleus remains in an excited state. In this case, the nucleus emits gamma rays in the form of electromagnetic radiation immediately after the corpuscular decay. If gamma rays are emitted, the parent nucleus remains the same in mass number, proton number and neutron number since solely massless photons are radiated. By this means, the core's energy decreases proportionally to the photon's energy emitted. The energy released by a photon reaches up to 2,5 MeV. In contrast to α or β decays, the gamma radiation does not go hand in hand with a physical transformation of the parent nuclide. (cf. Grupen & Rodgers, 2016, p. 13; cf. Krieger, 2019, pp. 114–115; cf. Rybach, 2019, p. 315)

Consider Caesium-137, an element named by Grupen and Rodgers (2016, p. 13), by which one can exemplify gamma irradiation and previous β decay. According to the table of nuclides, $^{137}_{55}Cs$ will decay by emitting a $\beta^-$ particle and an antineutrino. Additionally, during this decay, one neutron transforms into a proton and consequently changes the element by means of its proton number.

(4) $$^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba^{*} + e^{-} + \bar{\nu}$$ (Grupen & Rodgers, 2016, p. 13)

Following the β decay, barium "*is in an excited state*" (Grupen & Rodgers, 2016, p. 13), which is marked in equation (4) by an asterisk. This means that the β decay was not sufficient to release the excess energy. To get rid of this energy, the nucleus emits gamma rays. "*Since the energy difference between the excited nucleus and the ground state is fixed, these γ rays have a single, defined energy for each transition*" (Grupen & Rodgers, 2016, p. 13). Thus, the nucleus' excited state can transition into its ground state by emitting energy in the form of γ rays, which is presented in equation (5). (cf. Grupen & Rodgers, 2016, p. 13)

(5) $$^{137}_{56}Ba^{*} \rightarrow {}^{137}_{56}Ba + \gamma$$ (Grupen & Rodgers, 2016, p. 13)

## 3.4. Properties of Radioactivity

### 3.4.1. Activity

The activity $A$ describes "*the number of radioactive decays in a particular time*" (Grupen & Rodgers, 2016, p. 17). The activity is measured in Becquerel, a SI unit which is named after the discoverer of radioactivity, i.e., Henri Becquerel, and gives the decays of particular nuclei per second. The equation to determine the activity $A$ is presented in equation (6). (cf. Grupen & Rodgers, 2016, p. 17; cf. Rybach, 2019, p. 318)

(6) $$A = -\frac{dN}{dt}$$ (Rybach, 2019, p. 318)

$dN$ is the number of the decays that occurs in an infinitesimally small time span $dt$. The activity is measured in decays per second, hence $[A] = Bq = \frac{1}{s} = s^{-1}$. Until 1986, the unit for activity was "Curie", but this unit is no longer used. (cf. Grupen & Rodgers, 2016, p. 17; cf. Rybach, 2019, p. 318)

### 3.4.2. Radioactive Decay Law, Decay Constant λ and Half-Life

Marie Curie found out that an increase or decrease in the number of radioactive decays is proportional to the number of isotopes: The higher the number of isotopes, the higher the number of decays. After some time, only half of the first available

isotopes are left. Also, the activity decreases proportionally to the number of isotopes. The moment when a nucleus is going to decay is not predictable. The probability that the core will decay in a certain time interval, which is different for each isotope, and is known as decay constant $\lambda$. (cf. Krieger, 2019, p. 131; cf. Rutherford et al., 2010, p. 6; cf. Rybach, 2019, p. 316)

$$dN = -\lambda N dt \text{ (Rybach, 2019, S. 316)} \tag{7}$$

In equation (7), $N$ is the number of cores at time $t$ and $dN$ is the amount of cores that have decreased in time interval $dt$. The decay constant $\lambda$ indicates the probability for a decay to happen in a certain time interval. The higher this constant, the higher the probability that the existing isotope will decay in that time interval. The decay constant lambda varies depending on the isotope and is a constant for the respective isotope. (cf. Rybach, 2019, p. 316)

Combining equation (6) and equation (7), the activity can also be calculated by means of the decay constant. This can be seen in equation (8).

$$A = \lambda N \text{ (Rybach, 2019, p. 318)} \tag{8}$$

After integrating equation (7) with respect to time, one obtains

$$\ln N - \ln N_0 = \ln \frac{N}{N_0} = -\lambda t \text{ (Rybach, 2019, p. 316).} \tag{9}$$

The law of decay can be deduced from equation (9).

$$N(t) = N_0 e^{-\lambda t} \text{(Krieger, 2019, p. 132)} \tag{10}$$

When $t = 0$, there are $N_0$ initial cores that have not yet been decayed. When $t \neq 0$, the number of cores, starting at initial cores $N_0$, will decrease exponentially which is shown in $N(t)$. In addition, the activity after a defined time, $A(t)$, has an exponential decline similarly proportioned as the number of initial activities $A_0$ (equation (11)). (cf. Krieger, 2019, p. 132)

$$A(t) = A_0 e^{-\lambda t} \text{ (Krieger, 2019, p. 132)} \tag{11}$$

Considering that after some time there will be half of the origin cores, i.e., $\frac{1}{2}N_0$, the half-life can be deduced with the help of equation (10). (cf. Rybach, 2019, p. 316)

(12) $$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} \text{ (Rybach, 2019, p. 316)}$$

As presented in equation (12), the half-life $T_{\frac{1}{2}}$ describes the time it takes a large sample of radioactive nuclei to reach the point where only half of the initial cores are present. Every isotope has a respective half-life. Thus, if there is a mixture of different isotopes, every sort of isotope has another timespan in which half of them have decayed. A half-life for the complete mixture of different isotope cannot be defined. For each nuclide, the half-life depends on the respective isotope and can vary between some microseconds and millions of years. Additionally, the half-life of each isotope does not depend on the number of cores present. The half-life only describes the time it takes for half of the same isotopes to decay. After this period, the remaining cores require the same amount of time for half of them to decay. Hence, after two half-lives there is one quarter of the initial amount left. In Figure 2, the logarithmic decrease of the number of the remaining, non-decayed isotopes is presented. The x-axis shows the time elapsed while the y-axis presents the number of parent atoms. The half of half of half, etc. is never zero which is why there will always be a certain amount of the radioactive source material present. If this amount is very small, it becomes indistinguishable from the background radiation constantly surrounding us. (cf. Grupen & Rodgers, 2016, pp. 17–18; cf. Rybach, 2019, pp. 316–317)

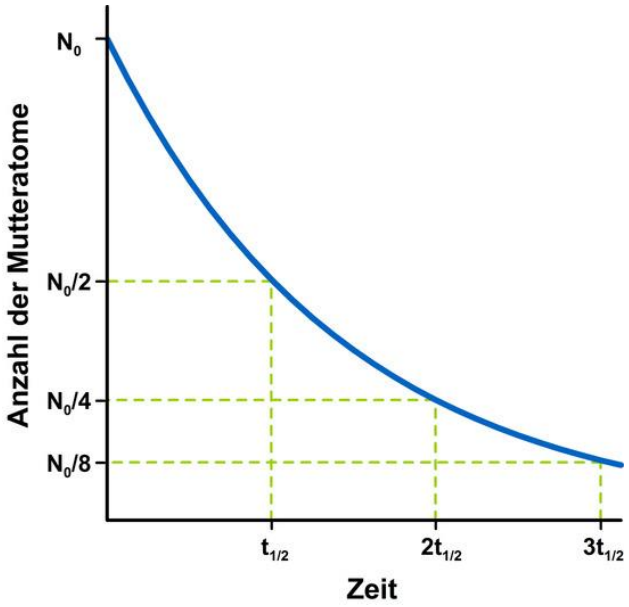


*Figure 2: Half-Life; Source: (Evers, 2021), https://physikunterricht-online.de/jahrgang-12/halbwertszeit-und-zerfallsgesetz/*

## 3.5. Effects on the Human Body

The effects of the radioactive radiation on the human body are described by three different variables. Firstly, there is the energy dose $D$ with its unit Gray. Secondly, there is the equivalent dose $H$ given in units of Sievert. Thirdly, there is the effective dose $H_{eff}$ with the same unit Sievert. (cf. Grupen & Rodgers, 2016, pp. 18–19)

In the following, these terms will be discussed in greater detail.

### 3.5.1. Energy Dose D

Consider two people who are both exposed to the same amount and kind of radiation (and hence receive the same total amount of energy from the radiation). One of the two people is very small and thin, the other one is very tall and thick. The energy dose tells us which of the two people has absorbed more energy from the rays per kilogram. Equation (13) shows this energy dose $D$ as the absorbed energy $E$ divided by the mass $m$. The unit for the energy dose is Gray which is Joule per kilogram in SI-units. (cf. Rutherford et al., 2010, pp. 18–19; cf. Rybach, 2019, p. 319)

$$D = \frac{E}{m} \text{ (Rybach, 2019, p. 319)} \tag{13}$$

In consideration of the weight of the two persons, the energy dose taken up by the tall and thick human is lower than the one that is smaller and thinner. (cf. Grupen & Rodgers, 2016, p. 19)

### 3.5.2. Equivalent Dose H

In contrast to the energy dose, the equivalent dose measures the biological effect on human beings. Different types of radiation have different weighting factors and therefore, different harm on the body. To be able to measure the different influences on the body by the respective radiations, the radiation weighting factor is introduced. In Austrian schoolbooks, the radiation weighting factor is referred to as "*Qualitätsfaktor* $Q$" (Sexl et al., 2013, p. 97) or "*Qualitätsfaktor RBW (relative biologische Wirkung)*" (Zunzer et al., 2019, p. 35). The equivalent dose $H$ is the product of energy dose $D$ and the radiation weighting factor $Q$, presented in equation (14). This value is measured in Joule per kilogram and therefore has the same unit as the energy dose $D$. To distinguish these two doses, the unit in which the equivalent dose is measured is Sievert. (cf. Grupen & Rodgers, 2016, p. 20; cf. Rybach, 2019, p. 319)

$$H = QD \ (\text{cf. Rybach, 2019, p. 319}) \tag{14}$$

The weighting factor $Q$ for the different types of radiation can be found in the literature. The value of $Q$ depends on the type of radiation and its energy. α particles have a very high energy and are, due to their mass, very slow. Compared to β particles and γ rays, the slower speed and the high release of energy of α particles in a short time offers the possibility to ionize more target atoms. The slower the particle or quantum, the greater the probability of interacting with matter. In addition, an α particle has twice the charge as a β particle, resulting in twice the Coulomb force on electrons in target atoms. For these three reasons (high energy, slow speed, and large charge), α particles have a high ionizing effect and hence, their weighting factor $Q$ is higher. The weighting factor for γ quanta, i.e., the energy packages of γ rays and β particles is 1. The weighting factor for α particles is 20. "*As an example, let us assume that a radiation worker in a reprocessing plant is accidentally exposed to an energy dose of 20 mGy from α particles, and one 50 mGy from γ radiation*" (Grupen & Rodgers, 2016, p. 20). The energy dose $D$ multiplied with the weighting factor $Q$ gives the equivalent dose $H$: "$(20\,mGy \times 20 + 50\,mGy \times 1)\,mSv = 450\,mSv$" (Grupen & Rodgers, 2016, p. 20). The lethal dose for humans is about 4000 mSv. Hence, if a person is exposed to an equivalent dose of 4000 mSv, it "*is giving a death*

*rate of 50% within a month*" (Grupen & Rodgers, 2016, p. 20). (cf. Grupen, 2008, pp. 8–9, 31–36; cf. Grupen & Rodgers, 2016, p. 20)

### 3.5.3. Effective Dose/Effective Dose Equivalent $H_{eff}$

When someone works with radioactivity, for example in medicine or in power generation, or is just a patient in the hospital, there is another factor that must be considered. Different types of radiation have different harm on different organs of the body. The equivalent dose $H$ measures the biological effect on the entire body. The effective dose $H_{eff}$ is somewhat more precise and gives the damage of the radioactive exposure to the individual organs. Hence, the equivalent dose has to be multiplied by the "*tissue weighting factor for the organ in question*" (Grupen & Rodgers, 2016, pp. 20–21). This weighting factor can be found in the literature. The numerical value of the respective tissue weighting factor depends on the ionization density (which depends in turn upon the energy output of the respective radiation type) and the cell division rate of the respective tissue. In the past, the tissue weighting factor has been researched via animal testing and the experience from cancer cases that occurred after the atomic bombings of Japan. Although different people's (for example) hearts respond differently to the same amount/type of radiation and age and gender both play a role, the tissue weighting factor is averaged over age and sex. For example, the chest and stomach each have a factor of 0,12 (12%) whereas the skin and the brain each have a factor of 0,01 (1%). The higher the number, the higher the stochastic risk of hereditary damage or cancer. To distinguish the respective harms on the different tissues, the organs of the body are classified in fourteen different parts and the sum of all weighting factors is 1 (100%). This opens a great possibility to compare the effect on different organs. The unit for the effective dose is also measured in Sievert. (cf. Grupen, 2008, p. 301; cf. Grupen & Rodgers, 2016, pp. 20–21; cf. Krieger, 2019, pp. 343–344)

$$H_{eff} = w_T H \ (\text{Schmiermund}, 2019, \text{p. } 359) \tag{15}$$

In equation (15), $w_T$ is the tissue weighting factor and $H$ describes the equivalent dose. If more than one organ is affected, then the corresponding effective doses are summed up. It is important to understand that particular tissues can be irradiated by higher doses because the weighting factor diminishes the effective dose. (cf. Grupen & Rodgers, 2016, pp. 21–22; cf. Krieger, 2019, p. 359)

### 3.5.4. Radiation Sickness

The energy a nucleus emits when it decays is high enough to release an electron from a “victim” atom in question. As a result, the atom that has lost the electron is ionized. This also happens in the human body and thereby damages the cells in the human body. It depends on the effective dose and type of radiation whether there are early and/or delayed effects on the human body. A low, whole-body effective dose of around 0,25 Sv can only be detected by means of a blood test. When the body is absorbing an effective dose of about 1 Sv, “*clear symptoms of radiation sickness*” (Grupen & Rodgers, 2016, p. 79) will occur. This amount is far from the lethal effective dose which is about 4 Sv. When a person absorbs an effective dose of 7 Sv, it is even possible that the person dies within a week. (cf. Grupen & Rodgers, 2016, p. 79; cf. Schmiermund, 2019, p. 379)

If a person absorbs a high effective dose of radiation, early effects can occur within the first hours. Symptoms range from headaches to vomiting. After some time, the symptoms disappear and it seems that the person recovers from irradiation. After one to two weeks, the “*second phase of […] radiation sickness*” usually starts with symptoms like “*fever, haemorrhage, vomiting of blood, bloody faeces and loss of hair*” (Grupen & Rodgers, 2016, pp. 79, 80). When receiving a very high radiation effective dose, it is possible that the symptom-less period does not occur. The mortality depends on the whole-body radiation dose as well as the swift and correct medical care. If the irradiated person lives longer than 8 weeks, there is a good chance for him/her to recover. (cf. Grupen & Rodgers, 2016, pp. 79–80)

After radiation exposures, it is possible that some symptoms appear first after a long period of time. This “*delayed radiation damage*” (Grupen & Rodgers, 2016, p. 81) could last for years and the consequences often involve cancer or genetic damages. The risk of delayed damages is stochastic in nature: The higher the effective dose of the radiation exposure, the higher the probability to get damaging effects. This linear relationship can be seen in Figure 3 in blue and is called the linear no-threshold model (in short: LNT). The x-axis shows the radiation dose, and the y-axis represents the risk for cancer. “*It is assumed that possible risks of radiation-induced cancer or genetic defects are linearly proportional to the dose, and that there is no threshold for detrimental effects of radiation*” (Grupen & Rodgers, 2016, p. 181). Due to the hypothesis of the linear no-threshold model, even a small dose of irradiation can be

harmful for the human tissues. But this does not necessarily mean that every effect of radiation is harmful in the same way. After being exposed to a dose of 10 mSv, $5 \cdot 10^{-4}$ persons get cancer. This is an average of 5 persons per 10 000. According to Schmiermund (2019, p. 380), this is the same probability as dying in an accident, including domestic accidents, car accidents etc. In Figure 3, the arrow at 100 mSv indicates the point below which "*there is little scientific evidence of any measurable adverse health effects at radiation doses*" (Canadian Nuclear Safety Commission, 2015). (cf. Grupen & Rodgers, 2016, pp. 81–83, 181)

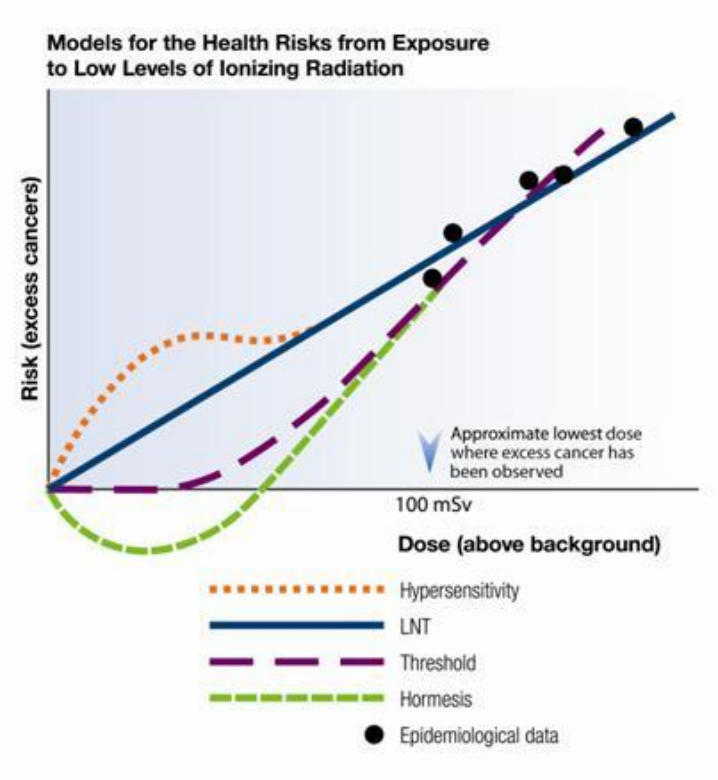


*Figure 3: Linear No-Threshold Model; (Canadian Nuclear Safety Commission, 2013), http://nuclearsafety.gc.ca/eng/resources/health/linear-non-threshold-model/index.cfm*

### 3.5.5. Irradiation vs. Contamination

Nearly every study about misconceptions regarding radioactivity contains something like *"many students have difficulty in clearly separating the ideas of irradiation and contamination.*" (Millar & Gill, 1996, p. 27). But what is the difference between irradiation and contamination? (cf. Millar & Gill, 1996, p. 27; cf. Morales & Tuzón, 2020, p. 19; cf. Plotz, 2017, p. 2)

Irradiation

If a nucleus breaks into two lighter nuclei by fission or when two nuclei form a new atomic nucleus by fusion, the core emits ionizing radiation. As already mentioned in Chapter 2.1., ionizing radiation "*can eject electrons from victim atoms*" (Johnson, 2014). "Irradiation" refers to the interaction of this radiation, for instance, with the human body. Ionizing radiation such as alpha, beta, and gamma can remove the electrons of the target atoms, resulting in the target atoms being ionized. Ionization, resulting from irradiation, can occur depending on the type of radiation. As mentioned later in Chapter 3.8.1., different types of radiation have different speeds, different energies, and different penetration depths. As a result, changes in the cell's properties through ionization can appear depending on the type of radiation. The question arises, what is dangerous about irradiation? The stability in molecules is given by binding electron pairs. If an electron is knocked out by ionization, resulting from irradiation, the molecule may break into two parts. This is particularly dangerous in the case of water molecules since radicals can be formed as a result of the splitting. These radicals can hit the cell nucleus and lead to mutation and cell death. Hence, the cell can no longer work properly. It is particularly dangerous when DNA molecules are hit and mutate. Radiation sickness and cancer are frequent consequences of such reactions. To sum up, "*ionizing radiation can damage a DNA molecule directly through ionization by a radiation particle or indirectly through generating free radicals*" (Johnson, 2014). (cf. Dienst, 1994; cf. Grupen & Rodgers, 2016, pp. 31–32; cf. Johnson, 2014; cf. Krieger, 2019, p. 237)

The energetic particles comprising the radiation, as a rule of thumb, do not interact with atomic nuclei. Although alpha particles consist of nuclear constituents, they have too low an energy to overcome the repulsion of the strong nuclear force. Even if the beta could get past the electrons in the electron cloud of the atom, it would be, considering its high speed, so unlikely to be captured by the nucleus that we can consider it a statistical impossibility. Because radioactivity is a nuclear phenomenon that is not affected by electrons being removed from the electron cloud via ionization, irradiation alone does not make an object radioactive. (cf. Johnson, 2014)

Contamination

In contrast to irradiation, contamination is "*pollution […] by radioactive substances*" (Grupen & Rodgers, 2016, p. 204). If a person is contaminated, he/she has radioactive materials on the surface of the skin and/or inside the body. Having these substances inside the body is very dangerous because then, in the exemplary case of alpha radiation, the emitted alpha particle cannot be stopped by clothes or other shielding. Since the alpha radiation has a very high energy and can therefore ionize many other atoms unobstructed, it is very dangerous when located inside the body. Especially laboratory workers who handle radioactive substances must pay crucial attention. Getting in contact with these substances can cause serious health issues. Wearing gloves and protecting clothes at work are the minimal protection measures that must be taken. A worker who is working with radioactive substances must test for contamination when leaving his/her workplace every day. If, for example, contamination of the skin is detected, measures must be taken immediately. Decontamination may only be carried out by trained personnel. The contaminated person must immediately remove his/her clothes, which are then stored separately and protected. Thorough washing with soap and water are sufficient decontamination measurements in most cases of superficial contamination. Nevertheless, the affected person is continuously monitored after the contamination incident. (cf. Grupen & Rodgers, 2016, pp. 145, 149, 154; cf. Johnson, 2014)

No matter whether it is irradiation or contamination, contact with radiation or radioactive material should be kept to a minimum. Both can lead to irreparable health issues. To prevent unwanted contact with ionizing radiation or radioactive substances, measures should be taken. For example, the ALARA-principle, see Chapter 3.8.1. Nevertheless, it is important for risk-based decisions to understand that if an object does not absorb radioactive material, it does not "*become a new source of radiation or become radioactive.*" (Prather & Harrington, 2001, p. 90). This is misunderstood by many pupils, who think that irradiation leads to contamination. When one proves them wrong by doing an experiment, for instance, irradiating a kiwi, they still have the opinion that the kiwi gets contaminated after a longer period of irradiation. (cf. Grupen & Rodgers, 2016, pp. 145–146)

## 3.6. Natural and Artificial Radioactivity

Radioactive decay can occur through natural phenomena but can also be induced by artificial means. The resulting product of radioactive decay is always ionizing radiation. (cf. Krieger, 2019, p. 91)

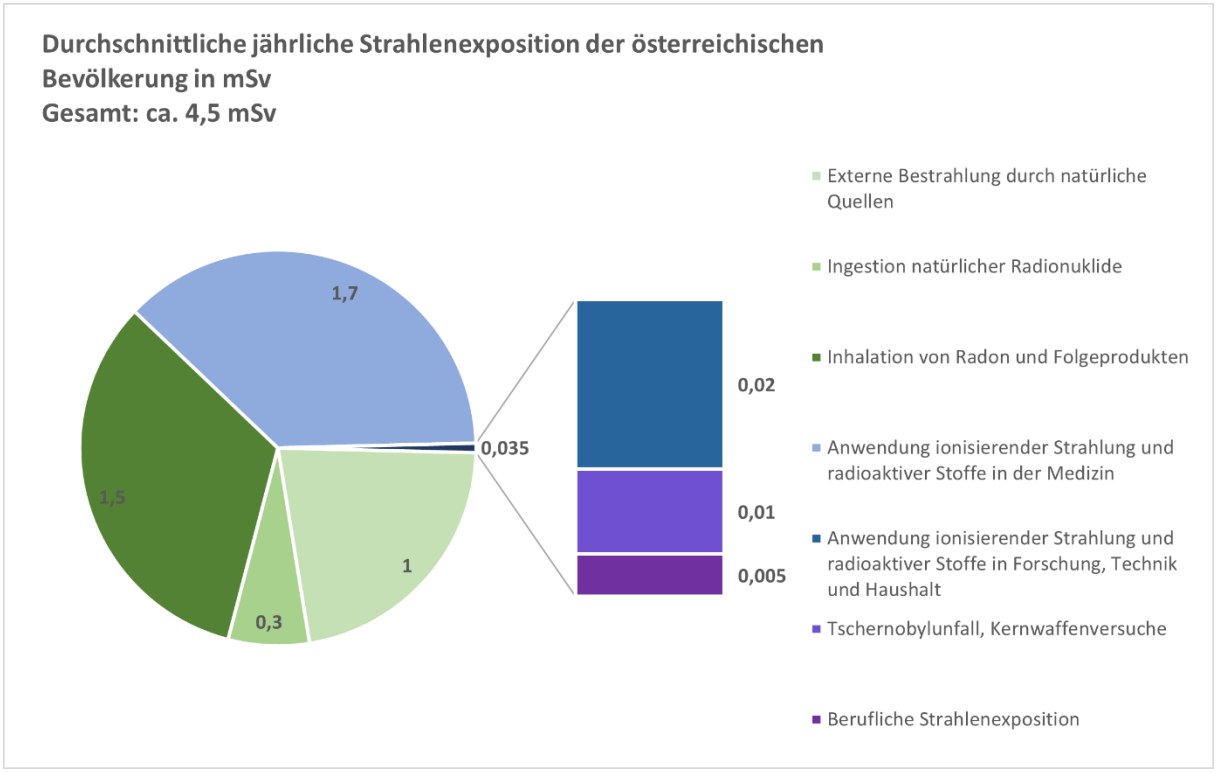


*Figure 4: Average Radiation Exposure in Austria; Source: (Cernohlawek et al., 2017), https://www.ages.at/download/0/0/6a89760dcbf1feb179051602b0af93d4be7cb3e2/fileadmin/AGES2015/Themen/Strahlenschutz_Dateien/Radioaktivit%C3%A4t_und_Strahlung_in_%C3%96sterreich_2017_bis_2019.pdf*

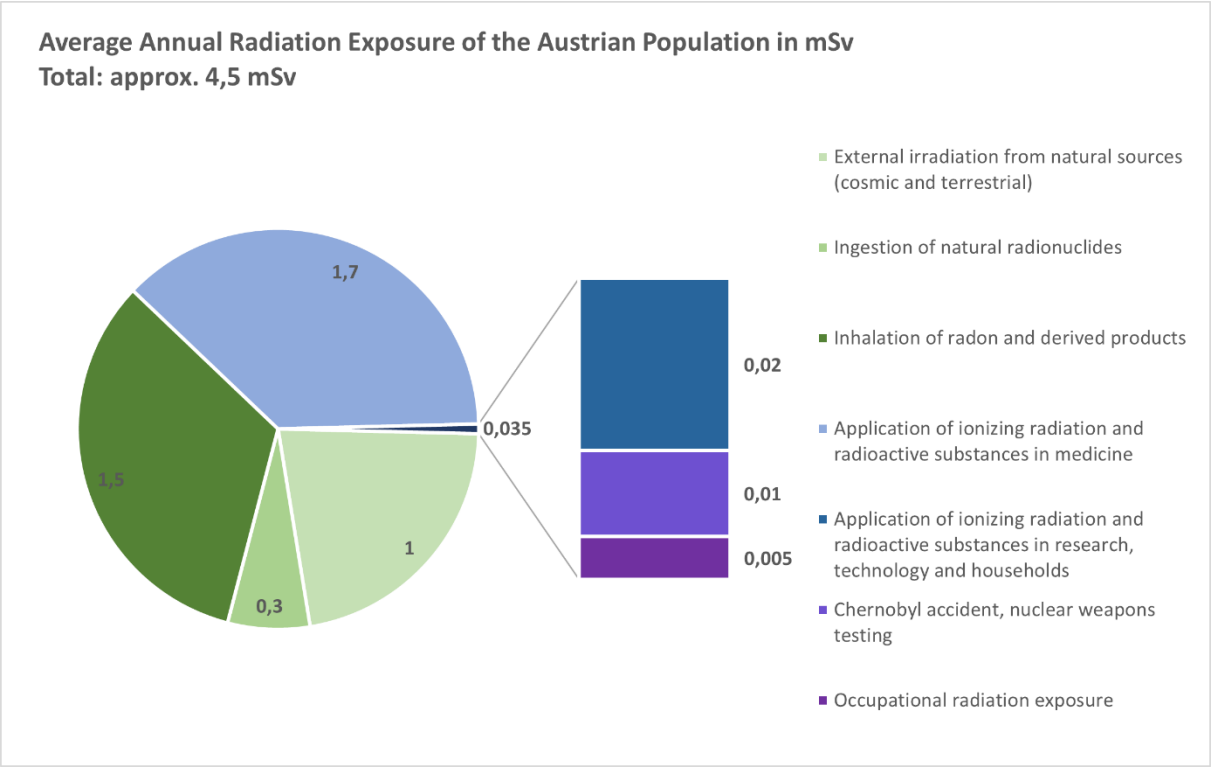


*Figure 5: Average Radiation Exposure in Austria translated in English; Source: (Cernohlawek et al., 2017), https://www.ages.at/download/0/0/6a89760dcbf1feb179051602b0af93d4be7cb3e2/fileadmin/AGES2015/Themen/Strahlenschutz_Dateien/Radioaktivit%C3%A4t_und_Strahlung_in_%C3%96sterreich_2017_bis_2019.pdf*

Figure 4 and Figure 5 show the average radiation exposure of people in Austria. In total, there is an average exposure of 4,5 mSv for each Austrian citizen which derives from location, professions, and medical applications. The green slices of the pie chart characterize the Austrian exposure by natural radiation whereas the blue slice of the pie chart describes the exposure by artificial radiation. In Figure 4 and Figure 5, it is noteworthy that radon inhalation accounts for more than half of the mean exposure of Austria citizen to natural radiations. (cf. Cernohlawek et al., 2017, pp. 7–8)

All the radionuclides can be absorbed through the mouth, the digestive tract, and the lung. "*The most important natural isotopes which occur in drinking water and in food are the isotopes of hydrogen (tritium: $^{3}H$), carbon ($^{14}C$), potassium ($^{40}K$), polonium ($^{210}Po$), radium ($^{266}Ra$) and uranium ($^{238}U$)*" (Grupen & Rodgers, 2016, p. 65). Because of this ingestion, the human body has an activity around 7000 to 9000 Bq. A very well-known radioactive food are bananas. But their radioactive level is so low, that it would be necessary to eat so many bananas to be harmed. So in general, the person is harmed from overeating before. (cf. Grupen & Rodgers, 2016, pp. 65–66; cf. Schmiermund, 2019, p. 376)

### 3.6.1. Natural Radioactivity

Natural radioactivity results from only a few sources and is important for the biodiversity on earth. Not every type of natural radioactivity is harmful for humans. In Austria, the natural radiation reaches 2,8 mSv per year on average. Mankind is exposed to natural radiation by the following variants. (cf. Cernohlawek et al., 2017, p. 8; cf. Grupen & Rodgers, 2016, pp. 65–67, 180–181)

Primordial Radionuclides

The primordial radionuclides developed during the formation of the earth, of the sun, and of other planets. 30 variants of primordial radionuclides are still detectable. Their half-life must be considerably long as we can still determine these radionuclides on earth today. The 30 primordial radionuclides have a mass number between 40 and 240 and there are 48 others, which are products from radioactive decays. (cf. Grupen & Rodgers, 2016, p. 61; cf. Krieger, 2019, pp. 150–153)

Cosmic Rays

Cosmic rays originate from space, for instance, from the sun. These rays come to earth in the form of high-energy, ionizing radiation, mostly realized by protons and α particles. "*Cosmic rays consist largely of protons (about 85%) and helium nuclei (about 12%). Only 3% are nuclei heavier than helium*" (Grupen & Rodgers, 2016, p. 62). In cosmic radiation, all elements can be found in different amounts. When arriving at the earth, these rays hit other atoms in the atmosphere and interact with them. The newly formed nuclides are called cosmogenic radionuclides and are a variation of many different particles, also known as secondary cosmic radiation which take the form of protons, neutrons, γ rays, and mesons. The radiation level caused by secondary cosmic rays is 0,3 mSv per year in central Europe. This dose varies, depending on the altitude and the latitude of residence. Protection from these rays by the earth's atmosphere decreases with rising altitude. At sea level, this atmospheric protection leads to a lower dose of radioactive exposure. Hence, a person absorbs a higher dose during a flight than while driving a car. Additionally, the secondary cosmic ray concentration is higher at the poles because of the weaker magnetic field. Muons have a higher penetrating power than electrons and protons. So, the number of muons at sea level is higher than the number of electrons and protons. (cf. Grupen

& Rodgers, 2016, pp. 62–64; cf. Hutchison & Hutchison, 1997, p. 502; cf. Krieger, 2019, p. 157; cf. Schmiermund, 2019, p. 375)

Terrestrial Radiation

The stones found in the earth's crust exhibit substance-dependent radioactivity. The activity radiating from these stones varies from one location to another. In central Europe, there is an average dose of 0,5 mSv per year stemming from such terrestrial radiation. Stones with a natural radioactivity often consist of "*potassium-40, uranium-238, thorium-232 and rubidium-87*" (Grupen & Rodgers, 2016, p. 64). These elements are also called primordial radionuclides because they originate from the earth's formation. Some building materials, for example concrete, contain radioactive material. Their activity leads to a rise in the environmental radiation for humans. One element in particular impacts the environmental radiation for humans: Radon, an intermediate product of terrestrial uranium, is found in the form of gas in the air we breathe. It is found in particularly high concentrations in cellars, caves and in groundwater. The inhalation of radon accounts for 1,5 mSv per year which constitutes about half of the exposure of natural radiation. (cf. Cernohlawek et al., 2017, p. 7; cf. Grupen & Rodgers, 2016, pp. 64–67; cf. Schmiermund, 2019, p. 376)

### 3.6.2. Artificial Radioactivity

Natural radioactive decays are uninterrupted and uncontrolled processes. Thanks to Ernest Rutherford, humanity found ways to create calculated and controlled artificial radioactivity. This artificially induced radioactivity is used for energy production, medical and technical applications, and various other utilizations. To induce radioactive processes, the stable neutron-proton relationship must be disrupted which leads the nucleus to radioactive decay. One possibility to create such an unstable core is to shoot neutrons, protons, or heavy particles on cores to achieve fusion. Depending on the corresponding interaction, once the target nuclei have reached an unstable state, they decay. In most cases, induced fission proceeds in a controlled manner. In medical applications, particular attention is paid to the effective dose absorbed by a human being. Some diseases are treated with the help of irradiation or injection of radionuclides. In these medical applications, the human body is exposed to an additional dose of radionuclides in contrast to the natural exposure. The treatment should be supervised and carried out in stages. "*If a patient needs to receive, say, an effective dose of 2 Sv to destroy a tumour, this dose might*

*be applied in ten separate fractions of 0,2 Sv, because in the intervals between these fractions, the healthy tissue will recover more easily than the cancerous tissue will*" (Grupen & Rodgers, 2016, p. 22). (cf. Grupen & Rodgers, 2016, p. 22; cf. Krieger, 2019, p. 161; cf. Schmiermund, 2019, pp. 391–393)

I will now present two possibilities of energy production through man-made radioactivity.

Nuclear Fission

In a nuclear fission, energy is released through the decay of a core. The initial core splits into two smaller nuclides and two to three neutrons. The binding energy per nucleon of the fission fragments (i.e., daughter nuclei) is greater than that of the initial core (i.e., parent nucleus). Hence, the resulting binding energy is greater after the decay. In addition, both fission fragments are smaller and lighter than the heavy initial core. The binding energy corresponds to the work that is needed to split the nucleus into constituent nucleons. The greater binding energy per nucleon in the daughter nuclei means that more work is needed to split the daughter nuclei into protons and neutrons: the daughter nuclei are more stable than the parent nucleus. The decrease in energy associated with this greater stability manifests itself as kinetic energy in the daughter nuclei, which is harnessed in fission power plants. The binding energy is dependent on the mass number of the respective element. The most used element for energy generation is uranium. The average binding energy of a uranium nucleon is 7,5 MeV. This energy can be calculated from the binding energy of the nucleus divided by the respective atomic mass. For example, when a neutron hits a uranium core, the result is a neutron capture and a compound core which is in an excited state. The core is changing its shape whereby the Coulomb force is becoming greater than the nuclear force and the core is divided. This can result in various realizations of fission fragments and a lot of energy in the form of γ rays. On average, there are 2,5 neutrons released per fission. The energy released after the nuclear fission corresponds to the mass difference between the initial core and the fission fragments. This difference is about 0,1% for a uranium fission, which means that the initial core was about 0,1% heavier than the total mass of the two fission fragments. The resulting fission fragments, mostly two, can be in an excited state and therefore continue to decay. The neutrons released during the fission can hit other cores and

induce another decays which is known as a chain reaction. (cf. Grupen & Rodgers, 2016, pp. 95–98; cf. Rybach, 2019, pp. 321–323)

Nuclear Fusion

Continuous nuclear fusion takes place in the sun. The sun would therefore create enough energy to supply the whole earth. Why is it not possible to recreate the sun on earth? (cf. Rybach, 2019, p. 326)

Nuclear fusion is the reverse process of nuclear fission. Smaller atomic nuclei are fused into a larger one. The obstacle that must be overcome in this process is the Coulomb barrier since the positively charged atomic nuclei repel each other. Consequently, the tunnel effect must occur. To achieve a nuclear fusion by overcoming the Coulomb barrier, temperatures in the range of $10^8$ Kelvin must be reached. To reach these high temperatures, plasma chambers are used. Inside the plasma, the atoms are highly ionized. Within these high gas temperatures, the gas is electrically conductive. (Grupen & Rodgers, 2016, pp. 103–106; cf. Rybach, 2019, pp. 324–325)

What is needed to recreate nuclear fusion? To create nuclear fusion, there must be two elements which can form compounds. These are usually hydrogen and helium. But it is not only hydrogen in its simplest form. For fusion reactions, deuterium and tritium, the isotopes of hydrogen, are used. Deuterium is easily found in water. Special care should be taken using tritium because this isotope is radioactive. However, the two elements alone and the presence of high temperatures are not enough to induce a fusion. There are two more factors required for nuclear fusion to take place. These two are listed under the Lawson criterion. Firstly, a nuclear fusion requires a high particle density to reach enough pressure. Secondly, the insertion times have to be long enough to increase the probability of fusion. If all conditions are met, a nuclear fusion is possible. The question many scientists are asking is if an economically profitable production of electricity by nuclear fusion may be possible in the future? (cf. Grupen & Rodgers, 2016, pp. 103–106; cf. Rybach, 2019, pp. 324–325)

## 3.7. How to Detect Radiation?

Particles or quanta which result from radioactive decays are not detectable with the senses of a human being. They do not have a taste, nor are they visible. Thus,

humans can not recognize whether they are in danger or not. Measuring instruments are needed to detect ionizing radiation. In Austrian schools, the most common instrument to measure the activity of ionizing radiation is the Geiger-Müller counter (in short: GM counter). Every single particle of ionizing radiation which enters the Geiger-Müller Counter is detected. The shape of the measure instrument is a tube which is filled predominantly with a noble gas. The metal walls of the cylinder are the negatively charged cathode and the wire inside the counter is the anode. The potential difference between them is in the kilovolt range. If a particle, for instance a β particle, reaches the noble gas, an electron is knocked out of the electron shell of a gas atom. The free electron is attracted by the anode, is accelerated by the electric field inside the tube and ionizes other atoms of the gas. Many electrons reach the wire. The ionized atoms or molecules are attracted by the walls of the cylinder. An electrical discharge occurs in the Geiger-Müller counter and the voltage is measured across a resistor in the circuit. "*Each ionising particle passing through the chamber causes a single brief discharge, and the count of these discharges gives an indication of the radiation level*" (Grupen & Rodgers, 2016, p. 165). This indication is shown at a display and is made audible through speakers. Hence, the typical "clicks" can be heard. The handling of a GM counter is very easy, and its size allows a practical use, especially at school. (cf. Grupen & Rodgers, 2016, pp. 165–166; cf. Rybach, 2019, pp. 320–321)

## 3.8. Protection from Radiation

In an uncontrollable situation, ionizing radiation can be dangerous for human beings. Whether it is a hazardous area or simply handling of radioactive substances, everyone should know how to protect oneself and fellow humans from excessive ionizing radiation. Especially at school, it is very important to give pupils an introduction of how to work with radioactive substances and ionizing radiation. Repeating the precautions more often during the lesson is necessary.

One command is that it is absolutely prohibited to drink or eat something while handling radioactive substances. If there is an absolute need, the person should leave the room or the danger area and should wash his/her hands with soap before eating or drinking. Through this safety measure, the ingestion of radioactive substances is prevented. (cf. Schmiermund, 2019, p. 407)

"*The fundamental principles for radiation protection are laid down in recommendations by the International Commission on Radiological Protection (ICRP), and the International Commission on Radiation Units and measurements (ICRU)*" (Grupen & Rodgers, 2016, p. 179). These recommendations show the limitations of radiation doses regarding the respective person. A distinction is made between "*radiation workers (…); patients; and members of the public*" (Grupen & Rodgers, 2016, p. 180). Radiation workers should not overcome the limit of "*20 mSv per year*" and the limit of the general public (18 years and older) is "*1 mSv per year*" (Grupen & Rodgers, 2016, p. 180). The limit refers to the effective dose, which indicates the damage to a human being caused by radiation. In case of medical treatment, the intake of a higher dose of radiation is allowed. For instance, a person who suffers from cancer needs radiation treatment. Hence, a higher effective dose is tolerated to treat the disease. Care must be taken not to damage the healthy cells during irradiation. When gaining a higher dose of radiation, it is important to avoid ionizing radiation treatments the next few years, so that the affected parts of the body and tissues have time to recover. Every single country can decide on their own if the recommendations for the limits fit for their country or if they should have stricter or lighter guidelines. All the recommendations and limits especially relate to radiation which is produced by technical applications since natural radiation can only be controlled to a limited extent. (cf. Grupen & Rodgers, 2016, pp. 179–183)

### 3.8.1. ALARA-Principle

The ALARA-principle offers tips on how to behave while being exposed to unavoidable radiation in a hazardous area and involves a mnemonic in German to easily remember the protective measures with the help of the four A's. ALARA stands for "*as low as reasonably achievable*" (Schmiermund, 2019, p. 408) and helps to reduce the doses by following the four A's. (cf. Grupen & Rodgers, 2016, p. 146; cf. Schmiermund, 2019, p. 408)

- "*Abschalten*
- *Abstand halten*
- *Aufenthaltsdauer beschränken*
- *Abschirmung ausnutzen*" (Schmiermund, 2019, p. 408)

Abschalten - turn off

If possible, it is very important to turn off instruments which produce ionizing radiation. This measure can only be implemented if it is not an uncontrollable accident caused by machines and instruments. The respective person must acknowledge that there could still be remaining radiation after are turned off the instruments. Thus, devices switched off do not guarantee an immediate protection from ionizing radiation. (cf. Schmiermund, 2019, p. 409)

After turning off an X-ray tube, there may be remaining radiation. This is not, as is often mistakenly believed, the result of the air or the walls becoming radioactive as a result of irradiation. Rather, this happens since the device needs time to reduce the acceleration voltage. Similarly, a nuclear reactor has remaining radiation because of their "*highly radioactive fission products*" (Grupen, 2008, p. 240). Hence, it is very important to maintain the cooling system even after the reactor is shut down. (cf. Dombrowski et al., 2017, p. 40; cf. Grupen, 2008, p. 240)

Abstand halten - keep your distance

The intensity of ionizing radiation decreases proportionally to the distance from the source squared (if the source of radiation is a point; modelling the source as such is adequate most of the time). Therefore, in the event of a hazard, the affected person should move away from the potential source of radiation as far as possible. The further the person moves away from the source, the lower the dose rate. To measure the decay counts per minutes, it is recommended to use a telescopic probe. This type of measurement guarantees a greater distance than a conventional GM counter. (cf. Schmiermund, 2019, pp. 409–410)

Aufenthaltsdauer beschränken - limit length of stay

The relation between dose and time is proportional: The shorter the time of irradiation by ionizing radiation, the smaller the dose. If a person is irradiated by the same origin of ionizing radiation for 6 hours, the absorbed dose is 6 times higher than if he/she was irradiated for only one hour. If the dose rate is known, the person working with radiation can calculate how long it is acceptable to be irradiated by such a dose. As a rule, the shorter the irradiation, the better. (cf. Schmiermund, 2019, p. 411)

Abschirmung ausnutzen - use shielding

For different kinds of radiation, different materials for protection are needed. The shielding can diminish the dose rate which depends on the material and the type of radiation. In addition, the penetration depth depends on the energy of the respective particle or quanta. In general, the denser the material, the better. (cf. Schmiermund, 2019, pp. 407, 412)

Alpha particles have very high energy but are massive and hence move slowly. As a result (and because of their large charge), they ionize many victim atoms in their vicinity. As a result, their range is very low. In air, their range is about 3,5 cm and in plastic, they can only travel 0,1 mm. To shield alpha particles, a sheet of paper is sufficient. (cf. Grupen, 2008, p. 301; cf. Johnson, 2014; cf. Schmiermund, 2019, pp. 338, 348)

In contrast to alpha particles, beta particles are faster, because of their lower mass. Beta particles have an ionizing character too, but they do not interact with as many victim atoms as alpha particles because of their lower charge. Hence, they do not ionize such a high number of atoms which means that the range of beta particles is greater - they reach several meters in air. To shield beta particles, 4 mm aluminium is sufficient. (cf. Johnson, 2014; cf. Schmiermund, 2019, p. 341)

Avoiding gamma rays is not easy because of their amazing penetrating power. Like with alpha and beta radiation, exposure decreases exponentially as shielding thickness increases. Whereas only a thin sheet of metal is sufficient to block alphas and betas to a level comparable with background radiation a meter-thick lead wall is necessary for gammas. Although complete shielding is not provided, exponential weakening is induced. The penetrating power of gamma rays in air is hundreds of meters. Gamma quanta can go through human bodies without interacting with any atom at all. It can also be possible that a gamma quanta interacts with one victim atom and ionizes it as a result. After that, the gamma quanta transfers its full energy to the detached electron and is thereby stopped. It can also happen that the gamma quanta transfers part of its energy to the detached electron. Then “*a new gamma with lower energy*” (Johnson, 2014) is produced. (cf. Johnson, 2014; cf. Schmiermund, 2019, pp. 348, 407, 412)

Every single step taken in consideration of the four A’s is a good way to diminish the dose rate. The best protection is provided when a combination of all suggestions is implemented. It is important to be able to assess the danger correctly and to implement the appropriate suggestions. (cf. Schmiermund, 2019, p. 414)

# 4. Students' Conceptions

## 4.1. Definition of Students' Conceptions

Pupils bring prior knowledge to the classroom, which does not have to be scientifically correct. If this knowledge is based on plausible but false explanations (which students build up during their everyday life) and not on physical concepts, then it is possible to define them as students' conceptions ("*alternative: students' ideas; (…) preconceptions; alternative frameworks*" (Schecker et al., 2018, p. 12)). According to Schecker et al. (2018, pp. 2-3, 9, 12), students have the tendency to create such preconceptions. This means that students tend to not distinguish between their way of describing physical concepts and the correct definition of physical descriptions. They are not able to describe their conceptions but will act according to their ideas. This behavior is called "*als-ob-Vorstellungen*" (Schecker et al., 2018, p. 9) (translated in english: "*as-if ideas*").

Where do these students' ideas come from? Schecker et al. (2018, p. 12) describe three main sources: "*everyday language, media, and everyday experience*" (Schecker et al., 2018, p. 12). In consideration of this thesis' scope and previous studies, more importance is attributed to everyday language and media.

Words used in everyday language often have more and/or false meanings which do not correspond to definitions in physics. Thus, everyday language may evoke ideas in some students that are further reinforced by media (and even some textbooks!) which utilize similar language. For example, Apolin (2008, p. 58) used the phrase "radioactive radiation" in his physics course book whereas Sexl et al. (2013, p. 84) describe that the term "radioactive radiation" is grammatically and physically incorrect. If there is already a wrong definition in the physics course book or other media, concomitant ideas are incorporated by students since they assume that what is written in a textbook corresponds to the truth. In addition, newspapers etc. often use simplified representations for enhanced readability. Students read such articles and memorize the simplified representation because of its simplicity. In some situations, it is acceptable to simplify representations: However, their integration becomes problematic when a teacher tries to create an additional representation or expand the simplified one which is then ignored in favor of the initial, simplified representation. Furthermore, it is possible that students also need individual time to

develop a definition. Thus, it is important to give students enough time to personally acquire a definition with the support of the teacher. (cf. Apolin, 2008, p. 58; cf. Schecker et al., 2018, pp. 12, 13, 14, 232; cf. Sexl et al., 2013, p. 84)

For effective instruction, it is necessary to know students' ideas, and it is also important to get to the bottom of their cause. This can be achieved through a teacher-student talk in which students are asked to justify or explain their assumptions. After having found the origin of the preconceptions, the teacher should create or change his/her lessons accordingly, to transform the pupils' thinking towards a scientifically correct manner. Usually, the ideas are not completely false but are composed of partially wrong explanations in the students' minds. Nevertheless, they hinder the learning of the acquisition of scientifically correct knowledge in physics. Even though the teacher provides new knowledge in a clear and compelling manner, the students are unable to process it. The longer students' ideas remain undetected, the harder it is to convert them into physically correct concepts. It is even possible that two or more (contradictory) preconceptions coexist. Which one of the students' idea will be applied, depends on the task. Therefore, the teacher should pay great attention and be sensitive in formulating the task. (cf. Schecker et al., 2018, pp. 2–3, 10–12)

The topic of this master's thesis is not student ideas and how to counteract them, but it forms a necessary part of this thesis' theoretical basis. As soon as one talks about students' conceptions, the theory of constructivism and conceptual change should be mentioned at least briefly. (cf. Schecker et al., 2018, pp. 28–29, 35)

### 4.1.1. Constructivism

A way to prevent the occurrence of students' conceptions during lessons is the constructivist process. The aim of constructivism is to design lessons and the methods used in ways which connect everyday lives of students with carefully chosen physical explanations to construct a new, better train of thought. But this is not about self-discovering learning (in German: "*selbstentdeckendes Lernen*" (Wiesner et al., 2018, p. 48)). The teacher must create a suitable learning environment to achieve the greatest possible learning success. Whether a teacher directly addresses students' conceptions via different methods in class, or works on them more covertly, always depends on the situation and the students' conceptions. The type of handling should therefore depend on the situation. It is particularly important that students' ideas are always treated with appreciation. That is, the

teacher should be sensitive to the students' reflections. If the students' ideas are met with a negative attitude, learners may be reluctant to disclose their ideas. This must not occur under any circumstances. To get the most out of the pupils according to Schecker et al. (2018, p. 2-8, 24-26) and Wiesner et al. (2018, pp. 29-33, 48-49), the students should be taught by means of a constructivist approach. This process includes the linking of knowledge from the long-term memory with the newly learned. Only when a successful link is established, one can speak of a learning success. During this individual process, the role of the teacher is to be supportive to build on previous experiences, to provide thought-provoking impulses and to offer assistance.

### 4.1.2. Conceptual Change

Conceptual Change is a theory of learning which is used to replace students' ideas induced by everyday thinking with scientifically correct concepts. Students enter the classroom with prior ideas and concepts. These are constructed during their everyday lives and school education and are satisfying for them. In some situations, it would be easier for the teacher if the students did not have such previous ideas on some topics. But there is no button which could erase all students' ideas and create a tabula rasa in their minds. "Empty" heads are not the goal either. It is important that students have individual ideas about how the world works. Students' ideas should be seen as something from which teachers and pupils can benefit. Nevertheless, teachers want to teach students to look at the world through scientific eyes. Students' conceptions influence their observation and how to solve the posed problem or task. If a teacher introduces a new topic or builds upon another, pupils could have difficulties. The taught concepts of the new topic may not coincide with the priorly established mental model in the students' minds. As a result, students may not accept the taught knowledge even when the teacher explains it correctly. The teacher's goal must be to make the students dissatisfied with their wrong explanations. To achieve this goal, the teacher must be aware of the students' ideas. Following this step, new concept must be made comprehensible for students by using understandable words. This new concept, or parts of it, must be plausible for students. In addition, students must be offered a range of problems which only can be solved when the student utilizes the new approach. If all these steps, from knowledge about the students' idea, to the acceptance of it, and the application of the new concept, are fulfilled, a conceptual change has taken place. There is no rule that

says how long such a change will take. It depends on the situation and the students' conceptions. (cf. Schecker et al., 2018, pp. 28–29, 35)

# 5. Didactical Research

This master's thesis is titled "The Public's Knowledge on Radioactivity in Austria Affected by the Time Passed After Graduation and the Type of School Attended". The aim is to find out the participants' knowledge about radioactivity depending on the type of school attended and the time passed since graduation. To answer the research questions which are listed in Chapter 5.1., I created an online questionnaire. This questionnaire can be seen in the Appendix Chapter 10.3 in German and in 10.4 in English. The format of the questionnaire does not correspond to the one the participants received. As explained in more detail in Chapter 5.3., the questionnaire was provided online. The survey was appropriate for all persons who have acquired a school leaving certificate from Austria. I used the responses given in this questionnaire to answer my research questions and to prove or disprove my created hypotheses, which are also listed in Chapter 5.1.

## 5.1. Research Question

Physics remains to be an unpopular topic in the general public. This may be due to the fact that a lot of adults do not remember anything they have learned at school. Can one make a statement about how much an adult knows about radioactivity based on the school type and the time passed since school graduation? Based on this question and the beforementioned consideration, two research questions and a question of interest (in the sense of being interesting, but not of central importance to this study) were created.

*RQ1: How does understanding about radioactivity change with the passing of time after graduation from school?*

*RQ2: How does understanding about radioactivity depend upon the school graduated from?*

*Question of interest*: *How does knowledge about radioactivity change after watching the TV series "Chernobyl"?*

Research question one (in short: RQ1) shall give an overview if there is an interdependency between the understanding about radioactivity and the passing of time after school graduation. Can it generally be said that people fresh out of school

know more about physics than those who have attended school a longer period of time ago, or can the exact opposite of this trend be identified, since students' interest may have decreased over the last few years. Alsop (2001) defines "*recent school leavers*" (Alsop, 2001, p. 265) to not be older than 25, which is why the time span for the factor level since the last school attendance is divided between 0 and 10 years (more about the factor level in Chapter 5.2.1. In response to RQ1, the following hypothesis (H1) was created:

*H1: Adults who have graduated from school more recently know more about radioactivity than those who have graduated a longer period of time ago.*

RQ2 asks if the understanding about radioactivity is affected by the type of school attended. In Austria there is a variety of different types of schools. For a better overview, the schools are divided into compulsory school (Pflichtschule), polytechnic school (polytechnische Schule), general secondary school (allgemeinbildende höhere Schule), vocational school (Berufsschule), 3-year vocational school (berufsbildende mittlere Schule), and 5-year vocational school (berufsbildende höhere Schule) in this thesis (cf. Bundesministerium Bildung, Wissenschaft und Forschung [BMBWF], 2022). The genesis of the associated hypothesis (H2) comes from my own experience. Since I was in a general secondary school the interest in physics was not very high. For a lot of students who have attended my former school, physics was an unpopular topic and rather a torment. Based on my own experience and the stereotype that students who attend a 5-year vocational school (especially the attendees from a HTL) are very often technically gifted, the following hypothesis (H2) was concluded:

*H2: Adults who have attended a 5-year vocational school have the highest understanding of radioactivity.*

The question of interest and the corresponding third hypothesis derive from the sudden increase in interest in the TV series "Chernobyl" published by Sky in 2019 (cf. Sky, 2021). This TV series deals with the nuclear disaster in Chernobyl in 1986. Enthusiasm towards this TV show rose rapidly. In 2021, "Chernobyl" was also shown in Austrian free and private TV where the series was available for almost everybody (cf. News ORF, 2021; cf. ProSieben, 2021). Why is watching this TV show part of a hypothesis? In "Chernobyl", besides the historical processes, the definition and the

effects of radioactivity are explained in an understandable way. Additionally, people who have seen this series have come into contact with the concepts of radioactivity again. The question of interest is whether watching this series influences the knowledge about radioactivity, which is why hypothesis 3 was formed:

*H3: Adults who have seen the TV show "Chernobyl" have a better understanding of radioactivity.*

## 5.2. Research Method

Since the questionnaire was created in SoSci (more in Chapter 5.3.), a lot of work was done automatically before I gathered the data. With the help of SoSci, the questions and their corresponding answers were divided into rubrics. An example of this would be the rubric half-life, in which there are 6 questions. These 6 questions and their answers were coded with short labels. For example, question 1 in the rubric half-life is coded as HW01 with its corresponding answers are labelled HW01_1, HW01_2, etc. When the data is transferred from SoSci to the statistical program RStudio, the data usually comes in the compatible format. Statistical programs require numerical data, which is why SoSci's nominal response options were transformed into 1 and 2. 1 means that the participant did not select the response option, while 2 means that the participant chose the option. For clarity, this data was transformed into dummy variables, also known as binary variables, containing 0 and 1. Where 0 stands for not selected and 1 means selected. Thanks to this step, nominal variables can be treated like metric variables. (cf. Backhaus et al., 2018, pp. 11, 26, 27; cf. Leiner, 2019; cf. R-Project, 2021)

Since the survey is about to compare different types of knowledge about radioactivity, the questionnaire is composed like a test. Points are awarded when the questions are answered correctly, and it is possible to acquire are partial points. To be able to define and be sure which answers are correct, an expert panel was consulted (more on this in Chapter 5.3.1. and 5.3.2.). The questionnaire contains 16 theoretical questions (Q4-Q18), with one point for each correct answer. Hence, the maximum score is 16 points. If the participant ticks a wrong answer, then he/she will get zero points for the respective question. All the other questions are there to classify people, to ask where their knowledge comes from, but also to find out how they performed filling out the questionnaire.

### 5.2.1. Analysis of Variance

To analyze the results, the three-way "*Analysis of Variance*" (Backhaus et al., 2018, p. 165) (in short: ANOVA) test was applied. The ANOVA tests whether the mean values of two compared factor levels within one factor are about the same or if there is a significant difference. The three-way ANOVA can be applied when there are one dependent variable and three independent variables. Croiser et al. (2000, p. 329) used a three-way ANOVA as their research design consisted of three independent variables: "*attitude scores [towards computers], ability [with computers] (high, low) and gender*" (Crosier et al., 2000, p. 329). In this thesis, the three independent variables are whether the series "Chernobyl" has been watched, the time passed from school, and the type of school attended. All of these three independent variables have two factor levels which can be seen in Table 1. An ANOVA shows if the dependent variable is affected by the three independent variables. In this master's thesis, the metrically and interval scaled dependent variable is the achieved test score, whereas the three nominal independent variables are "time passed since last school attendance", "types of schools" and, "have or have not seen the TV series 'Chernobyl'". Based on the relation between the mean value positions of the compared factor levels, the population can be inferred if the difference is sufficiently large. If the difference between the observed means is big enough, it can be assumed that the variance between the factor levels is greater than the variance within the factor levels. It can therefore be concluded that the factor levels did not achieve equal points and hence, do not have the same knowledge about radioactivity. The advantage of the three-way ANOVA compared to a one-way ANOVA is, besides the main difference of three instead of one independent variables, that the interaction effects are also considered. The interaction effect exists between two independent variables in all possible combinations as well as of all three independent variables together. This effect shows whether the individual independent variables differ from each other, or if there is no difference in the knowledge on radioactivity between a certain combination of independent variables. An example for a two-way interaction might be to not just compare the knowledge of participants who have or have not seen "Chernobyl" but to compare the knowledge of participants who have or have not seen "Chernobyl" with the passing of time since the participants' last school attendance. If we pool all respondents who saw Chernobyl together and compare them with all respondents who did not watch Chernobyl, we might see no

difference in scores. Likewise, if we consider all respondents who recently left school, we might see no difference when comparing with respondents who left school a long time ago. Nevertheless, we might find that respondents who watched Chernobyl AND graduated recently out-perform respondents who have not watched “Chernobyl” AND left school a long time ago. In this case, the ANOVA would show an interaction effect between the factor levels of “time passed since last school attendance” and “Chernobyl”. The factor levels are always considered in combination with regard to the achieved test score (dependent variable). (cf. Bortz & Schuster, 2010, p. 265; cf. Fahrmeir et al., 2016, pp. 478, 486)

To provide the two comparable factor levels in each factor, there are three independent variables (factors) with two factor levels, i.e., in total, six factor levels. The factors are marked by the number 1-3, which coincide with the numbers of the respective hypotheses. These factors are shown in Table 1.

*Table 1: Formation of Factor Levels for Analysis by Means of the Three-way ANOVA, Source: Own Composition*

| | Factor Level 1 | Factor Level 2 |
|---|---|---|
| Factor 1 | Adults who have graduated from school recently (in the last 10 years) | Adults who have graduated from school, but not recently (more than 10 years) |
| Factor 2 | Adults who graduated from a 5-year vocational school | Adults who have not graduated from a 5-year vocational school |
| Factor 3 | Adults who have seen “*Chernobyl*” | Adults who have not seen “*Chernobyl*” |

For the three-way ANOVA, I created three null hypotheses (in short: H0) to correspond to the three hypotheses followed.

*H0_1: Adults have the same understanding of radioactivity regardless of the passing of time after graduation from school.*

*H0_2: Adults have the same understanding of radioactivity regardless of whether or not they graduated from a 5-year vocational school.*

*H0_3: Adults have the same understanding of radioactivity regardless of if they have seen the TV show “Chernobyl”.*

The H0s state that there will be no significant difference between the mean values of the respective factor levels. In order to test this, the p-value is essential. The p-value offers an insight into how probable, i.e., how true, a hypothesis is. Hence, if the p-value is smaller than the defined level of significance (in short: $\alpha$), then the H0 must be rejected, and it can be assumed that there is a significant difference between the two factor levels ("$p < \alpha$" (Backhaus et al., 2018, p. 174)). If the p-value is greater than the defined level of significance, however, the H0 cannot be rejected, and it can be assumed that there is not a significant difference between the two factor levels ($p > \alpha$). Nevertheless, the test cannot provide any information about whether one factor level has a higher mean value than the factor level to which it is being compared. Graphical representations (e.g., boxplots) are often used together with ANOVA to supplement this information. (cf. Backhaus et al., 2018, p. 174; cf. Bortz & Schuster, 2010, pp. 583, 585)

To be able to perform an ANOVA, the conditions of a normal distribution and a data variance homogeneity (that is, that the variances of the data within the factor levels are approximately equal) must be met. I used the D'Agostino test of skewness to test if the data is normally distributed, and I used the Bartlett test of homogeneity of variances, to test whether the data shows variance homogeneity. The ANOVA may be executed when the p-value of each test is higher than the $\alpha$-error of 5%. The procedure and the results are presented in Chapter 5.4.3 and Chapter 5.4.4. (cf. D'Agostino, 1970, p. 680; cf. Keating & Leung, 2010, p. 61)

## 5.3. Questionnaire Development

### 5.3.1. How the Questionnaire is Structured

The questionnaire in this master's thesis was constructed to answer the research questions "*RQ1: How does understanding about radioactivity change with the passing of time after graduation from school? RQ2: How does understanding about radioactivity depend upon the school graduated from?*" and the question of interest: "*How does the knowledge about radioactivity change after watching the TV series "Chernobyl"?*". The questionnaire was created with the help of the book "*Developing a Questionnaire*" from Bill Gillham (2008), the theoretical part of this master's thesis, the misconceptions found in literature and the materials from "*Inquiry into Radioactivity*" (Johnson, 2014). The survey was generated by means of the online tool "*SoSci Survey*" (Leiner, 2019).

Instead of the classical Wh-questions (What, Where, Who, etc.), operators were used in the questionnaire. Operators give the participants a clearer instruction on what is required of them. Since there will be a variety of participants of different ages on this questionnaire, participants will be addressed formally as "Sie". Questions concerning the demographics and the highest level of education are at the end of the questionnaire. The sources used for the survey will be listed at the questionnaire's end too, in order not to distract or disturb the participants.

This questionnaire is semi-structured in that it consists of open-ended and closed questions. The open-ended questions provide additional information to categorize participants, especially those who have a prior knowledge based on their job. With this information, I can decide if I want to exclude these people from my interpretation and conclusions. The closed questions are mostly multiple-choice questions but also some single-choice questions. The aim is to achieve more than 400 participants. (cf. Gillham, 2008, pp. 2–6)

Before starting the questionnaire, there is a "*covering letter of explanation*" (Gillham, 2008, p. 37) provided to the participants. This letter will give an overview of the study's aim and its respective research questions to the readers. Additionally, it shows which requirements a participant needs to be part of the study, who receives the data, and what happens to it. The covering letter also explains that the participants must not feel bad if they do not understand every question. Every questionnaire answered makes a great contribution to this study. At the end of the letter, my name and contact information will be provided. Adapted from Gillham (2008, pp. 37-39), there is also a handwritten signature attached.

### 5.3.2. Validation Approach

As recommended by Gillham (2008, pp. 41-44), this questionnaire was initially tested by four survey validation interviewees of different age. None of them worked in a profession that would give them an above-average knowledge of radioactivity. I asked the tested persons to do the questionnaire next to me while they articulate their thoughts and questions aloud. Thus, I could see if and where problems arise. After four test runs, I corrected the estimated time for doing the questionnaire from 5-10 minutes to 10-15 minutes. None of the four participants had problems when filling out the questions. Even when they did not give the right answer, they gave me the

feedback that they understood what was asked of them. Their spoken-aloud thinking also indicated that they were interpreting the questions as intended.

After correcting the occurred problems which the survey validation interviewees had (presented in detail in the next paragraphs), the questionnaire was tested by an expert panel. The goal of the expert panel is to clearly define the correct answers to my self-generated questions. For those questions which I have taken from other sources, the correct answer is already given. For example, some survey items were taken from FAROS by Hull and Hopf (2020), which had been validated in prior research. Only those questions of the new prompts which are going to be answered correctly by eight out of ten members of the expert panel are part of the final questionnaire. This guarantees, on the one hand, the justification of the correct answers apart from their literature basis and, on the other hand, clarity of the tasks. Since the questionnaire is conducted online, emails were sent to physics professors from the didactics department of the university of Vienna, physicists, and physics school teachers. In the first round, six experts replied to my e-mail and filled out the questionnaire. The experts of round one consisted of two teachers, three physicists and one physics professor from the didactics department of the university of Vienna. In the email, I described the aim of the questionnaire and how important their participation in the survey was. Additionally, I explained to them that I will not provide them with more descriptions than the future participants to achieve the same conditions as for the target group. (cf. Gillham, 2008, pp. 41–42)

All new prompts, which did not come from external sources, were answered correctly by the expert panel. Only Question 4 (*What Makes a Measuring Device for Radioactivity Click/Beep)* and Question 18 (*Airplane*) were rewritten before the second expert panel run (in more detail in Chapter 5.3.3.). Difficulties were also encountered with Question 12 (Risk Management), which are explained in more detail in Chapter 5.3.3. The experts of round two consisted of one physicist, one teacher and two experimental physicists. After the edit, there arose fewer problems during the second expert round with these questions.

According to Hollenberg (2016, 6-7), my questionnaire meets all quality criteria, namely objectivity, reliability, and validity. The objectivity of the questionnaire is reassured by the fact that the order of the questions and the questions themselves were the same for all participants. The questionnaire can be filled out at any time of

the day, there are no open questions which are included in the evaluation, and which could cause misinterpretations during coding. After releasing of the finished questionnaire, three participants were tested twice within two weeks under the same conditions. These persons gave the same answers to more than 80% of the questions (approx. 13/16 questions). Thus, the criteria for reliability can be seen as confirmed. To justify the validity of my questionnaire, two rounds of expert panels, as mentioned earlier, were conducted. Each question was answered correctly by more than 80% of the participants, from which I can conclude that the individual questions measure what I expected. Consequently, I can assume that all quality criteria are fulfilled.

### 5.3.3. What Questions are in the Questionnaire and How Did They Arise?

After accepting the declaration of consent, the participants state whether or not they have contact with ionizing radiation in their job. If they answer this question with yes and the following free response fields indicate a radioactivity-related profession, I assume these adults have special knowledge that is not representative of the typical adult that I wish to investigate, and I exclude these people from my interpretation and conclusions. The third question asks whether or not the person has seen the popular miniseries “Chernobyl”. In the case of a “yes”, their knowledge about radioactivity can derive from watching the series instead of their educational background. Another connection which can be made is that the series could lead to a prejudice or produce bias based on negative emotions. This assumption can be checked in the 19$^{th}$ question, where the participants shall tick whether their emotions regarding radioactivity are positive, negative, or neutral. According to Neumann and Hopf (2013, p. 1537), who claim that people’s emotions tend to be bad in relation to radiation, I argue that especially for radiation released after a radioactive decay, emotions are mainly bad. Two of the four survey validation interviewees had seen the series, and they both indicated rather bad emotions whereas the emotions of the experts are rather neutral.

For a better understanding, some of the questions included in the questionnaire are added here. This is also the reason why the questions and answers on Figures 6 to 21 are in German. The figures are screenshots from the original run from the SoSci website. In the image description, the respective sources of the individual questions

or answers are given. The capital letter Q or A followed by a number, represents the respective question or answer. Some of them do not have a particular source because they were composed based on my own knowledge and ideas. In this case, no source is specified. (cf. Leiner, 2019)

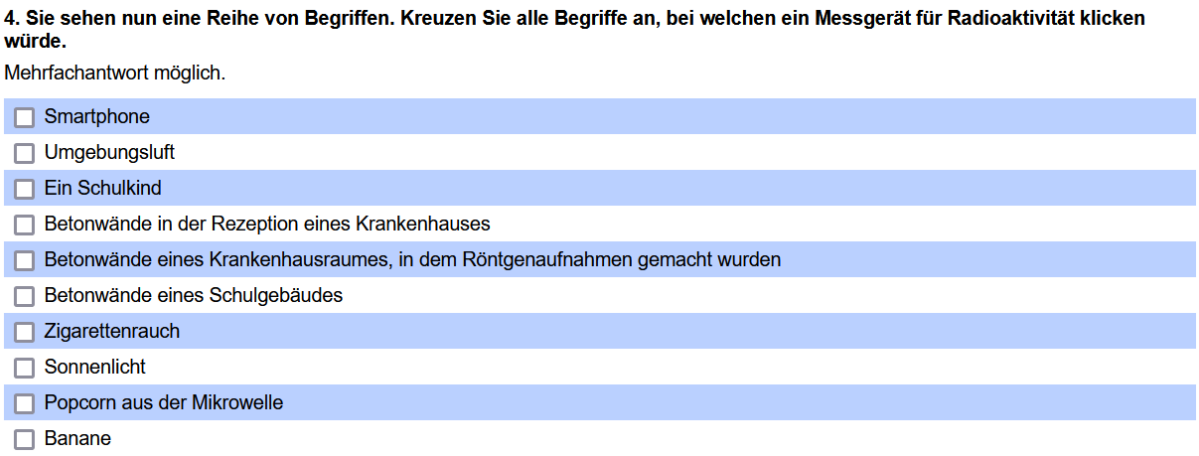


*Figure 6: Terms of the everyday life, sources: screenshot (Leiner, 2019), A1 (cf. Neumann & Hopf, 2011, p. 161; cf. Plotz, 2017, p. 3), A2 (cf. Grupen & Rodgers, 2016, pp. 62- 64), A3 (cf. Schmiermund, 2019, p. 376), A4-A6 (cf. Millar et al., 1990, p. 339; cf. Schmiermund, 2019, p. 376), A7 (cf. Johnson, 2021), A8 (cf. Neumann & Hopf, 2013, p. 1541), A9 (cf. Plotz, 2017, p. 4), A10 (cf. Grupen & Rodgers, 2016, p. 65)*

The 4th question (Figure 6) lists a lot of terms which the participants may know from their everyday experiences. The participants shall tick all the terms which they think will lead to count clicks in a measuring device for radioactivity. Most of these terms are taken from the literature. Particularly Millar et al. (1990, p. 339) cover the misconceptions of radioactive walls after an X-ray treatment. The debate and misunderstanding about irradiation and contamination is dealt with in Chapter 3.5.5. Some people do not distinguish between different kinds of electromagnetic waves. For them, every kind of radiation is understood as bad. Hence, objects and concepts such as a smartphone, a microwave or sunlight are also listed in the answers. Despite all, I assume that many people are unaware of the existence of ubiquitous radioactivity. This assumption was confirmed in the answers given by the survey validation interviewees. Three out of four survey validation interviewees only ticked the two terms A1 “smartphone” and A5 “concrete walls in a room where X-rays are performed in a hospital”. These answers may derive from the ongoing debate on how dangerous the radiation coming from smartphones is, and the misbelief that walls are becoming radioactive after an X-ray treatment. Another reason may be that some people are not aware of radioactivity in our everyday lives. The remaining survey validation interviewees ticked all terms. Half of the experts of the first round ticked all

terms whereas especially the teachers ticked nearly the same terms as the survey validation interviewees. To clear up that the goal is to know that the GM-counter will always display something, the question clarified that it is about clicks and not about what objects would be "registered" by a measuring device for radioactivity. After rewriting Question 4, the second expert group agreed that the measuring device for radioactivity will always click, regardless of the surrounding. Hence, participants will only get 1 point if they tick all the terms (I gave no partial credit in this question). (cf. Grupen & Rodgers, 2016, pp. 62–65; cf. Johnson, 2014; cf. Neumann & Hopf, 2011, p. 161, cf. 2013, p. 1541; cf. Plotz, 2017, pp. 3–4; cf. Schmiermund, 2019, p. 376)

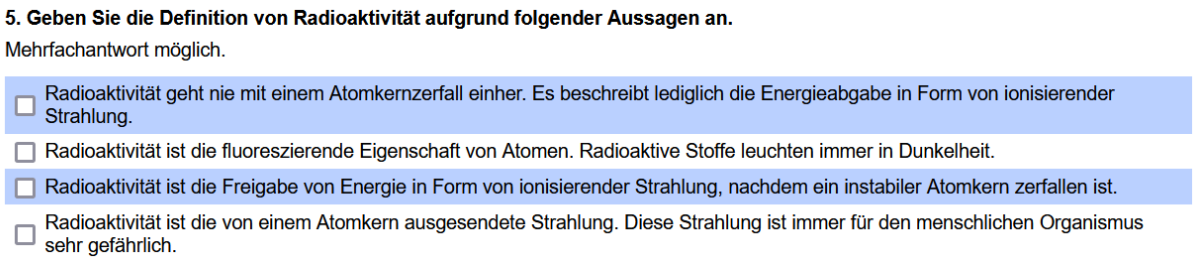


*Figure 7: Definition of Radioactivity, Sources: Screenshot (Leiner, 2019), A1 (cf. Hull et al., 2021b, p. 58), A2 (cf. Neumann & Hopf, 2013, p. 1535), A4 (cf. Eijkelhof & Millar, 1988, p. 37)*

Question 5 (Figure 7) asks about the correct definition of radioactivity. The definition is not always clear for the public. According to many authors, the public often thinks that radiation from a nuclear origin is radioactive such as "*cloud of radiation*" (Eijkelhof & Millar, 1988, p. 37; Millar et al., 1990, p. 338). This statement is also occasionally found in textbooks while some even cite the misconception about radioactive radiation: "*In diesem Kapitel erfährst du, warum und wie radioaktive Strahlung entsteht*" (Apolin, 2008, p. 58). According to researchers, a lot of mass media use the term radiation in a completely wrong context too. They do not separate the terms: "*radioactive matter/radiation/radioactivity*" (Lijnse et al., 1990, p. 74), and they also use these terms in a very negatively connotated context. The fourth survey validation interviewee falsely answered that radioactivity is the radiation emitted by a nucleus. One of the experts (a teacher) responded in the same incorrect manner as one of the survey validation interviewees (more information in Chapter 6.3.). Three of the four survey validation interviewees answered Q5 correctly, saying that radioactivity is the release of energy in the form of ionizing radiation after an unstable atomic nucleus decays. Another option a participant can choose in this question is that an atom is said to be radioactive if it can glow in the dark. In the study "*Children's Drawings About 'Radiation' - Before and After Fukushima*" (Neumann & Hopf, 2013,

p. 1535) of Neumann and Hopf (2013, p. 1535), pupils used the adjective *bright* among others in the context of radiation. Hence, the drawings of children about radiation contain green light coming from nuclear waste or nuclear power plants. This association often appears in comics and movies too. Consistent with the literature, eight out of ten experts chose the correct answer A3: “Radioactivity is the release of energy in the form of ionizing radiation. It happens after an unstable atomic nucleus decays”. (cf. Eijkelhof & Millar, 1988, p. 37; cf. Lijnse et al., 1990, p. 74; cf. Plotz, 2017, p. 2; cf. Schecker et al., 2018, p. 232)

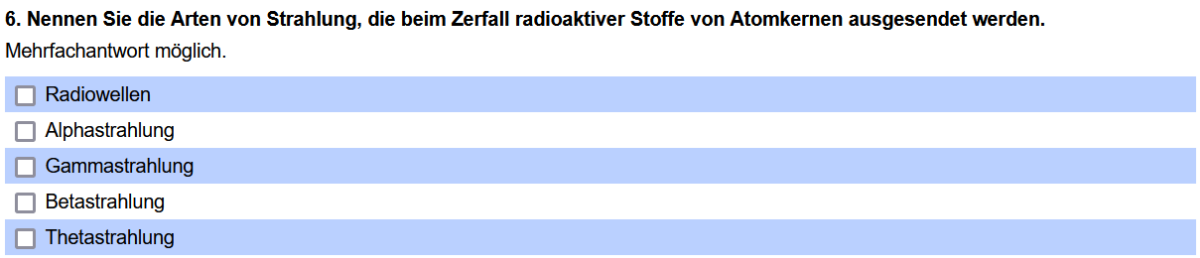


*Figure 8: Types of Radiation, Sources: Screenshot (Leiner, 2019), A1 (cf. Sesen & Ince, 2010, p. 97)*

Question 6 (Figure 8) is asking about the different types of radiation which emerge from a nuclear origin. In nearly every schoolbook, the types of radiation are presented in the beginning of the topic radioactivity. The interesting aspect which arises is, whether people recognize the types of radiation emerging from a nuclear origin with the help of the given answers. According to Sesen and Ince (2010, p. 97), a lot of people think that nearly every type of radiation, especially the one which originates from electronic devices, is ionizing radiation and is therefore harmful. For this reason, radio waves are mentioned in Q6. After pretesting the questionnaire, the assumption that the participants will remember the different types of radiation has turned out to be correct. Only one survey validation interviewee gave an incorrect answer. He/she answered that alpha radiation, radio waves and theta radiation are the types of radiation which emerge from a nuclear origin. Here Theta radiation is a made-up term. All experts have answered this question, as predicted, uniformly. Therefore, A2 “Alpha radiation”, A3 “Gamma radiation” and A4 “Beta radiation” are the correct answers. (cf. Apolin, 2008, pp. 58–60; cf. Nakiboğlu & Tekin, 2006, p. 1712; cf. Sexl et al., 2013, pp. 84–86)

**7. Kreuzen Sie die richtigen Aussagen über die Halbwertszeit an.**

Mehrfachantwort möglich.

- ☐ Die Halbwertszeit ist für alle Elemente gleich.
- ☐ Die Halbwertszeit gibt jene Zeit an, in der sich jeweils die Hälfte der ursprünglich vorhandenen Atomkerne in andere Atomkerne umwandeln.
- ☐ Halbwertszeiten gibt es nur im Nanosekunden-Bereich.
- ☐ Die Halbwertszeit ist jene Periode, in welcher der Stoff seine Radioaktivität verliert. Danach ist der Stoff nicht mehr radioaktiv.

*Figure 9: Definition Half-Life, Source: Screenshot (Leiner, 2019), A4 (cf. Hull et al., 2021b, p. 52; cf. Lijnse et al., 1990, p. 71)*

According to previous studies, statements about the half-life are usually tainted with students' conceptions. Question 7 can be used to find out whether the average population of Austria is also influenced by these typical misconceptions. One idea that a Delphi study by Lijnse et al. (1990, p. 71) discovered and which is also described by Hull et al. (2021b, p. 52) is that an isotope "*loses its radioactivity*" (Lijnse et al., 1990, p. 71) after one half-life. After this period, pupils expect that the isotope does not harm people anymore. Two out of four survey validation interviewees chose this misconception in Question 7 (Figure 9). The experts all agreed that answer A2 "The half-life is the time it takes for half of the original atomic nuclei to change into another atomic nuclei" is the correct one. Questions Q8 to Q11 all deal with the topic of half-life.

**8. Iod-131 ist ein Beispiel eines radioaktiven Atoms. Es hat eine Halbwertszeit von 8 Tagen. Stellen Sie sich vor, dass es zu Beginn 100 Millionen Iod-131-Atome gibt. Wieviel Iod-131 wird sich nach ... noch nicht umgewandelt haben?**

**... i. 8 Tagen? ii. 16 Tagen?**

i) ... nach 8 Tagen?

- ○ 100 Millionen Atome
- ○ 50 Millionen Atome
- ○ 0 Atome
- ○ 100 Millionen ODER 0 Atome
- ○ 65,5 Atome

ii) ... nach 16 Tagen?

- ○ 100 Millionen Atome
- ○ 25 Millionen Atome
- ○ 0 Atome
- ○ 100 Millionen ODER 0 Atome
- ○ 32,8 Atome

*Figure 10: Half-Life Iod-131, Sources: Screenshot (Leiner, 2019), Questions and Answers (Hull et al. 2021a)*

**9. Erklären Sie kurz, wie Sie zu Ihren Antworten (zu Fragen 8 i-ii) gekommen sind. Kreuzen Sie alle Aussagen an, welche Sie zu dieser Antwort geführt haben.**

Mehrfachantwort möglich.

- ☐ Nach der Halbwertszeit werden sich die Hälfte der Atome umgewandelt haben
- ☐ Es ist zufällig
- ☐ Man kann keine Hälfte eines Atoms haben
- ☐ Atome verschwinden nicht
- ☐ Nach zwei Halbwertszeiten haben sich alle Atome umgewandelt
- ☐ Zum Schluss haben sich alle Atome umgewandelt

*Figure 11: Justification of Q8, Sources: Screenshot (Leiner, 2019), Questions and Answers (Hull et al., 2021a)*

Question 8 to Question 11 consist of situations which probe whether the participants can apply the definition of half-life. The participants must indicate the remaining atoms of a given number of radioactive atoms after one and then two half-lives. Afterwards, they should justify their answers given in questions 8 i and 8 ii in Question 9. All survey validation interviewees and experts gave the same answer here. Hence, it can be assumed that A2 “50 million atoms” and “25 million atoms” are correct for each case in questions 8 i and ii (Figure 10) and A1 “After the half-life half of the atoms will have transformed” is correct in Question 9 (Figure 11). (cf. Hull et al., 2021a)

**10. Iod-131 ist ein Beispiel eines radioaktiven Atoms. Es hat eine Halbwertszeit von 8 Tagen. Stellen Sie sich vor, dass Ihr Kleiderschrank irgendwie mit Iod-131 – Gas gefüllt wurde. Der Schrank ist so mit Klebeband versiegelt, dass das Gas nicht herauskommen kann. Sie stehen draußen vor dem Kleiderschrank, bewahren aber wertvolle Dinge im Schrank auf. Wie lange würden Sie warten bis Sie das Klebeband wegnehmen und die Tür öffnen?**

- ○ Weniger als 1 Tag
- ○ Mehr als 1 Tag aber weniger als 8 Tage
- ○ 8 Tage
- ○ Mehr als 8 Tage aber weniger als 16 Tage
- ○ 16 Tage
- ○ Mehr als 16 Tage, aber ich würde die Tür irgendwann öffnen
- ○ Ich würde die Tür nie öffnen
- ○ Es hängt von verschiedenen Faktoren ab

*Figure 12: Closet Question, Sources: Screenshot (Leiner, 2019), Questions and Answers (Hull & Hopf, 2021)*

**11. Erklären Sie kurz, wie Sie zu Ihrer Antwort gekommen sind. Kreuzen Sie alle Aussagen an, die Sie zu dieser Antwort geführt haben.**

Mehrfachantwort möglich.

- ☐ Ich warte bis sich 100% aller Atome umgewandelt haben
- ☐ Es werden sich nie 100% aller Atome umwandeln
- ☐ Nach der Halbwertszeit werden sich die Hälfte der Atome umgewandelt haben
- ☐ Nach der Halbwertszeit halbiert sich die Menge der Strahlung
- ☐ Nach zwei Halbwertszeiten haben sich alle Atome umgewandelt
- ☐ Nach zwei Halbwertszeiten gibt es keine Strahlung mehr
- ☐ Mehr Information wird benötigt
- ☐ Der Kleiderschrank wird radioaktiv
- ☐ Strahlung kommt durch die Tür

*Figure 13: Justification of Q10, Sources: Screenshot (Leiner, 2019), Questions and Answers (Hull & Hopf, 2021)*

In Question 10 (Figure 12) and Question 11 (Figure 13), the survey validation interviewees were unsure about the right answer. Here, the participants shall decide when and if they would open a closet which is filled with radioactive iodine gas and afterwards justify their answers in Question 11. The answers to these two questions emerged from the options that students gave as open-ended responses to this question in a previous piece of research. More on the history of this prompt can be found in Hull and Hopf (2021). The main difference between Question 8 to Question 9 and Question 10 to Question 11 is, that in the above question (Question 8) the number of isotopes is indicated. This is one reason why Question 11 can be answered with the answer A7 "more information is needed". Two of the interviewees tried to answer the question “How long would you wait to remove the tape and open the door?” with the information given at Question 8 and Question 9. Their explanations as to why they scrolled to Question 8, were that they do not know how many isotopes were in the closets. To avoid confusion, I put Question 8 and Question 9 on other pages than Question 10 and Question 11. In contrast to Question 8 and Question 9, neither the pretested individuals nor the experts had any consensus in answering Question 10 and Question 11. Most of the experts checked A6 “more than 16 days but I would open the door sometime” for Question 10. After consulting my co-supervisor, I decided that in addition to answer A8 “It depends on several factors”, A6 “More than 16 days but I would open the door sometime” could also be considered correct; If the person who wants to open the closet waits longer than two half-lives, the probability of a health hazard is reduced. On the other hand, A7 “I would never open the door” in Q10 is considered “incorrect” in this study because it reflects the wrong perception of being able to avoid ionizing radiation altogether. According to Alsop (2001, p. 271), many people believe that radioactivity seems to be

"*quintessentially eternal and never stopping*" (Alsop, 2001, p. 271) and this "*idea […] is stronger than the idea about half-life being active or dangerous time*" (Hull et al., 2021a). This may explain why some people would select A7 "I would never open the door". The survey validation interviewees were unsure about Question 11. Instead of selecting a justification for the answer they had given in Question 10, they ticked all answers which they thought were generally correct. Hence, A2 "Never 100% of all atoms will be transformed" and A3 "After the half-life, half of the atoms will have transformed" were often selected. There are also some misconceptions hidden in the answers to this question, such as "I wait until 100% of all atoms have transformed", "After two half-lives, all atoms will have transformed" etc. According to Hull and Hopf (2020), at Question 11, A7 "More information is needed" is considered to be correct. (cf. Hull et al., 2021a)

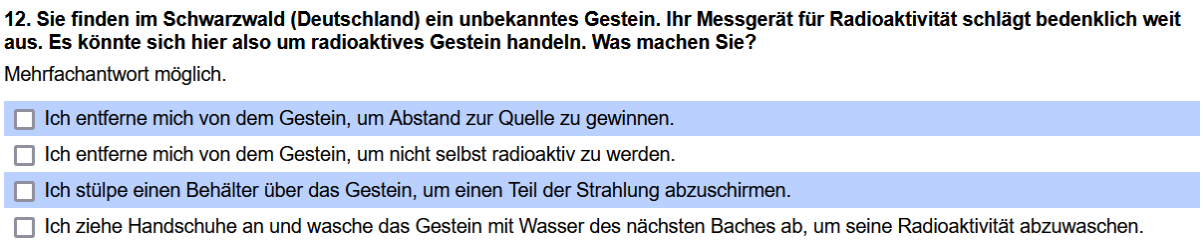


*Figure 14: Black Forest, Sources: Screenshot (Leiner, 2019), A1 (cf. Schmiermund, 2019, pp. 408- 410), A2 (cf. Alsop, 2001, p. 272; cf. Millar & Gill, 1996, p. 31), A3 (cf. Schmiermund, 2019, pp. 407, 412), A4 (cf. Lijnse et al., 1990, p. 76)*

As already mentioned, the questionnaire was pretested by four different people with different ages. Particularly for Question 12 (Figure 14), exciting results arose during testing. This question is concerned with how people would act if they found a radioactive source. Two of the four persons have seen the miniseries "Chernobyl". One of the persons who has seen it, read the obsolete answer "I take the ore and put it in a safe container so that I am not exposed to the radiation for too long.", and afterwards he/she said, "Oh no! I am not allowed to touch it!". I think this reaction derives from the fact that in the series, a man grabs a contaminated part of the power plant after the explosion and his hand starts bleeding immediately. In addition, Millar et al. (1990, pp. 339, 340) wrote that people are identifying radiation with danger, and they want "*to avoid contact with 'it'*" (Millar et al., 1990, p. 339). One person who has not seen the series said, "I will take it and give it in a box, so I am not exposed to the radiation for too long." For him/her, touching the ore for a short time is not dangerous. These two contrary statements illustrate the influence the series might have on the results of the survey. Although there were exciting differences across the answers to

this question in the pretest between those people who saw “Chernobyl” and those who did not see “Chernobyl”, the options were changed for the final draft to be consistent in the style of answers, i.e., multiple choice questions. One answer was changed to “I put a container over the rock to shield part of the radiation”. Additionally, the location mentioned in the prompt was changed to achieve a reference to the everyday life of the participants. Because there are no active nuclear power plants in Austria, Chernobyl became the Black Forest in Germany. Additionally, a pretested person asked me who Geiger Müller is. He/she thought that the question is about a person and not about what to do after detecting an alarming number of counts per minute with the help of a measuring instrument. The confusion based on the given name of the measure instrument could originate from the fact that “*most schools […] are likely to have one Geiger counter at most*” (Millar et al., 1990, p. 340) and due to safety conditions, pupils are not always allowed to do experiments with the counter on their own. To avoid this confusion, the term “Geiger Müller” was changed to the term “radioactivity measuring tool”. No member of the pretest group chose the answer that one can wash off radioactivity of an ore. Only two of the six experts in the first round chose both A1 “I move away from the rock to gain distance from the source” and A3 “I put a container over the rock to shield part of the radiation”. The others only ticked either A1 or A3, with A1 being picked more often. No other answers were selected by the six experts. Responses from experts in the second round were similar. As a result, a respondent is coded as correct for selecting “A1”, selecting “A3”, or selecting “A1 and A3”. (cf. Grupen & Rodgers, 2016, p. 65; cf. Lijnse et al., 1990, p. 76; cf. Millar & Gill, 1996, p. 31)

**13. Vor Ihnen liegt folgender Versuchsaufbau, welcher in Abbildung 1 zu sehen ist. Diese Abbildung zeigt eine radioaktive Quelle. Von dieser wird Strahlung ausgesendet (welche in dieser Skizze nicht gezeigt wird). Diese Strahlung trifft auf eine Kiwi. Die radioaktive Quelle und die Kiwi sind 2 cm voneinander entfernt.**

**Versuchsaufbau:**

**Abbildung 1: Versuchsaufbau**

**Geben Sie jenes Objekt/jene Objekte (radioaktive Quelle, Strahlung und Kiwi) an, welches/welche radioaktiv ist/sind?**

- ○ Die radioaktive Quelle, die Strahlung und die Kiwi sind radioaktiv.
- ○ Die radioaktive Quelle und die Strahlung sind radioaktiv.
- ○ Die radioaktive Quelle und die Kiwi sind radioaktiv.
- ○ Die radioaktive Quelle ist radioaktiv.

*Figure 15: Experiment with a Kiwi, Sources: Screenshot (Leiner, 2019), Question and Answers (cf. Johnson, 2021; cf. Johnson & Maidl, 2014, p. 9)*

**14. Die radioaktive Quelle wird nach 24 Stunden entfernt. Ist die Kiwi jetzt radioaktiv?**

- ○ Ja, die Kiwi ist durch die Strahlung radioaktiv geworden – unabhängig von der Distanz.
- ○ Ja, die Kiwi ist durch die Strahlung radioaktiv geworden, weil sie nah genug an der Quelle war.
- ○ Ja, die Kiwi ist durch die Strahlung radioaktiv geworden, weil sie während des Experiments lange genug neben der radioaktiven Quelle war.
- ○ Nein, die Kiwi ist durch die Strahlung nicht radioaktiv geworden, weil sie, um radioaktiv zu werden, eine längere Dauer neben der Strahlungsquelle verweilen müsste.
- ○ Nein, die Kiwi ist durch die Strahlung nicht radioaktiv geworden, weil die Strahlung Objekte nicht radioaktiv macht.

*Figure 16: Experiment with a Kiwi II, Sources: Screenshot (Leiner, 2019), Question and Answers (cf. Johnson, 2021; cf. Johnson & Maidl, 2014, p. 9)*

The idea for Question 13 (Figure 15) comes from the contents of "*Inquiry into Radioactivity*" (Johnson, 2014) and the article "*Students Coming to Understand Ionizing Radiation - A Radiation Literacy Challenge*" (Johnson & Maidl, 2014). This question was chosen because in nearly every previous study, the interchanging of the concepts irradiation and contamination arose. To test whether this student conception is similarly widespread in Austria, the question concerned with an irradiated kiwi by a radioactive source is very suitable. Based on literature, most people will answer that both the radioactive source and the kiwi are radioactive. Maybe some of them will answer that the radiation itself is radioactive too. Surprisingly, three out of four people of the survey validation interview answered A4 "*The radioactive source is radioactive*" (Johnson, 2014), which, due to the material of "*Inquiry into Radioactivity*" (Johnson, 2014), is correct. The fourth person said that everything is radioactive (the source, the radiation itself, and the kiwi). The sub-question concerned with the kiwi digs deeper into the participants' ability to justify. Here it is asked why the kiwi has become radioactive or not. All three persons who

answered A4 in Question 13 also answered Question 14 (Figure 16) with A5 “*No, the [kiwi] did not become radioactive due to the radiation because radiation does not make objects radioactive.*” (Johnson, 2014). The survey validation interviewee who said before that everything is radioactive now answered that the kiwi became radioactive because it was close enough to the source. The experts were all in agreement on this question and chose A4 (the correct answer) for Q13. Compared to Question 5, it is peculiar that the teacher who picked that radiation is radioactive, answered Question 13 without choosing answer A1 or A2, where the radiation itself is radioactive too. After being asked, he/she argued that the term "*radioactive radiation*" is a term that society uses. He/she is aware that the radiation itself is not radioactive, but since he/she uses the term "radioactive radiation" regularly, he/she thinks that he/she has slipped up. To sum up, all ten experts chose A4 for Question 13 and A5 for Question 14, validating them as correct answers. (cf. Johnson, 2014; cf. Johnson & Maidl, 2014, p. 9; cf. Millar & Gill, 1996, pp. 27–32; cf. Morales & Tuzón, 2020, pp. 19–20; cf. Nakiboğlu & Tekin, 2006, p. 1712; cf. Plotz, 2017, p. 2; cf. Prather & Harrington, 2001, p. 92)

**15. Radioaktivität ist:**

- ○ Natürlich
- ○ Von Menschen erzeugt
- ○ Kann natürlich auftreten und kann vom Menschen erzeugt werden
- ○ Keine der Antwortmöglichkeiten ist richtig

*Figure 17: Properties of Radioactivity, Sources: Screenshot (Leiner, 2019), Question and Answers (cf. Morales & Tuzón, 2020, pp. 10, 18; cf. Schecker et al., 2018, p. 231; cf. Sesen & Ince, 2018, p. 97)*

**16. Der radioaktive Zerfall ist:**

- ○ Kontrollierbar
- ○ Unkontrollierbar
- ○ Kann kontrollierbar und kann unkontrollierbar sein
- ○ Keine der Antwortmöglichkeiten ist richtig

*Figure 18: Properties of Radioactivity II, Sources: Screenshot (Leiner, 2019), Question and Answers (cf. Morales & Tuzón, 2020, pp. 9, 13)*

**17. Radioaktivität ist für den Menschen:**

- ○ Gefährlich
- ○ Ungefährlich
- ○ Kann gefährlich und kann ungefährlich sein
- ○ Keine der Antwortmöglichkeiten ist richtig

*Figure 19: Properties of Radioactivity III, Sources: Screenshot (Leiner, 2019), Question and Answers (cf. Hull et al., 2020, p. 58; cf. Morales & Tuzón, 2020, pp. 13, 18; cf. Tsparlis et al., 2013, p. 1984)*

**18. Wie verändert sich die Strahlung in einem Flugzeug im Vergleich zum Boden?**

- ○ Sie nimmt mit der Höhe zu
- ○ Sie nimmt mit der Höhe ab
- ○ Sie bleibt gleich
- ○ Keine der Antwortmöglichkeiten ist richtig

*Figure 20: Properties of Radioactivity IV, Sources: Screenshot (Leiner, 2019), Question and Answers (cf. Grupen & Rodgers, 2016, pp. 63, 71)*

**19. Sind Ihre Emotionen bezüglich Radioaktivität positiv, negativ oder neutral?**

- ○ Positiv
- ○ Negativ
- ○ Neutral
- ○ Keine Angabe

*Figure 21: Emotions, Sources: Screenshot (Leiner, 2019), Question and Answers (cf. Morales & Tuzón, 2020, p. 13; Neumann & Hopf, 2032, p. 1536)*

Questions 15 to 19 (Figure 17, Figure 18, Figure 19, Figure 20 and Figure 21) deal with properties and emotions connected to radioactivity or nuclear decays. These questions are about the participants' assessment of whether radioactivity is controllable or uncontrollable and the like. The answer options in Q15, Q16, Q17,

Q18 and Q19 have the same structure. The answers are opposites. However, the participants can also choose that both of the answers or none of the given answers are correct. For this kind of questions, I was inspired by Morales and Tuzón (2020, pp. 8-13) as well as Neumann and Hopf (2013, p. 1536). With the help of these questions, it is possible to find out whether the participants have a positive or negative opinion towards this topic. Questions such as whether radioactivity is man-made or natural indicate such a positive or negative tendency. This tendency can be confirmed or refuted by Question 19 which asks for emotions regarding this radioactivity. According to Hull, Janksy, and Hopf (2021b, p. 58), I also expected a lot of people to articulate negative emotions because for students, "*it is easier to label the ionizing radiation as 'bad' or 'dangerous'*" (Hull et al., 2021b, p. 58). A negative view is easier to understand and does not present students with the conflict of how radioactivity may also have positive applications. The pretest group articulated a negative tendency. The majority labeled radioactivity as dangerous, manmade and uncontrollable. Additionally, their emotions regarding radioactivity are negative. One of the participants said that radioactivity has to do with discomfort, but he/she believes that this derives from a lack of knowledge regarding this topic. The experts answered that they feel neutral about radioactivity, and when it came to properties, they often decided that radioactivity can be both i.e., manmade and natural. However, the experts disagreed on Question 16. Due to their comments, some of them considered this question as a whole and marked A3 "can be controllable and can be uncontrollable" as correct, whereas others related this question to a single atom, making them mark A2 "uncontrollable". Hence, whether the participants tick A2 or A3, both are correct. (cf. Schecker et al., 2018, p. 231; cf. Sesen & Ince, 2010, p. 97; cf. Tsaparlis et al., 2013, p. 1984)

Since there was disagreement among experts on Question 18 "whether radioactivity increases or decreases with altitude" this question was edited. Some experts have stated that radioactivity increases with altitude. Others have written that radioactivity first decreases due to terrestrial radiation and then increases with altitude due to secondary and cosmic radiation. Since the question could not be defined more precisely without providing tips for the answer, it was rewritten to a specific context of being in an airplane.

Towards the end of the questionnaire, questions about the type of school attended and the time passed since school graduation are asked. These questions allow me to answer the research questions. The following schools are cited from the "*Bundesministerium Bildung, Wisschenschaft und Forschung*" (BMBWF, 2022). The schools are divided into the categories: compulsory school, polytechnic school, general secondary school, vocational school, 3-years vocational school, and 5-years vocational school. If the participants choose the general secondary school, the 3-years vocational school, or the 5-years vocational school, subcategories will appear. The attended school can then be selected more precisely with the help of a sub-question which lists the schools in their short form. The short form was used to provide the participants a more targeted search for their school. In case the participants do not know the abbreviated name of their school, a blank line is provided, to type in the school type. Additionally, a question about the time passed since their school graduation is included. The time passed since graduation is divided into time-categories of 0-5, 5-10, etc. up to 40+ years. An additional sub-question asks those participants who are still in school to indicate their current school level. This case may occur as they may have finished compulsory school (which consist of nine years in Austria), but still be enrolled in school. A school graduation of any kind is mandatory for this study regardless of whether this is compulsory school or a different school type. I decided on this requirement because the topic of radioactivity is already taught in the $4^{th}$ lower grade and is therefore taught within compulsory school. Hence, a knowledge regarding radioactivity can be assumed. To further divide the questionnaire's results into categories, demographics are asked. The participant is asked to state his/her biological sex and age. (cf. BMBWF, 2021; cf. BMBWF, 2022)

Finally, participants are asked if they had any difficulty answering the questions. If this is the case, he/she should give reasons for his/her answer. These results are presented in the form of a bar plot in Chapter 6.3. Therefore, it can be seen which problems arose and why the participants had any difficulties. In accordance with Morales and Tuzón (2020 p. 1968), and Neumann and Hopf (2013, p. 1547), they are also asked where their knowledge about radioactivity comes from. There are answers provided, as well as a blank line for the participants to give additional answers.

After the participants finished the questionnaire, they can leave their E-Mail. In this case, the participant voluntarily agrees to talk to me in detail about his/her questionnaire, if necessary.

## 5.4. Results

### 5.4.1. Participants of the Questionnaire

In this chapter I want to introduce the participants of the questionnaire. The questionnaire could be filled out online on the SoSci platform from November 11th to November 29th, 2021. During this time, 416 people completed my questionnaire. As I mentioned earlier, an Austrian school-leaving qualification is required to take part in this research, which is why the target group is very wide ranged. Those persons who stated that they work with ionizing radiation in their profession were excluded from the evaluation, resulting in a participation rate of 386. The majority of the appointed experts work in medical professions or research.

To get a good overview, frequency tables and bar plots were created. Particular focus is placed on grouping participants according to the two research questions. These are firstly, the division into the different types of school, and secondly, the classification according to the time passed since last school attendance.

Tables 2 to 17 and Figures 22 to 88 are created with the help of the program RStudio. (cf. R-Project, 2021)

*Table 2: Distribution of Participants According to Biological Sex, Source: Own Composition*

| | absolute frequency | relative frequency in % |
|---|---|---|
| **male** | 166 | 43.01 |
| **female** | 219 | 56.74 |
| **diverse** | 1 | 0.26 |

From 386 participants, 166 identified as male, 219 as female and one as diverse (Table 2). The relative frequency indicates the number of male, female and diverse participants in percentage. To calculate this, the respective absolute frequency is divided by the total number $n$ of participants. For example, 166 male participants divided by 386 participants yields 0.4301 and this times one hundred equals 43.01%. (cf. Fahrmeir et al., 2016, p. 30)

*Table 3: Distribution of Participants According to Age Categories in Years, Source: Own Composition*

| | absolute frequency | relative frequency in % |
|---|---|---|
| **17 or younger** | 2 | 0.52 |
| **18 - 25** | 117 | 30.31 |
| **26 - 35** | 149 | 38.60 |
| **36 - 45** | 41 | 10.62 |
| **46 - 55** | 38 | 9.84 |
| **56 or older** | 39 | 10.10 |

Table 3 shows the distribution of participants according to age categories in years. At first glance, it is noticeable that the largest number of participants are in the age categories “18 - 25” and “26 - 35”. 68,91% of all survey participants are part of these two age groups. Only two participants are in the group “17 or younger” and the remaining groups (i.e., “36 - 45”, “46 - 55”, “56 or older”) each account for 10% of survey participants.

*Table 4: Distribution of Participants According to Different School Types, Source: Own Composition*

| | absolute frequency | relative frequency in % |
|---|---|---|
| **Compulsory School** | 8 | 2.07 |
| **Polytechnic School** | 4 | 1.04 |
| **General Secondary School** | 177 | 45.85 |
| **Vocational School** | 31 | 8.03 |
| **3-year Vocational School** | 20 | 5.18 |
| **5-year Vocational School** | 146 | 37.82 |

Table 4 shows the distribution of participants according to the different school types. 83,67% of the participants have a “Matura”, as they have either attended the general secondary school or the 5-year vocational school. Eight participants have attended a compulsory school whereas four have attended a polytechnic school. The third largest group with 31 persons went to a vocational school, followed by the 3-year vocational school which was attended by 20 participants of this survey. Since the group sizes are very unbalanced, the relative frequency was used for each school type for the graphical representation (Chapter 5.4.2.) of the answered questions.

*Table 5: Distribution of Participants According to Years Passed Since School Attendance, Source: Own Composition*

| | absolute frequency | relative frequency in % |
|---|---|---|
| **0 - 5** | 51 | 13.21 |
| **6 - 10** | 173 | 44.82 |
| **11 - 15** | 44 | 11.40 |
| **16 - 20** | 19 | 4.92 |
| **21 - 25** | 28 | 7.25 |
| **26 - 30** | 19 | 4.92 |
| **31 - 35** | 11 | 2.85 |
| **36 - 40** | 19 | 4.92 |
| **40+** | 22 | 5.70 |

In Table 5 one can see how much time has passed since the individual participants have left school. 44,82% of the participants left school between six to ten years ago. The groups immediately prior and following this "6 - 10" years passed group have more participants than all other groups. “31 - 35” years passed since last school attendance is the group with the least participants.

*Table 6: Distribution of Participants Who Have and Have Not Seen “Chernobyl”, Source: Own Composition*

| | absolute frequency | relative frequency in % |
|---|---|---|
| **Yes** | 137 | 35.49 |
| **No** | 249 | 64.51 |

Since “Chernobyl” is a very popular TV series in Austria, the participants were asked if they have seen it. The distribution of participants who have and those who have not seen “Chernobyl” is pointed out in Table 6. Only 35,49% of participants have seen “Chernobyl” whereas 64,51% have not seen this TV series.

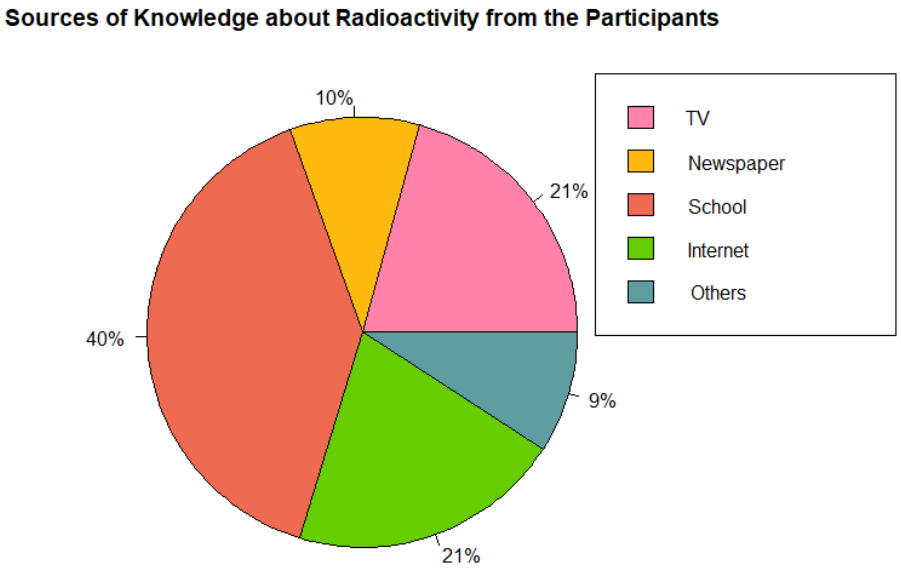


*Figure 22: Sources of Knowledge about Radioactivity from the Participants, Source: Own Composition*

In accordance with Morales and Tuzón (2020), and Neumann and Hopf (2013), I asked the participants where their knowledge about radioactivity comes from. On the pie chart in Figure 22, it can be seen that the group “school” is the largest pie slice with 40%, which reinforces the motivation for my research questions. 300 participants ticked that their knowledge concerning radioactivity comes from school. The TV and the internet are equally used as sources of knowledge with 156 and 155 ticks and the newspaper takes up the lowest appointed source with 73 ticks. Some of the participants have provided their own sources such as studies, reference books, movies, friends, the fire department, and the armed forces.

### 5.4.2. Scores Achieved

As already mentioned, the questionnaire functions like a test in which up to 16 points can be scored. The following bar plot (Figure 23) visualizes the number of participants in relation to the number of points scored. The total points scored are plotted on the x-axis and the number of persons on the y-axis. It is clear to see that most participants are positioned in the midfield. This impression is reinforced above all by the mean value, which is 9,57. This means that on average, a score of 9,57 points was achieved. The mean value is calculated by adding up the points of all participants and dividing this number by the total number of participants. The standard deviation is 2,95 which means that the results of all participants differ on average from the mean by 2,95 points. (cf. Fahrmeir et al., 2016, pp. 49–50, 64–65)

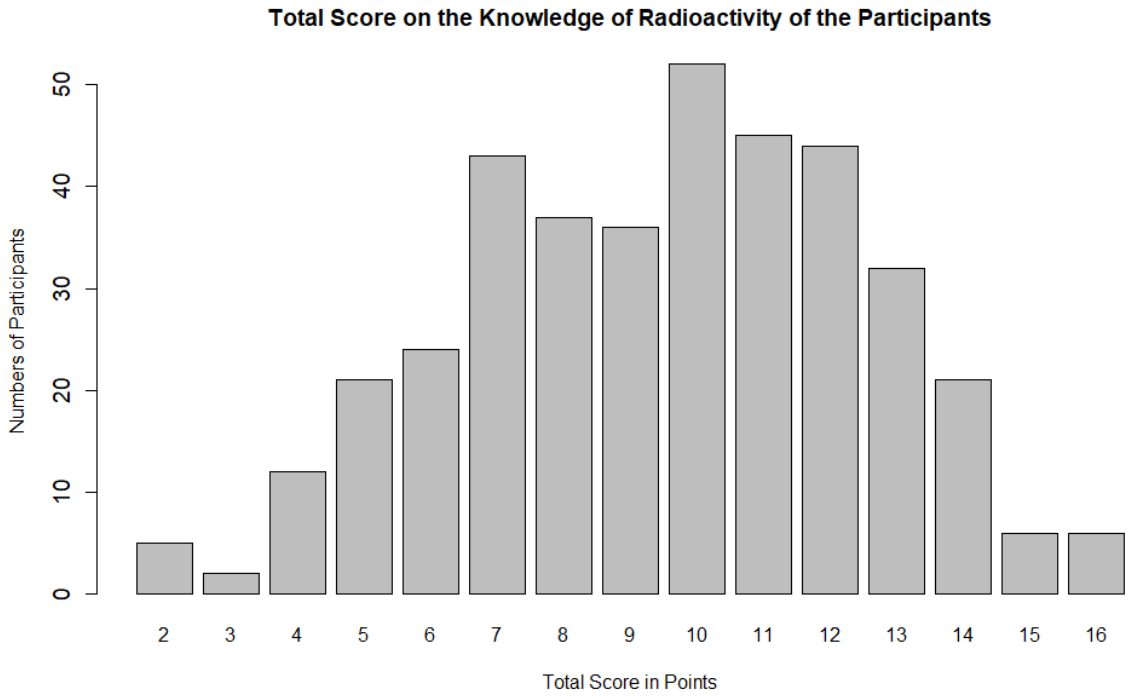


*Figure 23: Total Score on the Knowledge of Radioactivity of the Participants, Source: Own Composition*

In this section, the total scores will be compared within the three main categorizations. These are the categorizations into the different types of schools, the time passed since last school attendance and people who have or have not seen "Chernobyl". To ensure better comparability, the mean value of the individual subcategories is used.

## Categorization: Types of Schools

*Table 7: Mean Value and Standard Deviation in Points According to the Different Types of Schools Part 1, Source: Own Composition*

| | Compulsory School | Polytechnic School | General Secondary School | Vocational School | 3-year Vocational School | 5-year Vocational School |
|---|---|---|---|---|---|---|
| **Mean Value in Points** | 7.96 | 4.58 | 10.07 | 8.32 | 7.17 | 9.79 |
| **Standard Deviation in Points** | 4.01 | 1.95 | 2.88 | 2.82 | 2.98 | 2.65 |

In Table 7, the different school types with their mean value and standard deviation of scored points are listed. The school type with the best mean score is the general secondary school with a value of 10,07 points followed by the 5-year vocational school with a mean value of 9,79 points. This difference is small in comparison to the standard deviations. The vocational school, the 3-year vocational school and the compulsory school are similarly close to each other in terms of points scored, and

they are not far below the general mean value of 9,57 points, in comparison to the standard deviations. The standard deviation of 4,01 points for the compulsory school is higher than those of the other types of schools. The school type with the least mean value is the polytechnic school with 4,58 points. This trend can also be seen in the following bar plot (Figure 24).

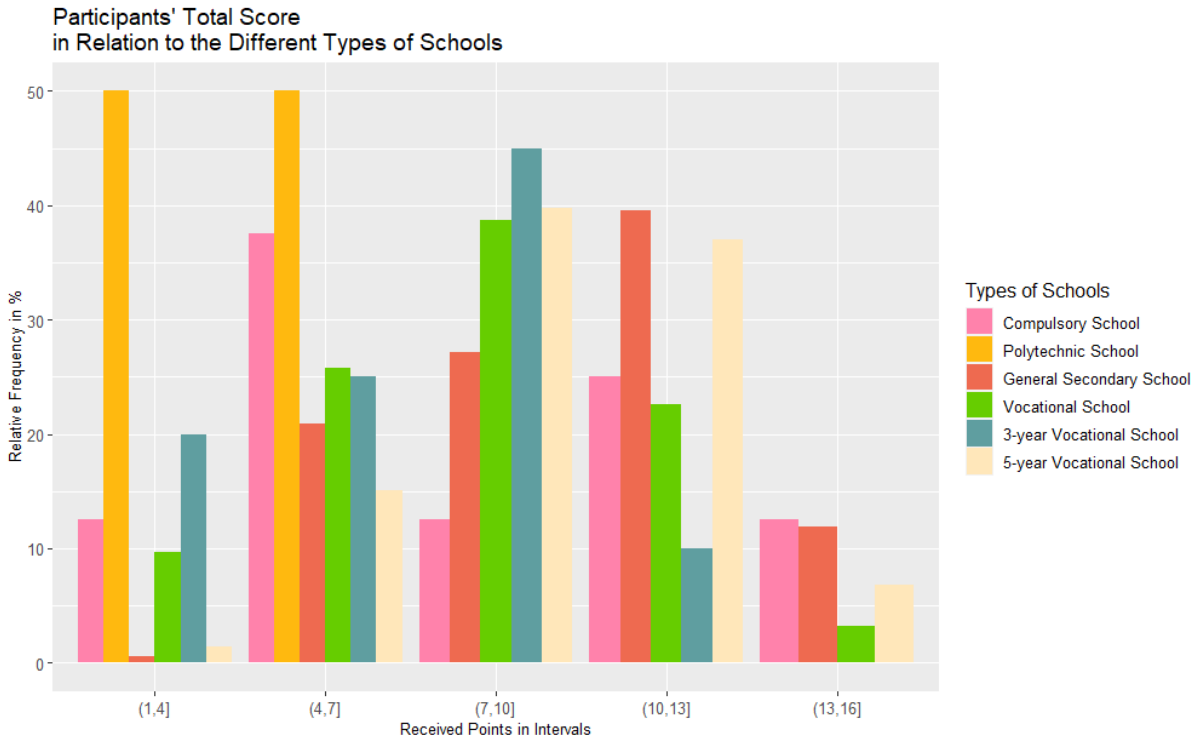


*Figure 24: Participants' Total Score in Relation to the Different Types of Schools, Source: Own Composition*

Figure 24 shows the received points in intervals according to Scott (1979, p. 608) on the x-axis and the relative frequency in percent on the y-axis. The bin width was set at 3 points. The decision to use this bin width was based upon Scott's normal reference rule to calculate the bin width. The points are classified based on equation (16). $h_n$ is the bin width, $\sigma$ the standard deviation, and $n$ the number of measured values.

(16) $$h_n = \frac{3{,}49 \cdot \sigma}{\sqrt[3]{n}}$$ (Scott, 1979, p. 608)

Equation 16 yields a bin width of 4,23 points. Since the achieved points range from 2 to 16, hence 15 values, it seems to be very reasonable to actually choose a bin width of 3 points, which gives 5 bins. (cf. Scott, 1979, p. 608)

In Figure 24, the relative frequency is used to compare the different types of schools. Since there are a lot of participants who attended a general secondary school or a 5-year vocational school, a diagram with the number of participants on the y-axis would not be informative if a comparison within the school types constitutes the research interest. Hence, for all graphs, the relative frequency given in percent is used.

The highest percentage of participants (around 37%) who attended compulsory school have reached four to six points and about 14% were able to reach fourteen to sixteen points. The compulsory school graduates also made up the strongest group among the highest points scored. As already shown for the mean values, the polytechnic school is positioned in the two lower-points groups. 50% of the polytechnic participants have reached one to three points while the other 50% are located between four and six points. Vocational school is represented in all score groups. The general secondary school is mainly represented in the midfield, but also shows high scores. This school type has the highest mean value in points (see Table 7). 3-year vocational school graduates have not reached points from the highest score group. 20% of the participants of the 3-year vocational school, and thus the second highest percentages of this score group, are represented in the lowest point group. The 5-year vocational school is highly represented in the groups (10,13] and (7, 10] and less represented in the lowest group of (1, 4] points.

Since the groups are newly formed for the ANOVA, I want to introduce the frequencies and received scores of the factor “different types of schools” (the groups are referred to as factor within ANOVA). This categorization was carried out according to the hypothesis that adults who have attended a 5-year vocational school have the highest understanding of radioactivity. As a consequence of this hypothesis, the different types of schools were divided into two factor levels: “5-year vocational school” and “others”.

*Table 8: Distribution of Participants According to the Factor School Types, Source: Own Composition*

| | absolute frequency | relative frequency in % |
|---|---|---|
| **5-year Vocational School** | 146 | 37.82 |
| **Others** | 240 | 62.18 |

Table 8 shows that 146 participants attended a 5-year vocational school and 240 attended one of the other school types. Table 9 and Figure 25 present the scores of the newly formed factor levels of school types.

*Table 9: Mean Value and Standard Deviation in Points in Relation to the Different Types of Schools Part 2, Source: Own Composition*

| | 5-year Vocational School | Others |
|---|---|---|
| **Mean Value in Points** | 9.79 | 9.44 |
| **Standard Deviation in Points** | 2.65 | 3.11 |

As one can see in Table 9, the mean value in points between the two factor levels is almost equal. The mean values of these two factor levels do not differ even by one point. The standard deviation is approximately three points. When comparing Table 9 and Figure 25, one can see that the participants who have attended a 5-year vocational school have a relative frequency between 30% and 40% in the point-groups (7,10] and (10,13], respectively. Only approximately 7% received the highest score. The participants of the other school types have a relative frequency of 9% in the highest score. In the midfield, they did not reach the point-groups (7,10] and (10,13] as often as the graduates of the 5-year vocational school. If one takes a look at the two lowest point-groups, the factor level “others” reached a higher relative frequency than the participants of the 5-year vocational school. In other words, we see clustering around middle scores by 5-year vocational school graduates. The graduates from other schools exhibit a spread in scores, with the high-scoring graduates balancing out the low-scoring ones.

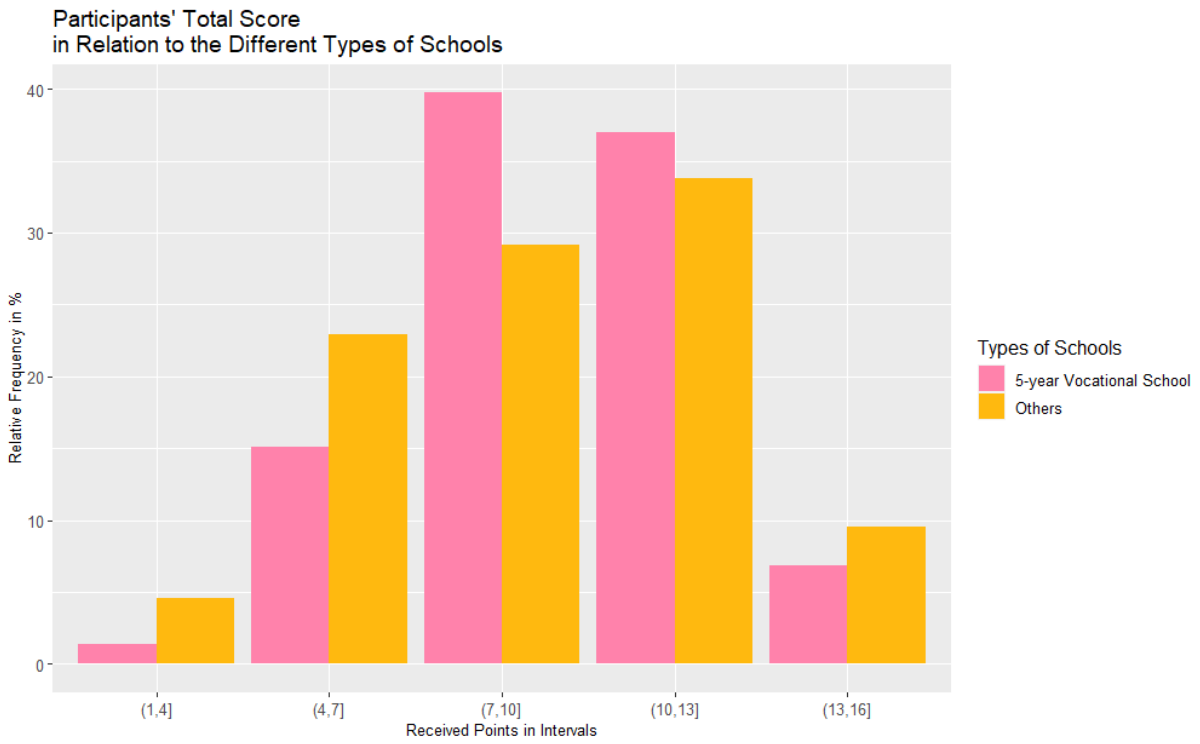


*Figure 25: Participants' Total Score in Relation to the Different Types of Schools Part 2, Source: Own Composition*

The hypothesis H2 states that graduates from the 5-year vocational school have the highest understanding of radioactivity. In particular, there is a common image that HTL is the type of school that many technically gifted students have attended and continue to attend. Therefore, I looked more carefully at the 5-year vocational school to see how HTL graduates performed in comparison to graduates from other 5-year vocational schools.

*Table 10: Distribution of Participants According to the Subtypes of the 5-year Vocational School, Source: Own Composition*

| | absolute frequency | relative frequency in % |
|---|---|---|
| **HTL** | 55 | 37.68 |
| **HAK** | 28 | 19.18 |
| **HLM** | 1 | 0.68 |
| **HBLA** | 17 | 11.64 |
| **HLF** | 1 | 0.68 |
| **HLW** | 21 | 14.38 |
| **HLFS** | 1 | 0.68 |
| **BAfEP** | 8 | 5.48 |
| **BASOP** | 4 | 2.74 |
| **others** | 10 | 6.85 |

Table 10 shows that HTL is the school type attended by most participants. 55 participants attended this type of school. The HAK, HLW and HBLA were also attended by many participants. The HLM, HLF and HLFS were attended by only one participant each. The BAfEP, BASOP and others are in the midfield, but these types of schools were not chosen as often. For a more detailed explanation of the abbreviations and school types, please refer to the website of the "*Bundesministerium für Bildung, Wissenschaft und Forschung*" (BMBWF, 2022).

*Table 11: Mean Value and Standard Deviation in Points in Relation to the Subtypes of the 5-year Vocational School, Source: Own Composition*

| | HTL | HAK | HLM | HBLA | HLF | HWL | HLFS | BAfEP | BASOP | others |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mean Value in Points** | 9.60 | 9.42 | 10.67 | 9.60 | 9.44 | 9.80 | 5.67 | 9.28 | 9.19 | 9.96 |
| **Standard Deviation in Points** | 2.95 | 3.04 | 3.30 | 3.22 | 3.50 | 2.69 | 0.94 | 2.59 | 1.33 | 3.50 |

As can be seen in Table 11, the HLM-graduates actually outperformed HTL-graduates. Generally speaking, however, all subtypes of 5-year vocational high school achieved the mean value of all respondents in this research, with the exception of the HLFS, which achieved a very low mean value. However, the HLFS was attended by only one participant. Since it has been shown here that the former HTL students do not have the highest knowledge about radioactivity compared to the other school types of the 5-year vocational school, the original grouping based on ANOVA is reused for the next diagrams.

## Categorization: Time Passed Since Last School Attendance

*Table 12: Mean Value and Standard Deviation in Points in Relation to the Time Passed Since Last School Attendance Part 1, Source: Own Composition*

| | 0 - 5 | 6 - 10 | 11 - 15 | 16 - 20 | 21 - 25 | 26 - 30 | 31 - 35 | 36 - 40 | 40+ |
|---|---|---|---|---|---|---|---|---|---|
| **Mean Value in Points** | 8.93 | 10.52 | 9.38 | 9.88 | 8.14 | 8.96 | 8.52 | 7.25 | 8.61 |
| **Standard Deviation in Points** | 2.40 | 2.69 | 3.09 | 2.59 | 3.05 | 3.22 | 1.91 | 3.14 | 3.40 |

Table 12 shows the mean value and standard deviation of scored points according to time passed since last school attendance. Compared to Table 7, there are not as many differences in the individual mean values. The category with the highest mean value is the group “6 - 10”. The group with the second-best mean value is “16 - 20” closely followed by “11 - 15” and “26 - 30”. The differences are all small in comparison to the standard deviations. The group with the least mean value is “36 - 40”.

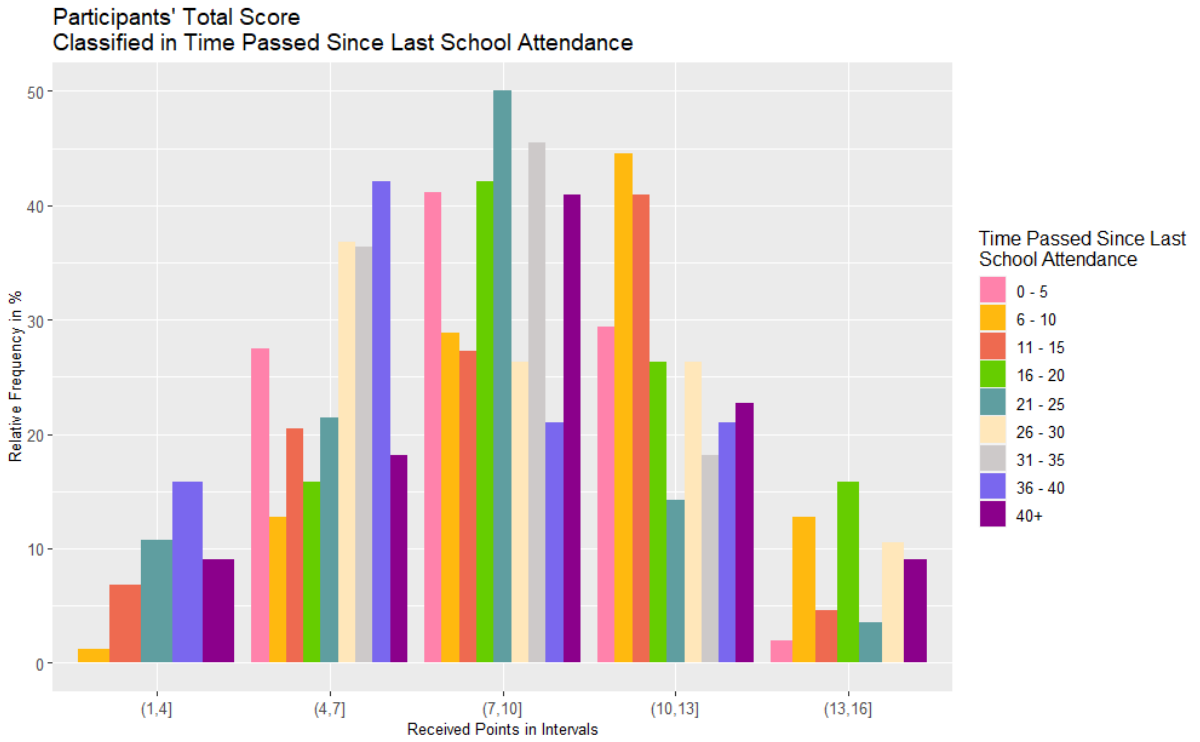


*Figure 26: Participants' Total Score Classified in Time Passed Since Last School Attendance Part 1, Source: Own Composition*

In the legend of Figure 26, there are a lot of different groups which indicate the time passed since the last school attendance from the participants of the questionnaire. As with Figure 24 and Figure 25, the x-axis describes the received points in intervals and the y-axis shows the relative frequency in percent. As already seen in Table 12 and in Figure 26, the category of medium points is strongly represented by all groups.

When comparing the two groups of most recent school leavers (i.e., “0 - 5” and “6 - 10”), it is worth mentioning that especially those from group “6 - 10” performed better than those from group “0 - 5”. The group of “16 - 20“ years since leaving school are represented the strongest with 16% among the highest score points group (13,16]. The group that is mainly represented in the lowest two categories is that of “36 - 40” years passed. These two observations of the highest and lowest representative groups are also clearly evident in Table 12 of mean values. It is very conspicuous that the group "40+" is highly represented in the (7, 10] points category with more than 40% and in the (10, 13] points category with more than 20%.

Again, since the groups are newly formed for the ANOVA, I want to introduce the frequencies and reached scores of the factor “time passed since school attendance”. This categorization was carried out based on the hypothesis formed for this master’s thesis. As a consequence of this hypothesis, the time-passed factors were divided into two factor levels: “recent school leavers” and “non recent school leavers”.

*Table 13: Distribution of Participants According to the Factor Time-Passed, Source: Own Composition*

| | absolute frequency | relative frequency in % |
|---|---|---|
| **Recent School Leavers** | 224 | 58.03 |
| **Non Recent School Leavers** | 162 | 41.97 |

Table 13 shows that 58,03% of the people who filled out the questionnaire are “recent school leavers” which means that they have attended school within the last 10 years. 41,97% of those are participants, who have attended school more than 10 years ago, which are called “non recent school leavers”. (cf. Alsop, 2001, p. 265)

*Table 14: Mean Value and Standard Deviation in the Point Intervals in Relation to the Time Passed Since Last School Attendance Part 2, Source: Own Composition*

| | Recent School Leavers | Non Recent School Leavers |
|---|---|---|
| **Mean Value in Points** | 10.16 | 8.76 |
| **Standard Deviation in Points** | 2.71 | 3.08 |

Table 14 presents the mean value and the standard deviation in points of the factor levels “recent school leavers” and “non recent school leavers”. The mean value of the “recent school leavers” is 10,16 points, which is higher than the mean value of the

“non recent school leavers”. The category of “non recent school leavers” has reached an average of 8,76 points.

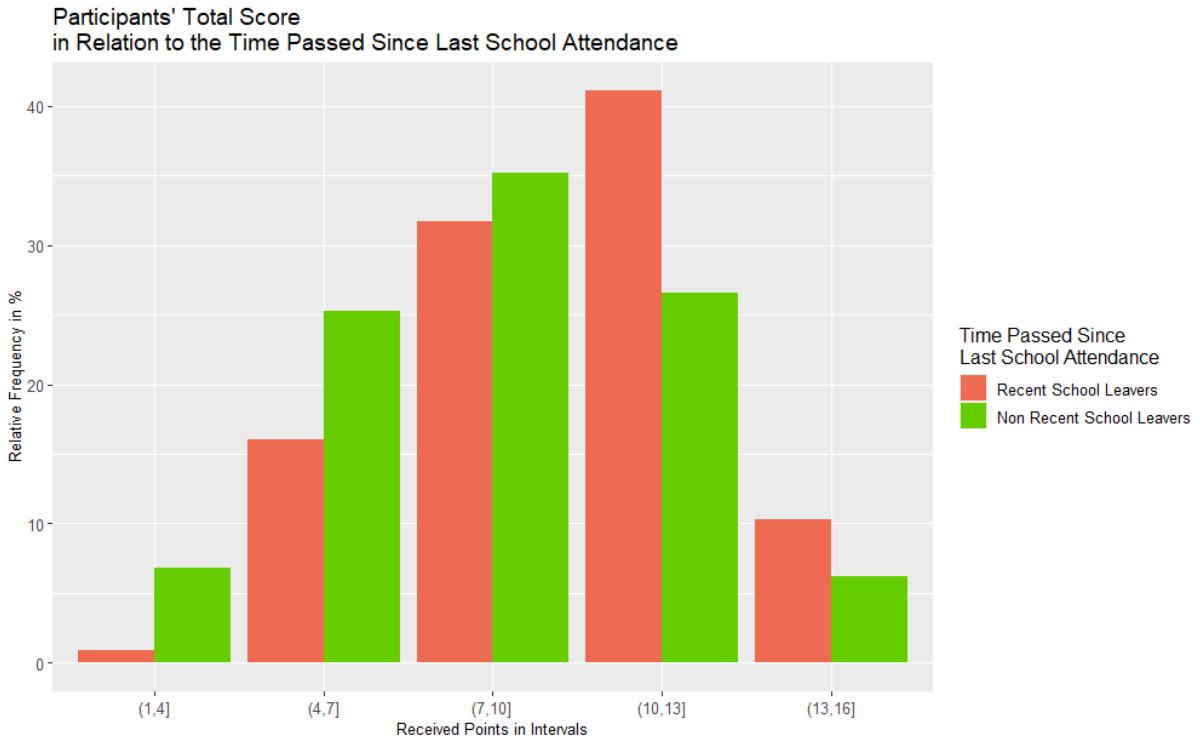


*Figure 27: Participants' Total Score Classified in Time Passed Since Last School Attendance Part 2, Source: Own Composition*

Figure 27 shows the participants’ total score in relation to the time passed since last school attendance. It is evident that the "recent school leavers" are more strongly represented in the categories of (10, 13] and (13, 16]. The “non recent school leavers” have a stronger representation in the three lowest categories (i.e., (1, 4], (4, 7], (7, 10]).

Categorization: Adults Who Have and Have Not Seen “Chernobyl”

*Table 15: Mean Value and Standard Deviation in Points in Relation to the Participants Who Have and Have Not Seen “Chernobyl”, Source: Own Composition*

| | Adults Who Have Seen Chernobyl | Adults Who Have Not Seen Chernobyl |
|---|---|---|
| **Mean Value in Points** | 9.78 | 9.46 |
| **Standard Deviation in Points** | 3.10 | 2.86 |

Table 15 shows the mean value and standard deviation of scored points of participants who have or have not seen “Chernobyl”. The mean values are very close as they do not differ even by one point. Additionally, the standard deviations in points also do not differ even by one point.

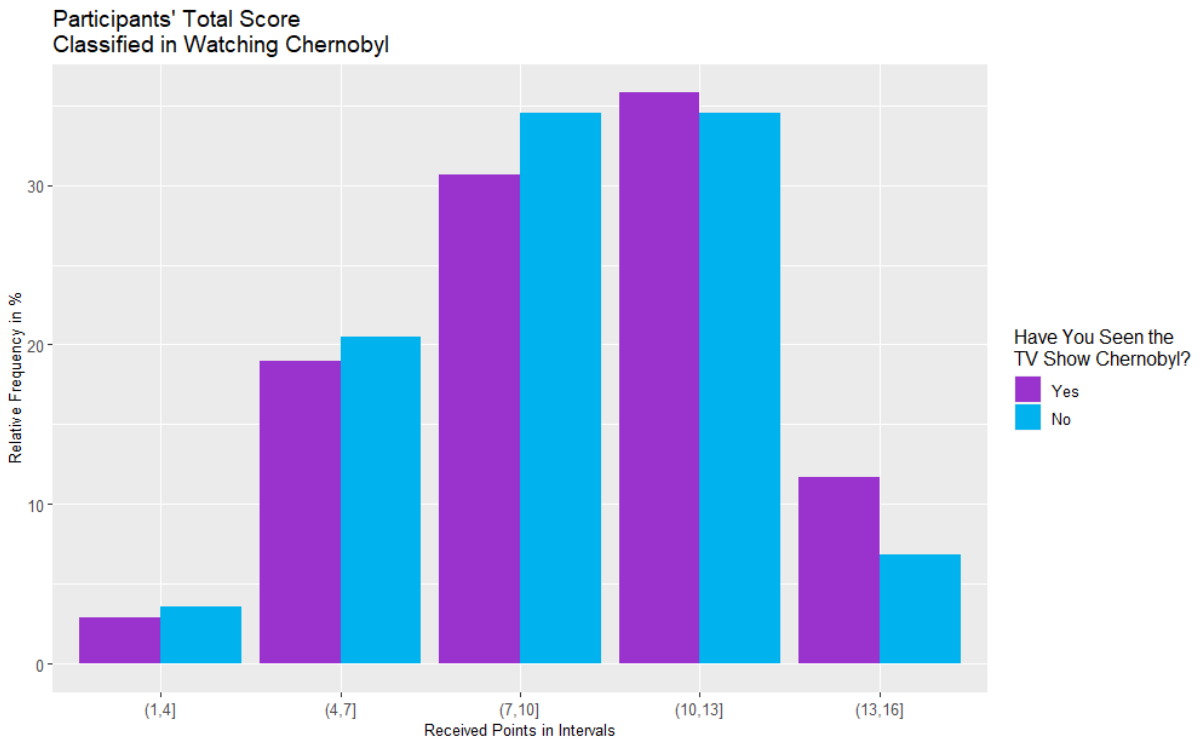


*Figure 28: Participants' Total Score Classified in Watching "Chernobyl", Source: Own Composition*

Comparing the mean values from Table 15 with the bar chart in Figure 28, especially in the two highest groups (10, 13] and (13, 16], the persons who have seen "Chernobyl" score higher more often. The differences between the two bars within each factor level balance each other out, which is why the mean scores of the two factor levels are almost equal.

Distribution of Answers Within the Individual Questions

In this part, the answers to the individual questions are examined in more detail, classified according to the two main factors: different types of schools and time passed since last school attendance. The factor of participants who have seen or have not seen "Chernobyl" will not be presented in detail as this is not the main focus of this thesis, but merely a "question of interest". As a rule, the heading gives an insight into what the question is about, the legend shows the different factors within their factor levels and their respective color, the x-axis shows the different answers to every question and the y-axis shows the relative frequency in percent.

In the following, every question and its respective answers are shown first in the category of school types and second in the category of time passed since last school attendance. The single questions, which will be used now, can be read in Chapter 5.3.3. and the complete survey is available in the Appendix. The point here is not to

show factor levels which answered correctly, but rather to show a trend between individual factor levels.

Question 4 - What Makes a Measuring Device for Radioactivity Click/Beep?

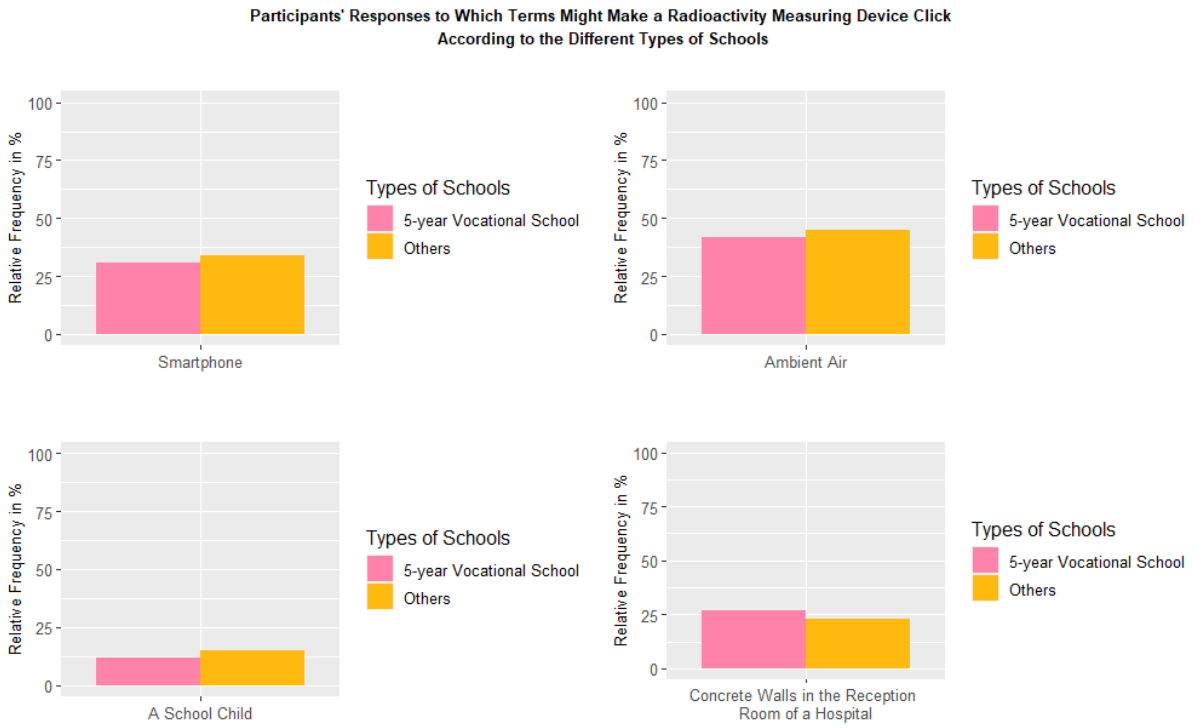


*Figure 29: Participants' Responses to Which Terms Might Make a Radioactivity Measuring Device Click Part 1, Source: Own Composition*

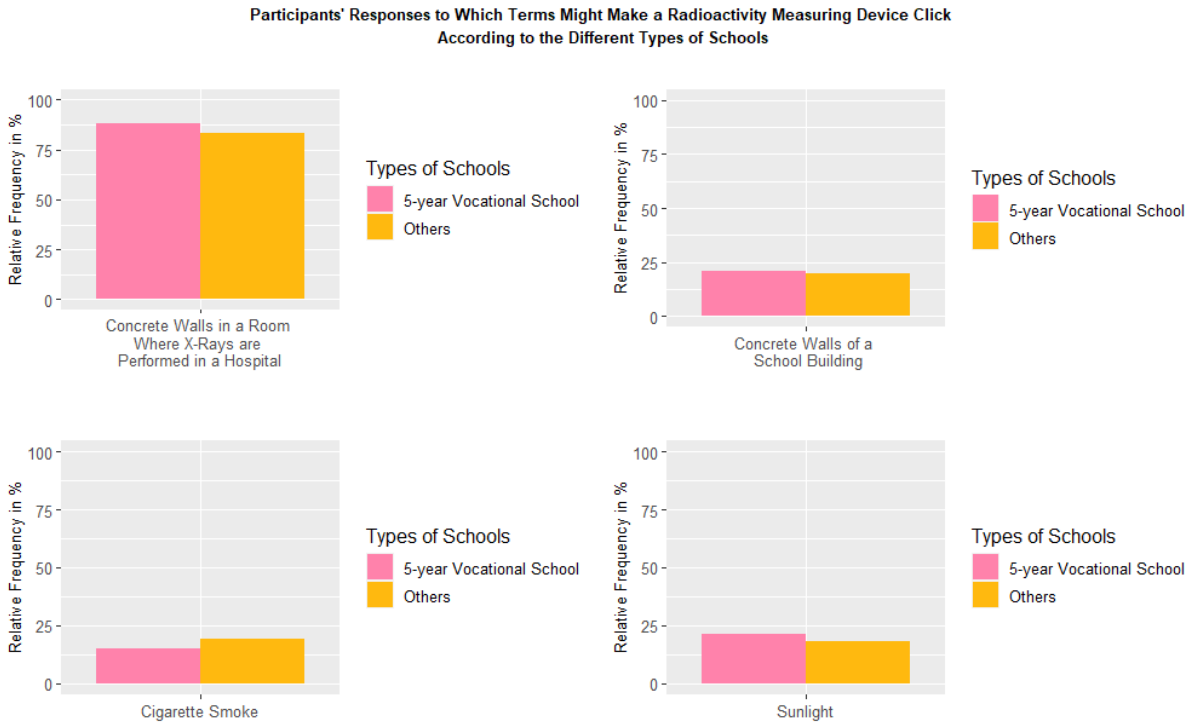


*Figure 30: Participants' Responses to Which Terms Might Make a Radioactivity Measuring Device Click Part 2, Source: Own Composition*

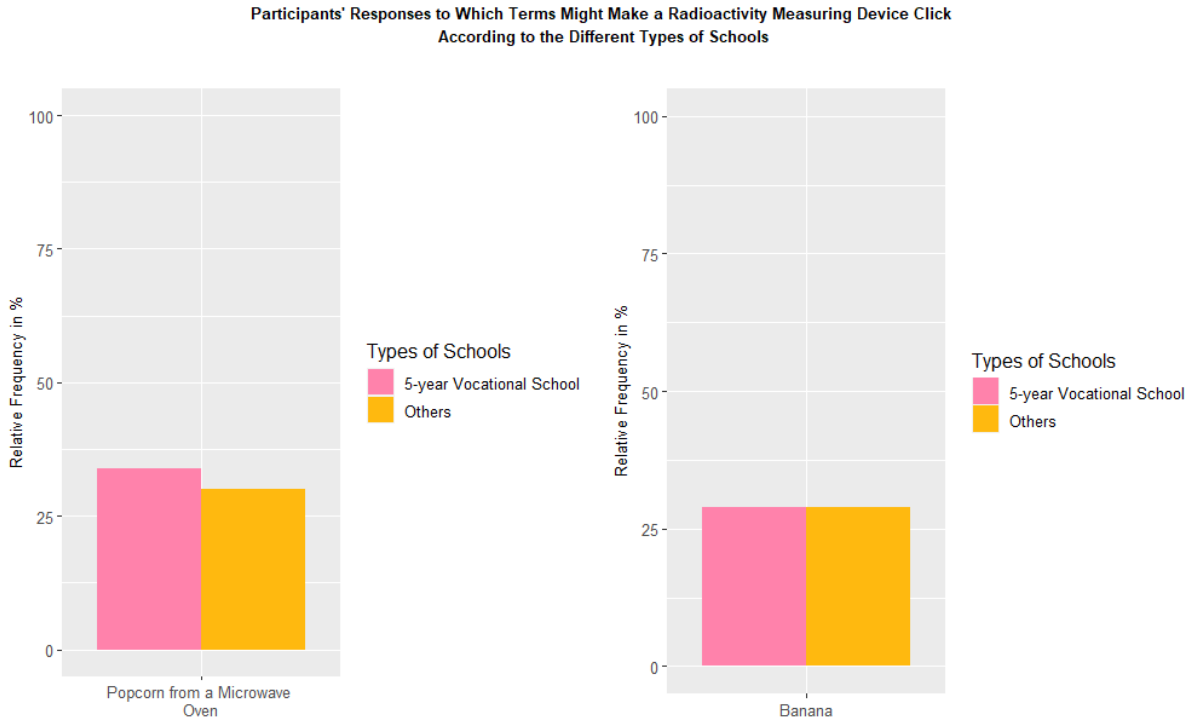


*Figure 31: Participants' Responses to Which Terms Might Make a Radioactivity Measuring Device Click Part 3, Source: Own Composition*

Figure 29 to Figure 31 show the participants' responses to different terms which might make a radioactivity measuring device click. The correct answer is to check all

items. Nine out of ten terms were ticked with a relative frequency of less than 50% regardless of the type of school. The terms “Smartphone”, “Popcorn from a Microwave Oven” and “Banana” were chosen by both factor levels with a relative frequency of 20% to 40% each. The option “Ambient Air” was the second most often picked answer but only with a relative frequency of 40% to 50%. The terms “A School Child”, “Concrete Walls of a School Building”, “Cigarette Smoke” and “Sunlight” were chosen by the participants of both school types with a relative frequency of under 25% each. It follows that less than one-quarter of all “types of schools”-factor levels did not select these terms. The term “Concrete Walls in the Reception Room of a Hospital” was selected by the “5-year vocational school” participants with a relative frequency of just over 25%, whereas the graduates from other schools reached a relative frequency of just under 25% for the same term. Nearly all participants from both types of schools considered the term “Concrete Walls in a Room Where X-rays are Performed in a Hospital” to make the measuring device for radioactivity click. The other concrete walls were not picked that often. The term “concrete walls from the reception room of a hospital” was chosen more often than the term “concrete walls of a school building”.

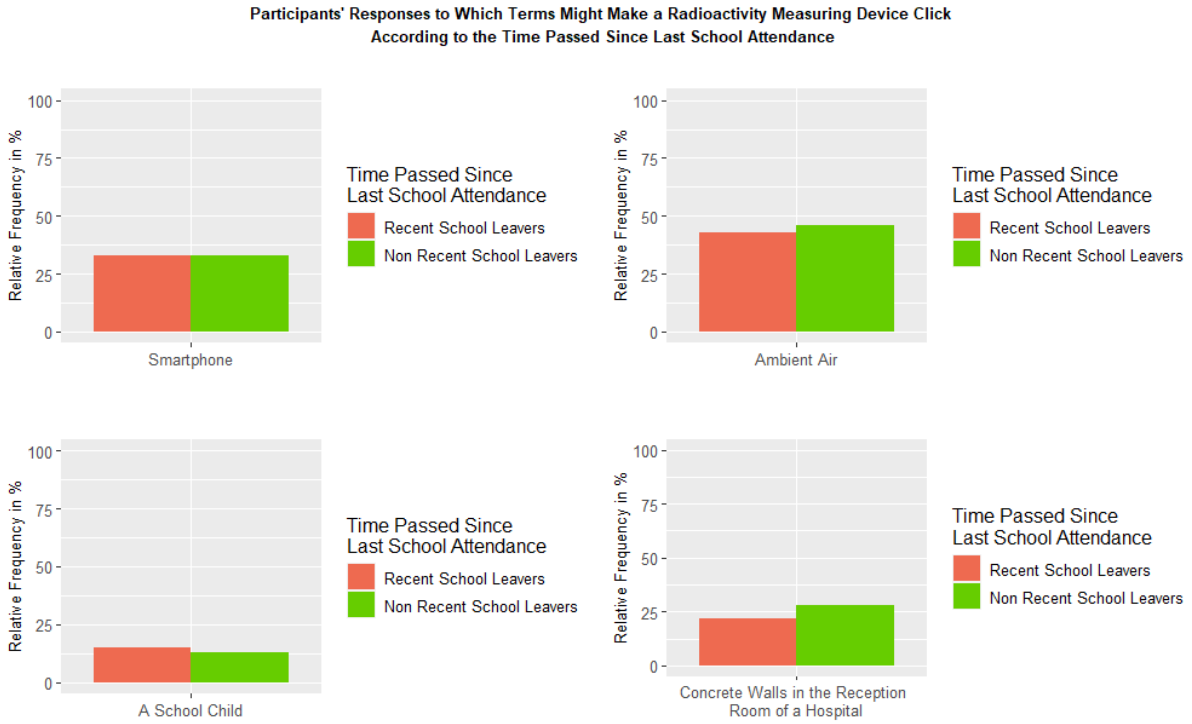


*Figure 32: Participants' Responses to Which Terms Might Make a Radioactivity Measuring Device Click Part 4, Source: Own Composition*

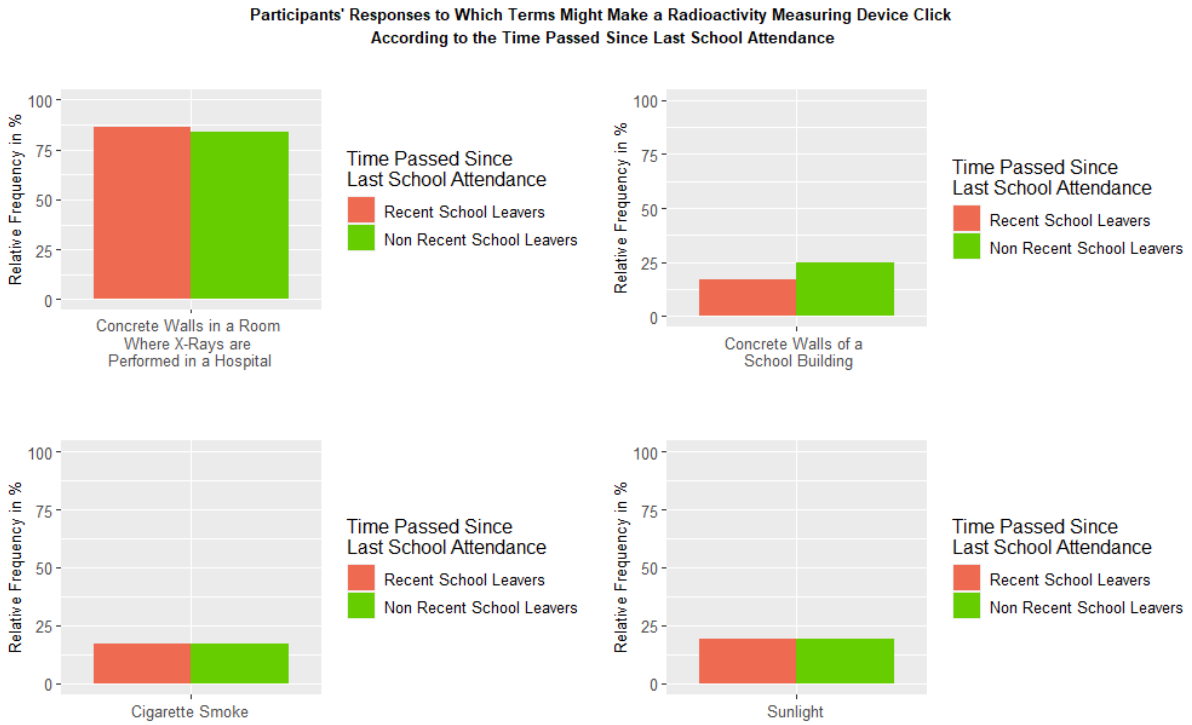


*Figure 33: Participants' Responses to Which Terms Might Make a Radioactivity Measuring Device Click Part 5, Source: Own Composition*

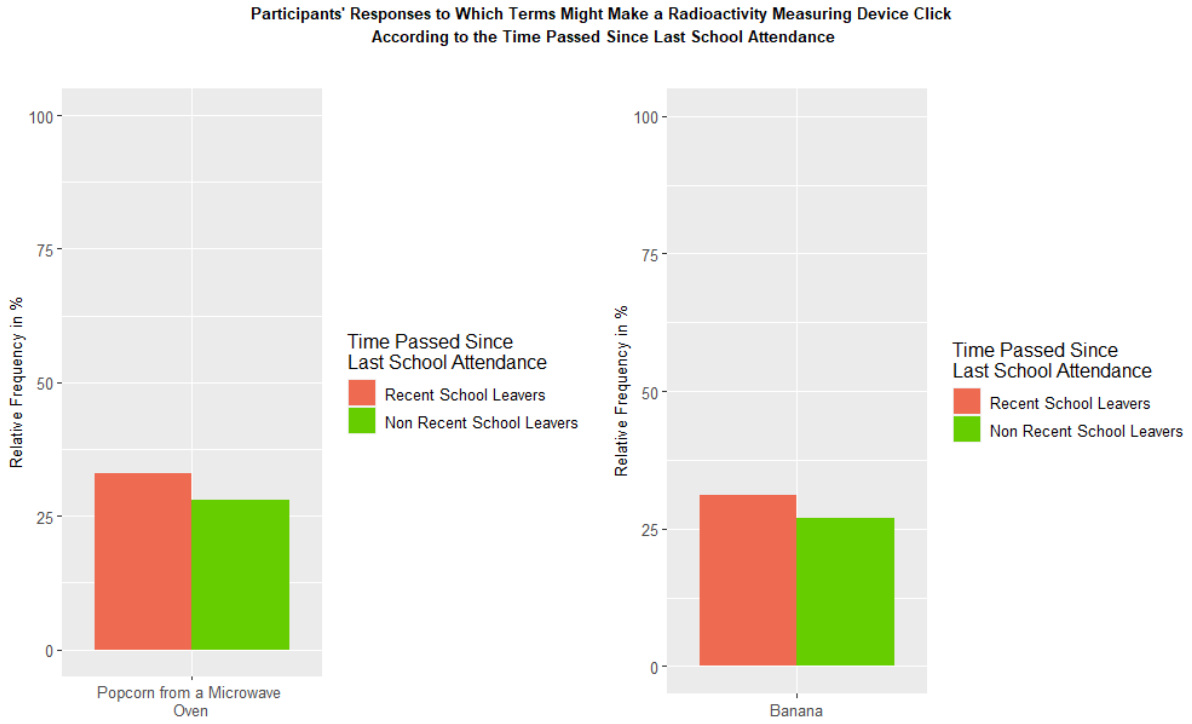


*Figure 34: Participants' Responses to Which Terms Might Make a Radioactivity Measuring Device Click Part 6, Source: Own Composition*

Figure 32 to Figure 34 also show the participants' responses to different terms which might make a radioactivity measuring device click. Now, however, the answers are

classified according to the time passed since the last school visit. Also, in this categorization, less than 50% of respondents in either factor level selected nine to ten of the terms. The options “Smartphone”, “Ambient Air”, “Popcorn from a Microwave Oven” and “Banana” were chosen with a relative frequency of 25% to 50% each by both factor levels, i.e., the recent and non-recent school leavers. Within this factor, the term “Ambient Air” was the second most picked answer. The participants of “recent school leavers” and “non recent school leavers” reached a relative frequency of less than or equal to 25% for the terms “A School Child”, “Concrete Walls of a School Building”, “Cigarette Smoke” and “Sunlight”. The term “Concrete Walls in the Reception Room of a Hospital” was selected by both recent and non-recent school leavers by several percent more than the term “Concrete Walls of a School Building”. The term which was chosen the most was “Concrete Walls in a Room Where X-rays are Performed in a Hospital” with a relative frequency of more than 80%.

Question 5 - Definition of Radioactivity

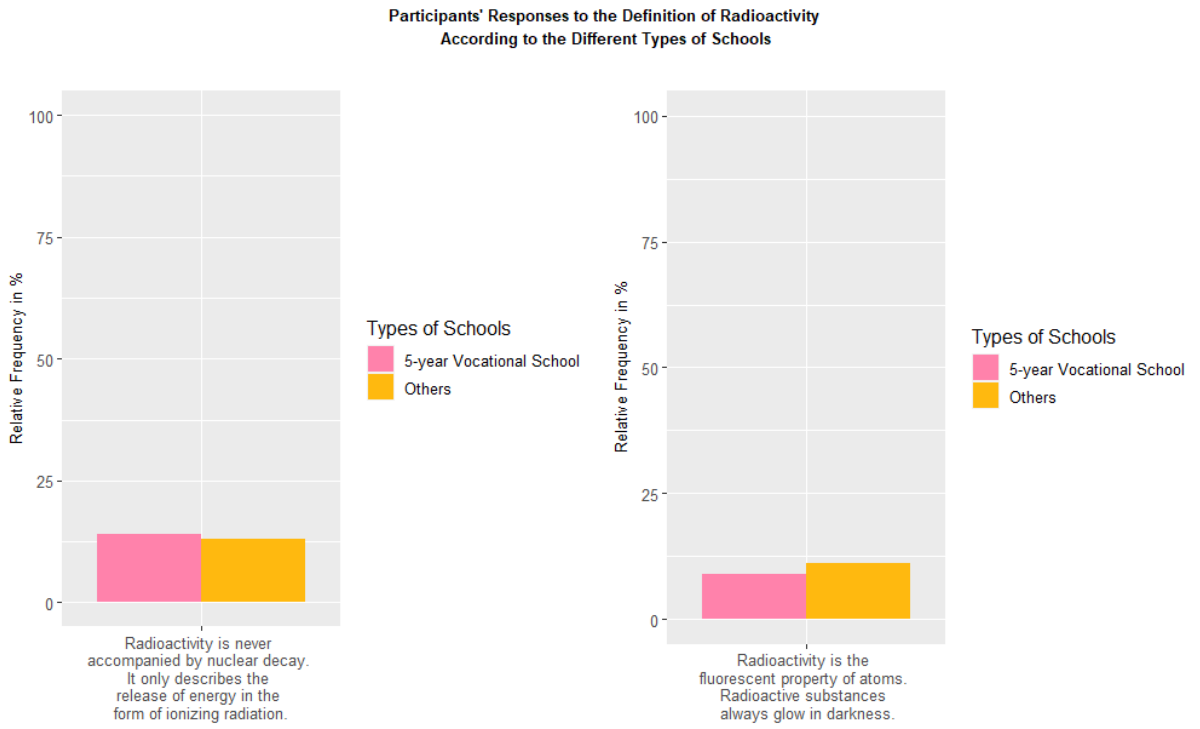


*Figure 35: Participants' Responses to the Definition of Radioactivity Part 1, Source: Own Composition*

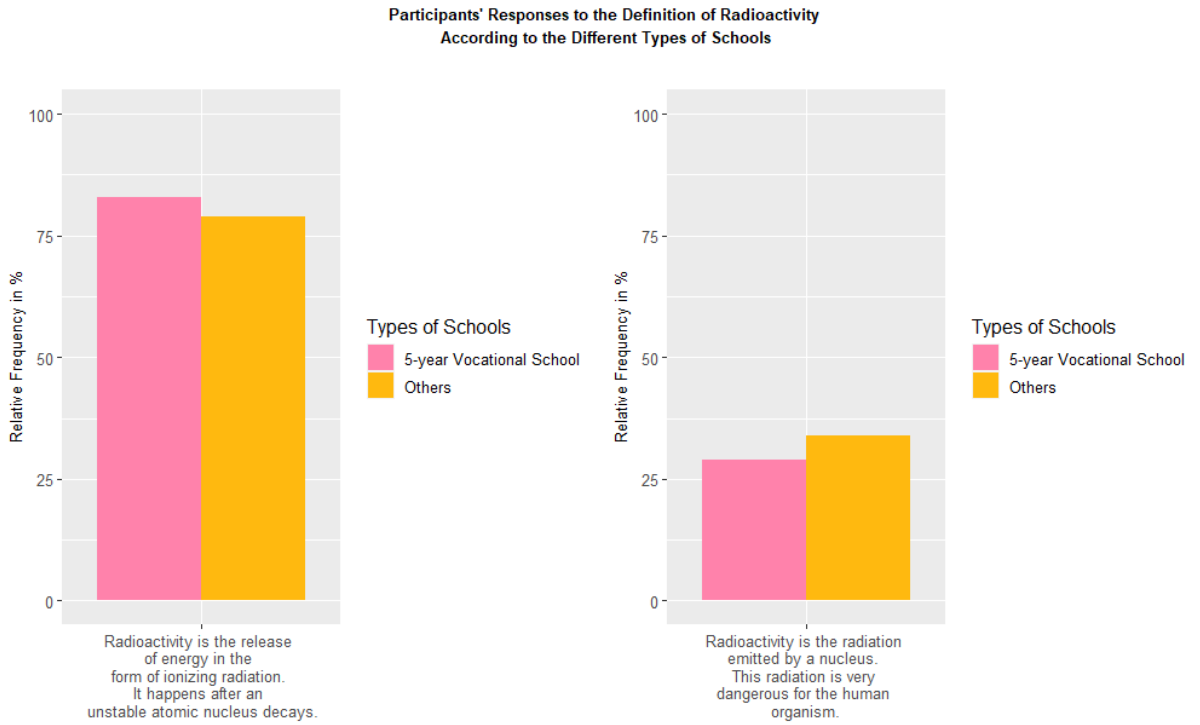


*Figure 36: Participants' Responses to the Definition of Radioactivity Part 2, Source: Own Composition*

Figure 35 and Figure 36 present the participants' responses to the definition of radioactivity according to the different types of schools. The answers that "radioactivity is never accompanied by a nuclear decay (…)" and "radioactivity is the fluorescent property of atoms (…)" were least selected by both factor levels of non-recent and recent school leavers. These two options were chosen by a relative frequency of less than 15% each.

The correct answer "Radioactivity is the release of energy in the form of ionizing radiation. (…)" was chosen by more than 75% of the participants of both factor levels. Nevertheless, more participants of the "5-year vocational school" than "others" have chosen this answer. The students' conception that "Radioactivity is the radiation emitted by a nucleus (…)" was chosen by nearly one-quarter of each factor level, with the factor level "others" considering this option as true more often.

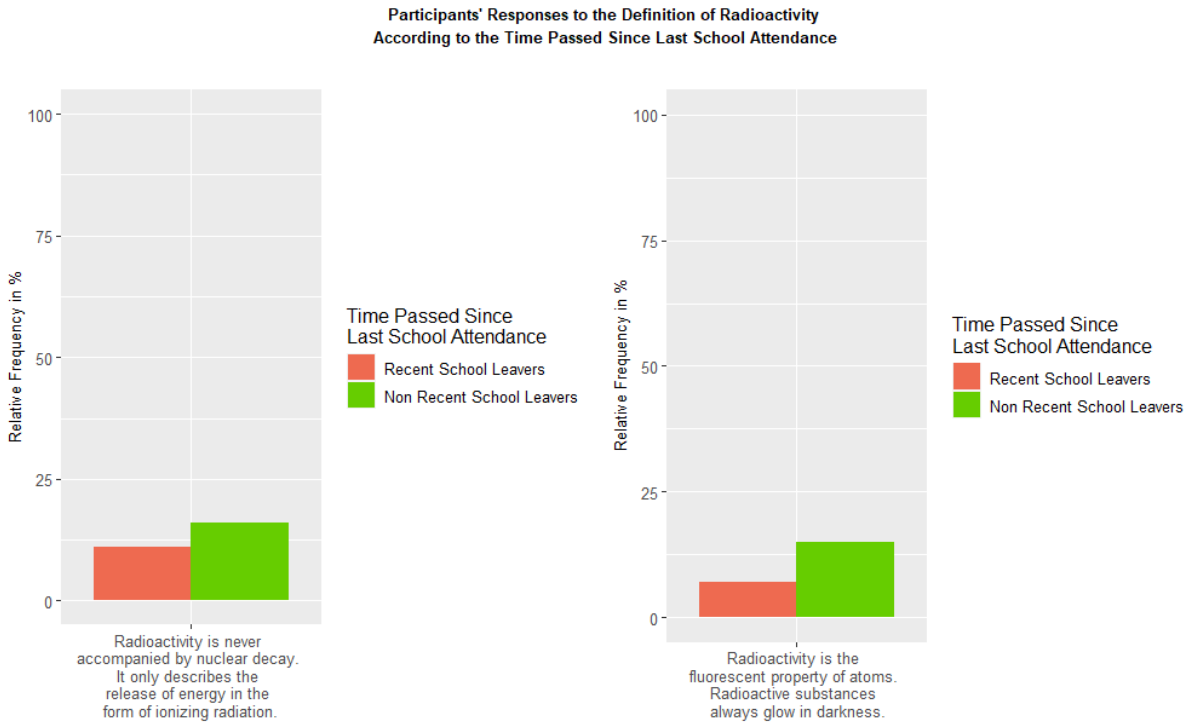


*Figure 37: Participants' Responses to the Definition of Radioactivity Part 3, Source: Own Composition*

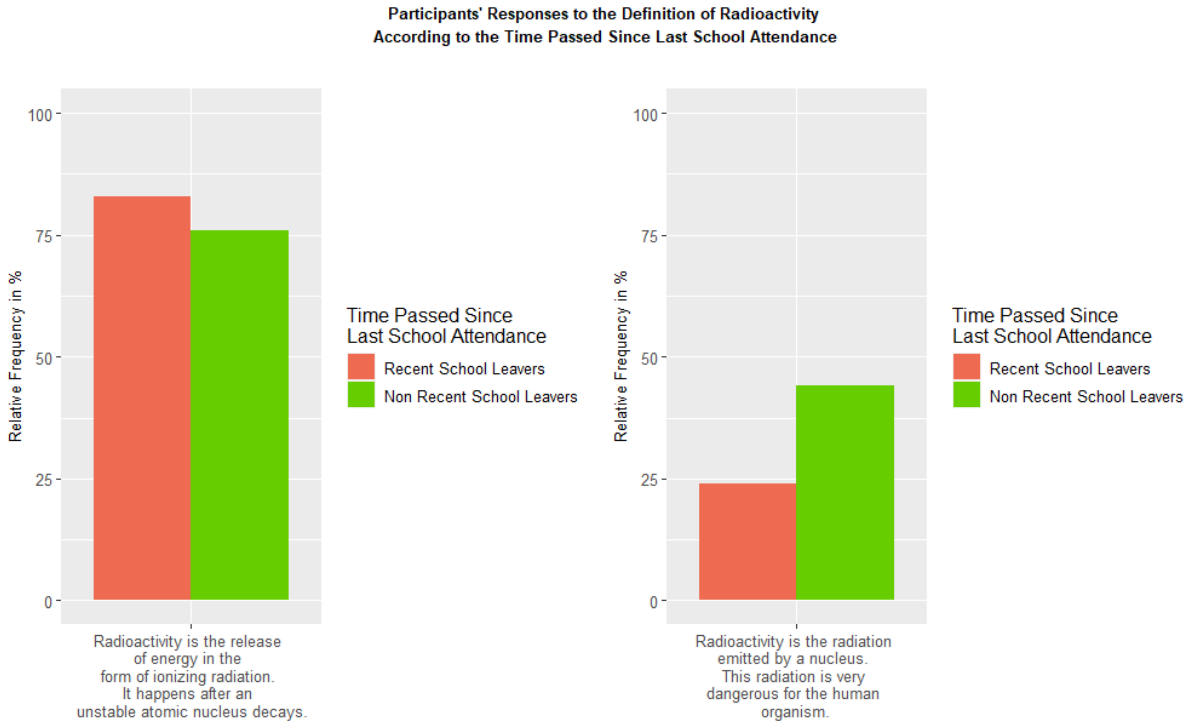


*Figure 38: Participants' Responses to the Definition of Radioactivity Part 4, Source: Own Composition*

In Figure 37 and Figure 38 the participants' responses to the different definition options of radioactivity are presented in relation to the time passed since last school attendance. The percentage of people agreeing that "radioactivity is never accompanied by nuclear decay (…)" increases with time out of school. Nevertheless,

this option has a relative frequency of less than 20% for each factor level of the non-recent and recent school leavers. The answer that “radioactivity is the fluorescent property of atoms (…)” was assumed as true from less than 20% of the participants of each factor level too. The answer with the highest agreement among all factor levels (more than 75% from the participants of all factors) was that “Radioactivity is the release of energy (…) after an unstable atomic nucleus decay”. This option was chosen by “recent school leavers” more often than by “non recent school leavers”. That “Radioactivity is the radiation emitted by a nucleus (…)” was considered to be true by a relatively large number of “non recent school leavers”. They reached a relative frequency of nearly 50%, whereas the “recent school leavers” have chosen this option by a relative frequency of just under 25%.

Question 6 - Types of Radiation Emitted from Nuclei When Radioactive Materials Decay

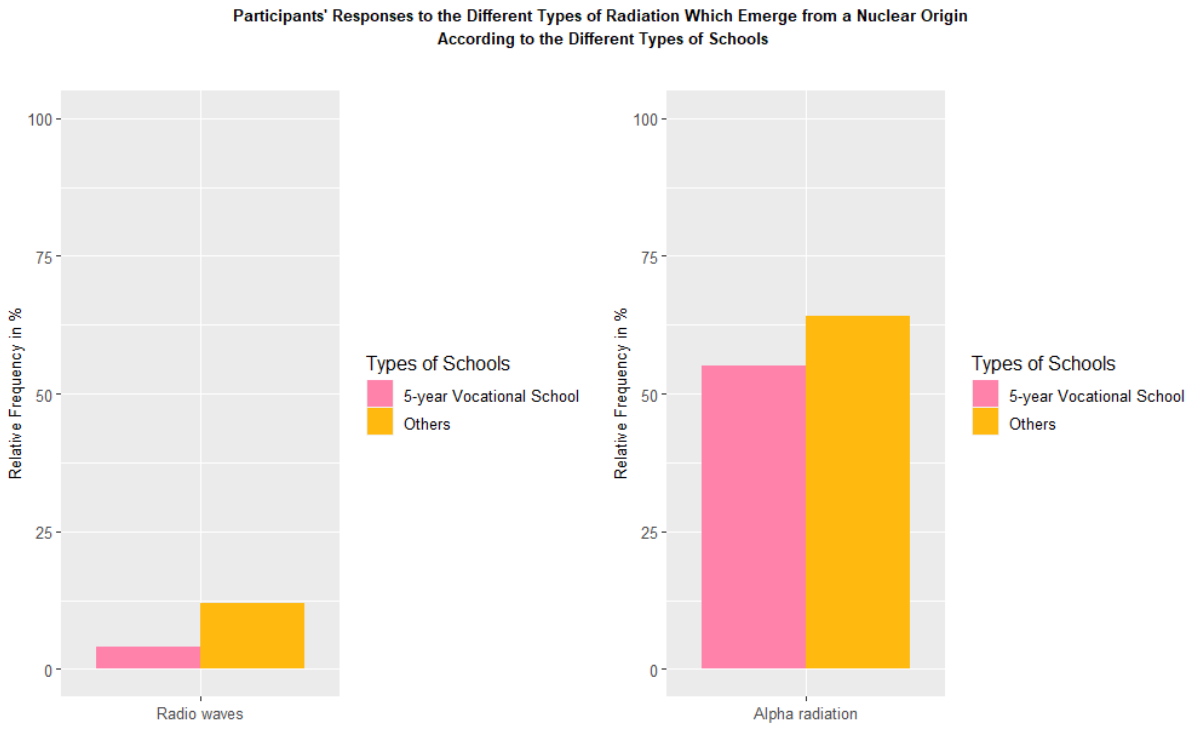


*Figure 39: Participants' Responses to the Different Types of Radiation Which Emerge from a Nuclear Origin Part 1, Source: Own Composition*

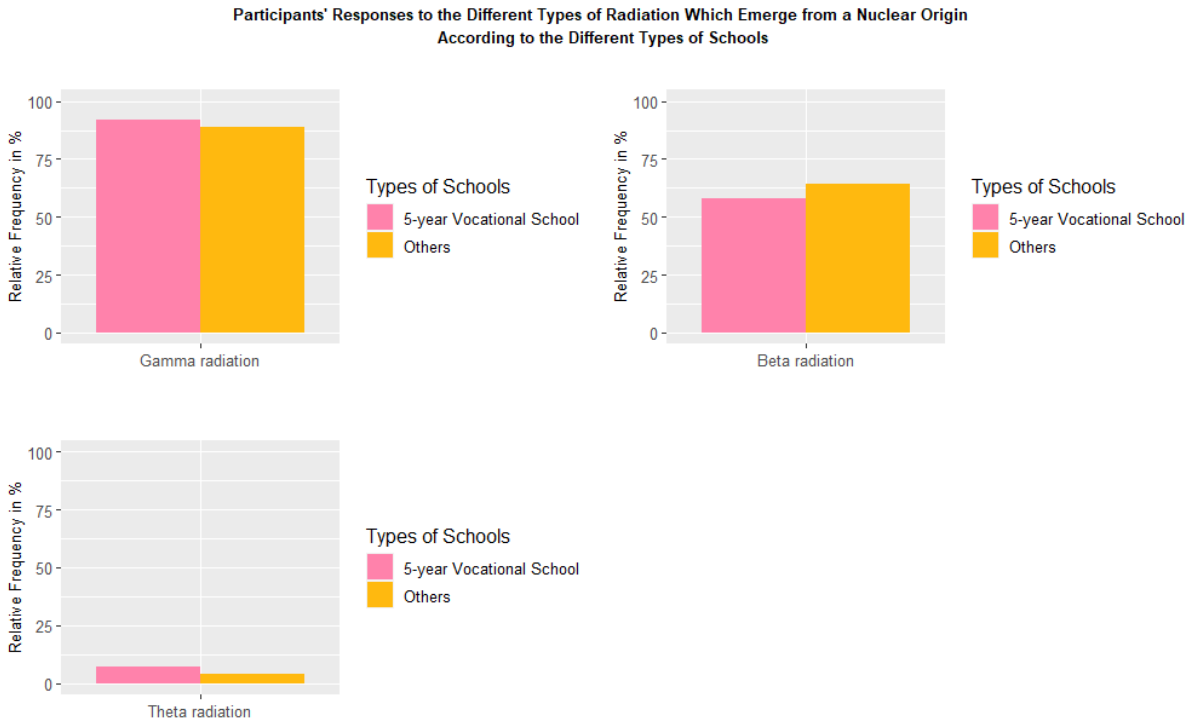


*Figure 40: Participants' Responses to the Different Types of Radiation Which Emerge from a Nuclear Origin Part 2, Source: Own Composition*

Figure 39 and Figure 40 present the participants' responses to the different types of radiation which emerge from a nuclear origin in relation to the different types of schools. Here the term radiation corresponds to the German term "Strahlung". Hence, I wrote alpha respectively beta radiation instead of alpha respectively beta particle. These terms are used similarly in numerous physics course books, which is why I used it.

Radio waves were chosen by both types of schools but with a low frequency, of less than 13% each. The made-up type of radiation called "Theta" was picked only by a very small number of members of both factor levels.

When comparing the relative frequencies of the individual school types in regard to alpha, beta and gamma radiation, it can be seen that gamma radiation was chosen with the highest relative frequency by both factor levels. More than 80% of the participants of all schools considered the option "Gamma radiation" to be correct. The term "Alpha radiation" was chosen with a relative frequency of more than 50% of the participants of all schools. Nevertheless, a higher frequency of the participants of the factor level "others" have chosen this term. The term "Beta radiation" was approximately chosen as equally often as the term "Alpha radiation" by the respective

factor levels. It is particularly striking that the terms “Alpha radiation” and “Beta radiation” were chosen more often by the factor level “others”. In comparison, the term "gamma radiation" was selected more often by the graduates of the “5-year vocational school”. Since the correct answers (alpha, beta, and gamma) were chosen by more than half of the participants of all types of schools and the fact that only a few participants have chosen the option “Theta radiation”, serves as evidence that respondents were taking the survey seriously and were not just randomly guessing.

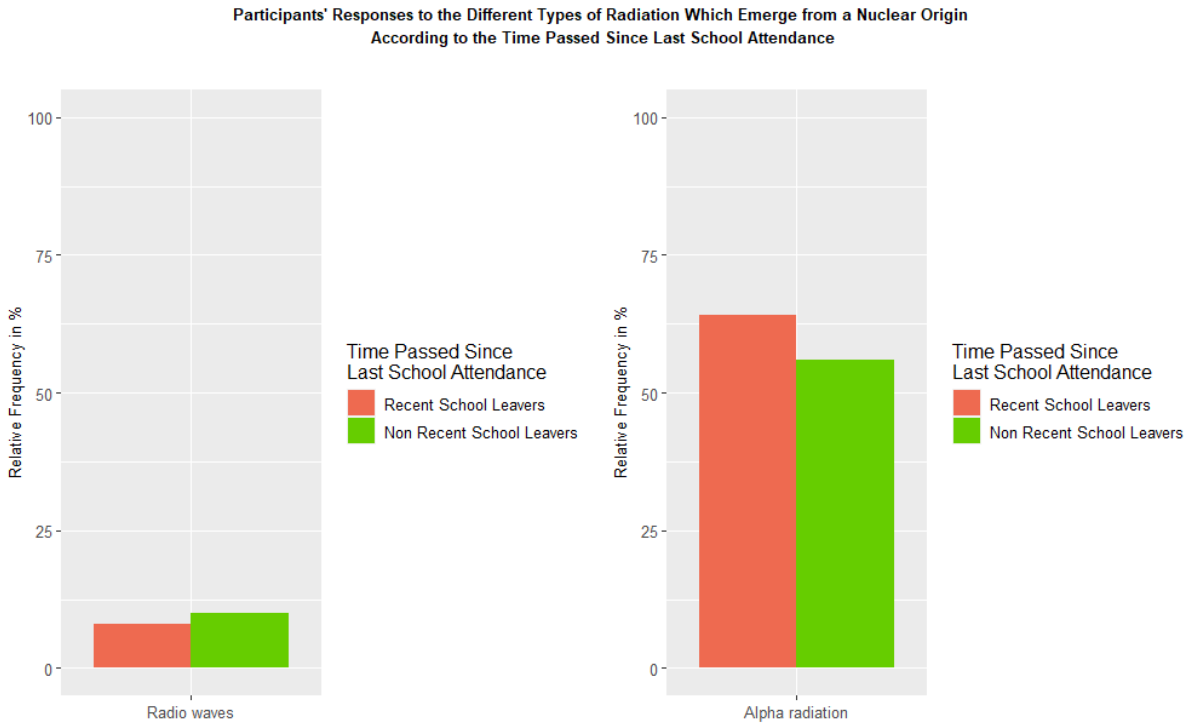


*Figure 41: Participants' Responses to the Different Types of Radiation Which Emerge from a Nuclear Origin Part 3, Source: Own Composition*

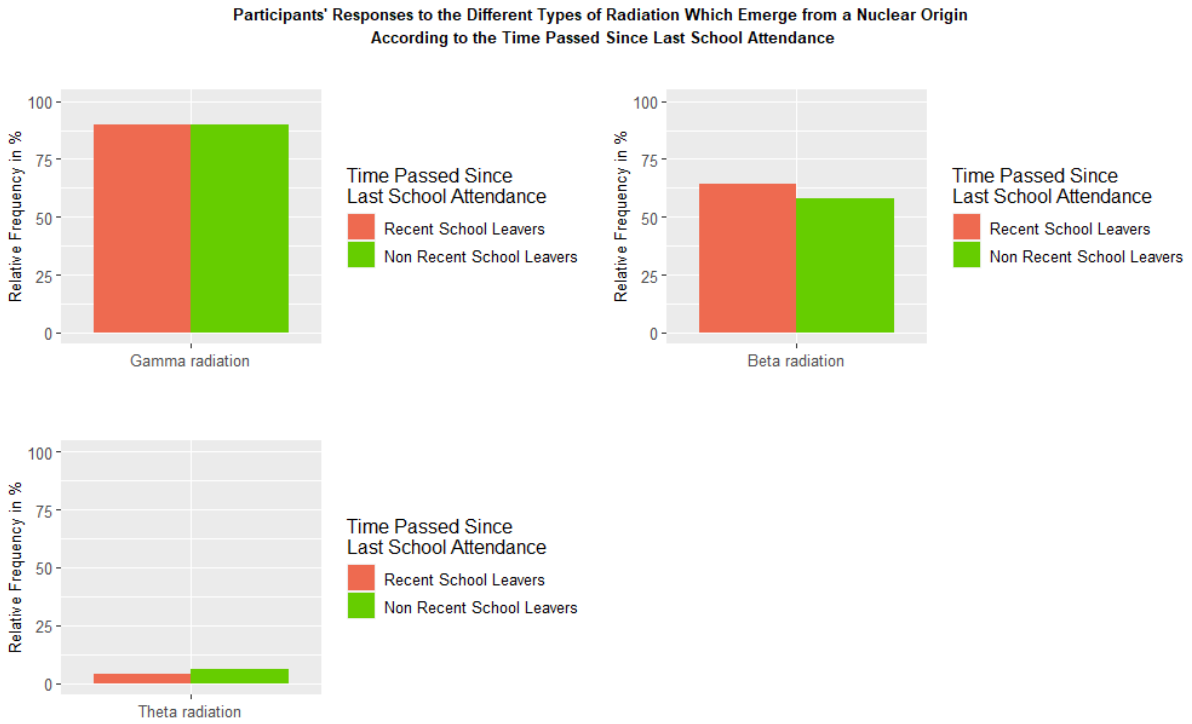


*Figure 42: Participants' Responses to the Different Types of Radiation Which Emerge from a Nuclear Origin Part 4, Source: Own Composition*

The participants' responses to the different types of radiation which emerge from a nuclear origin classified by time passed since last school attendance can be seen in Figure 41 and Figure 42. Compared to Figure 39, in Figure 41 there is also only a small number of participants (a relative frequency less than or equal to 10% each) of both factor levels who considered radio waves to be a type of radiation emitted from nuclei when radioactive materials decay.

It can also be seen in the factor levels of the time passed since last school attendance that the three emitted radiation types were recognized by the majority of the participants. Especially gamma radiation was ticked by a relative frequency of more than 80% by each time period factor level. The terms "Alpha radiation" and "Beta radiation" were ticked by a relative frequency of 50% to 75% each by both factor levels. Nevertheless, these terms were ticked more often by the "recent school leavers".

## Question 7 - Definition of Half-Life

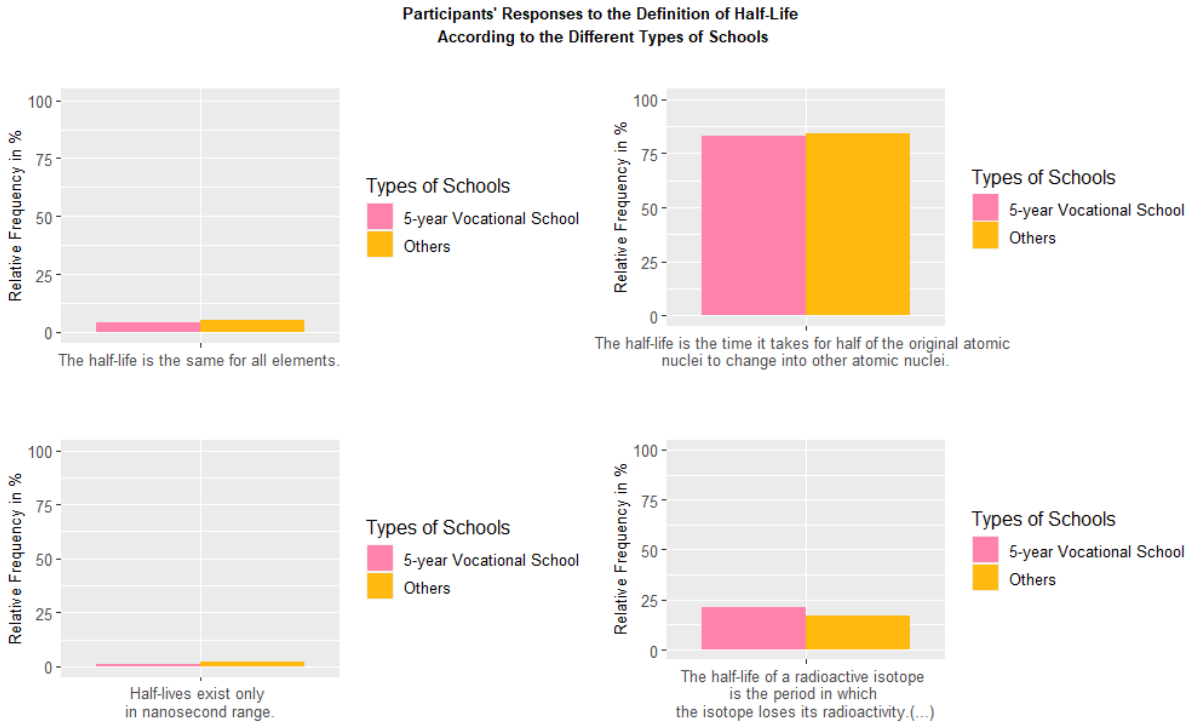


*Figure 43: Participants' Responses to the Definition of Half-Life Part 1, Source: Own Composition*

Figure 43 shows the participants' responses to the definition of half-life according to the different types of schools. One can see that the participants of both school types are clear about the definition of the half-life. Both factor levels have a relative frequency of greater than 75% each for the correct answer „The half-life is the time it takes for half of the original atomic nuclei to change into other atomic nuclei." The options "The half-life is the same for all elements" and "Half-lives exist only in the nanosecond range" were rarely picked by the factor levels "5-year vocational school" and "others". "The half-life (…) is the period '*in which the isotope loses its radioactivity*' (Lijnse et al. 1990, p.71) (…)" was chosen by the graduates of the "5-year vocational school" with a relative frequency of just under 25% and from the graduates of other schools by a relative frequency of approximately 20%. This option is the second most often chosen answer.

*Figure 44: Participants' Responses to the Definition of Half-Life Part 2, Source: Own Composition*

Figure 44 clearly shows that both factor levels classified by time passed since last school attendance were able to assign the correct definition of half-life. Each factor level has a relative frequency greater than 75%, with the “recent school leavers” choosing this option more often. Just as in Figure 43, the same options (i.e., “The half-life is the same for all elements” and “Half-lives exist only in the nanosecond range”) were chosen with negligible frequency by both factor levels. 25% of the “non recent school leavers” considered the option "The half-life (…) is the period ‘*in which the isotope loses its radioactivity*’ (Lijnse et al., 1990, p. 71) (…)" correct. The “recent school leavers” also chose this option but not as often. When comparing all four options, it is particularly striking that the correct option was chosen more often by “recent school leavers” than “non recent school leavers” whereas all the other options were chosen more often by the “non recent school leavers”.

Question 8 - Decay of a sample of Iodine-131

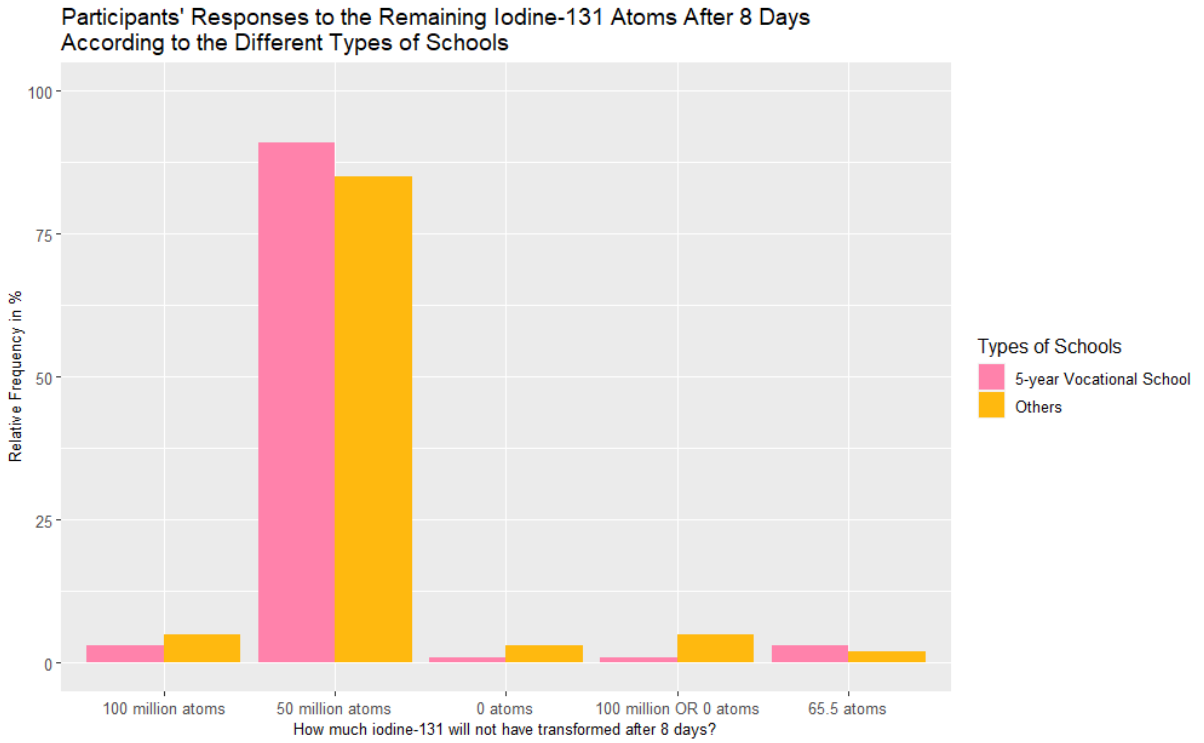


*Figure 45: Participants' Responses to the Remaining Iodine-131 Atoms After 8 Days Part 1, Source: Own Composition*

Figure 45 presents the participants' responses to the question about the remaining Iodine-131 atoms after one half-life. The graduates of the "5-year vocational school" have chosen the correct option "50 million atoms" with a relative frequency of just over 85%, whereas the participants of the other types of school have chosen this option with a relative frequency of approximately 80%. The participants of the factor level "others" show a higher frequency than the graduates of the "5-year vocational school" at the options "100 million atoms", "0 atoms" and, "100 million OR 0 atoms". The graduates of the "5-year vocational school" chose the option "65,5 atoms" with a higher relative frequency than the graduates of the other school types. Nevertheless, it is clear that most of the participants of both school types have chosen the correct option.

The questionnaire also asked how many of the iodine-131 atoms are left after two half-lives. The results are presented in Figure 46 below.

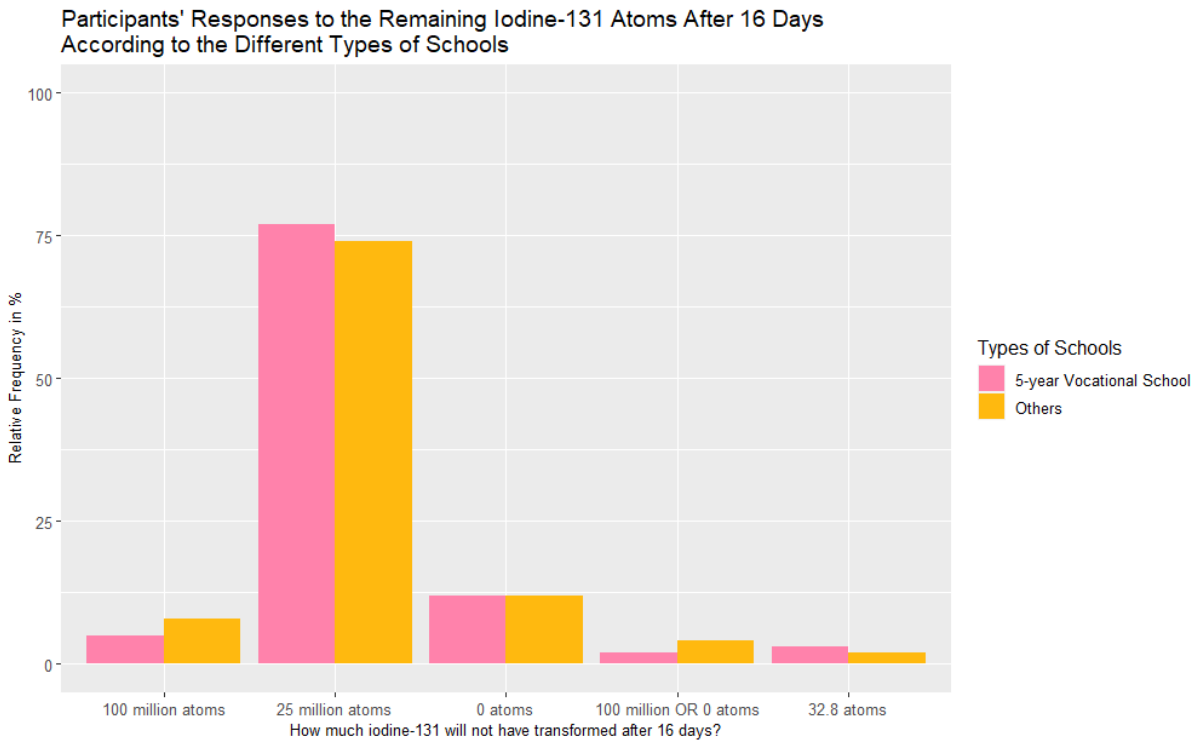


*Figure 46: Participants' Responses to the Remaining Iodine-131 Atoms After 16 Days Part 1, Source: Own Composition*

When comparing Figure 45 and Figure 46, the relative frequency for the correct option “25 million atoms” decreased by about 10% for both factor levels. Hence, from those who gave a correct answer at Figure 45, approximately 10% do not know how many Iodine-131 atoms are left after two half-lives. While some participants gave the correct answer of how many atoms are left after one half-life, some could not conclude how many are left after two half-lives. Moreover, the bars indicating the selection of the option “0 atoms” increased for both factor levels. In comparison to Figure 45, the bars at the option “100 million atoms” in Figure 46 increased for the factor level of the participants of both factor levels. This may be the result of a small number of respondents misinterpreting the question as asking “how many Iodine-131 atoms have fissioned” instead of “how many Iodine-131 atoms remain”. The distribution of the answers after one and two half-lives "100 million OR 0 atoms" and “65,5 atoms” to "32,8 atoms" almost remained the same.

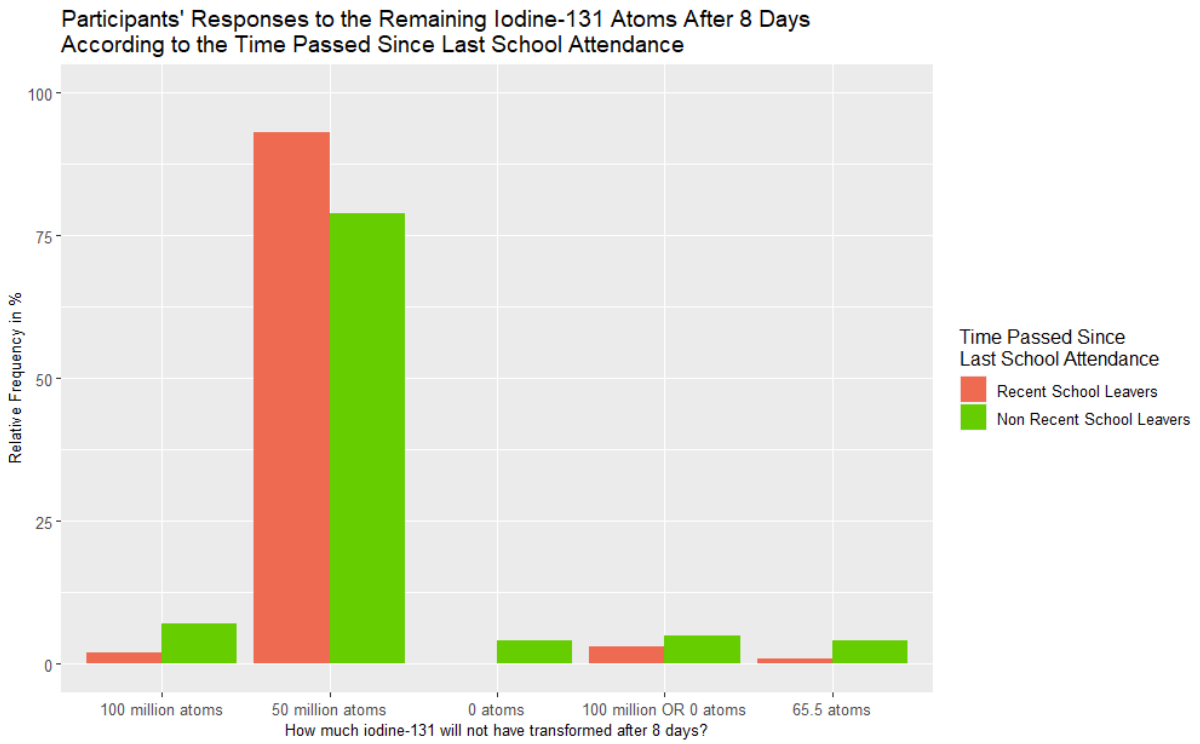


*Figure 47: Participants' Responses to the Remaining Iodine-131 Atoms After 8 Days Part 2, Source: Own Composition*

Figure 47 shows the participants' responses to the question about the remaining iodine-131 after one half-life in relation to the time passed since last school attendance. Figure 47 shows that almost all participants who are "recent school leavers" chose the correct answer "50 million atoms". They therefore show a relative frequency of approximately 90% at the correct answer. In comparison to the "recent school leavers", the "non recent school leavers" chose this correct option with a relative frequency of approximately 80%. For all other options, the "non recent school leavers" reached a higher relative frequency than the "recent school leavers". The option "0 atoms" was not chosen at all by the "recent school leavers". Approximately 10% of the "non recent school leavers" think that after one half-life there are somehow still "100 million [I-131] atoms" left.

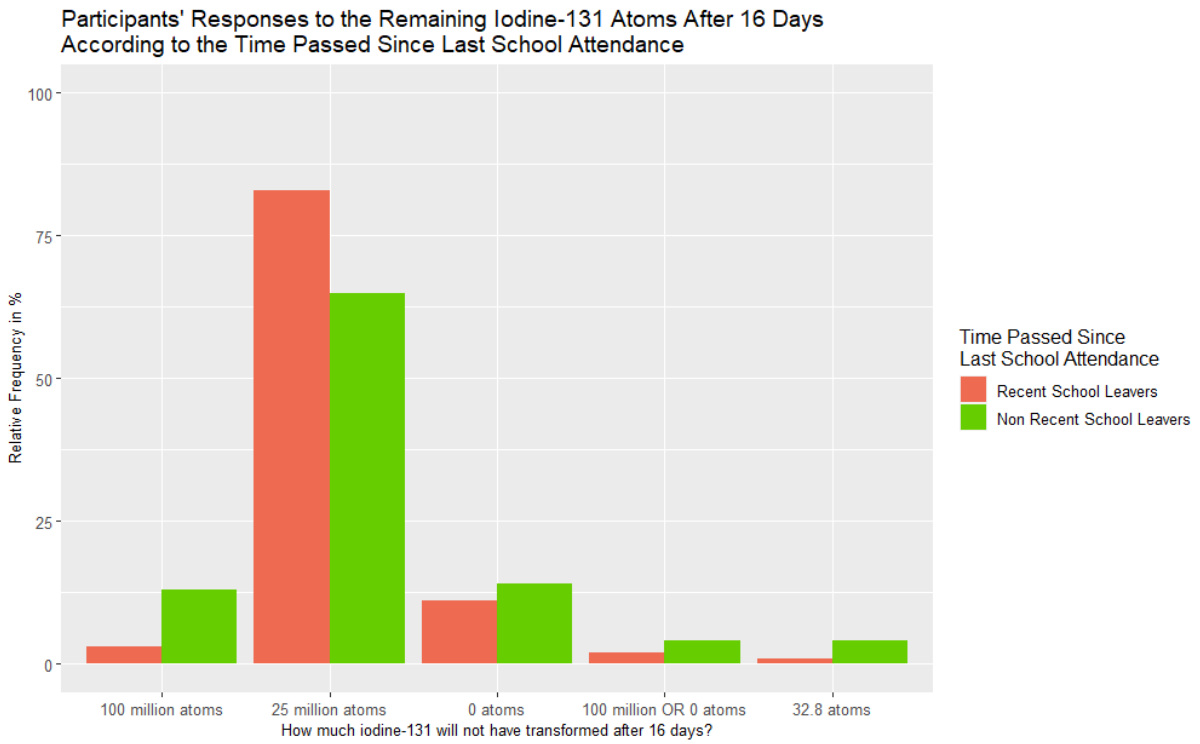


*Figure 48: Participants' Responses to the Remaining Iodine-131 Atoms After 16 Days Part 2, Source: Own Composition*

As for the relative frequency of school types from Figure 45 to Figure 46, the relative frequency of the correct answer concerning the remaining atoms after two half-lives in Figure 48 also decreases. The relative frequency of the individual factor levels, which indicated in Figure 47 that "50 million atoms" remain after one half-life, decreases at the answer of "25 million atoms" after two half-lives. The decrease can be recognized in both factor levels by a relative frequency of approximately 10% to 15%. It is particularly striking that the relative frequency for the “non recent school leavers” increased for the option “100 million atoms”. Additionally, when comparing Figure 47 and Figure 48, it is evident that approximately 10% of the “recent school leavers” think that after two half-lives "0 atoms" are left. This option was not selected by any participant of the “recent school leavers” after one half-life (Figure 47). The relative frequency at the option “100 million OR 0 atoms” increased infinitesimally for both factor levels. It seems that the relative frequencies for the option “65,6 atoms” in Figure 47 and “32,8 atoms” in Figure 48 remain the same for “recent school leavers” and “non recent school leavers”.

## Question 9 - Justification of the Iodine-131 Example

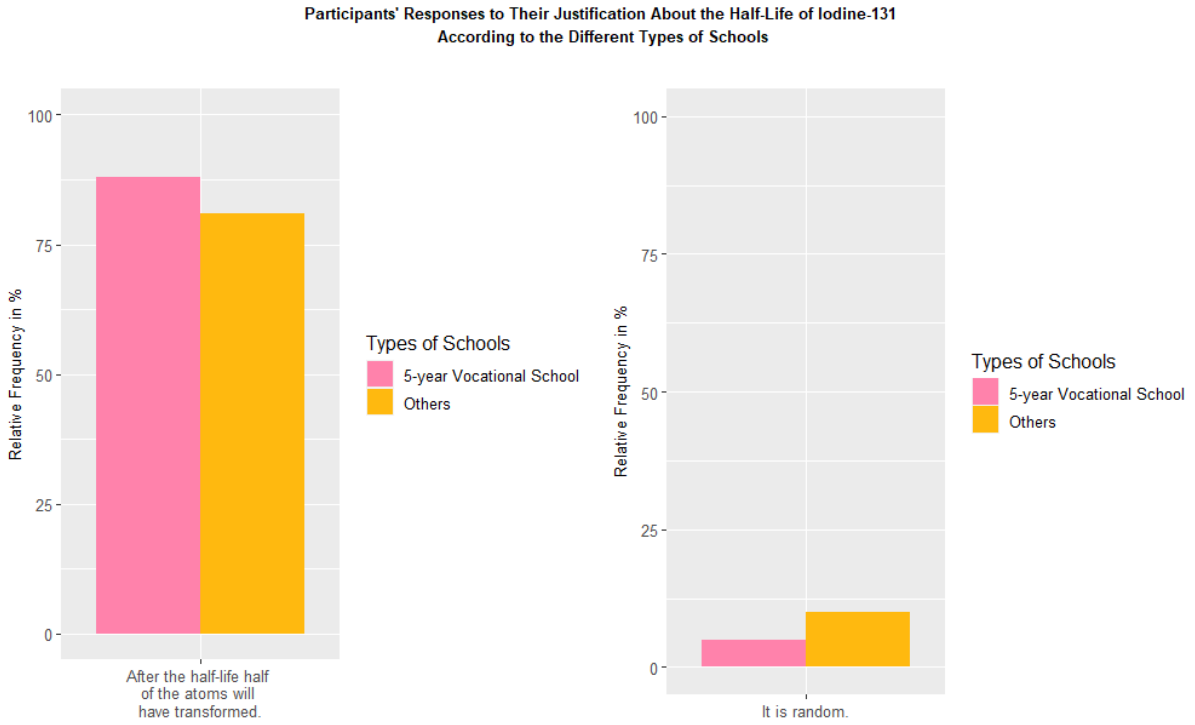


*Figure 49: Participants' Responses to Their Justification About the Half-Life of Iodine-131 Part 1, Source: Own Composition*

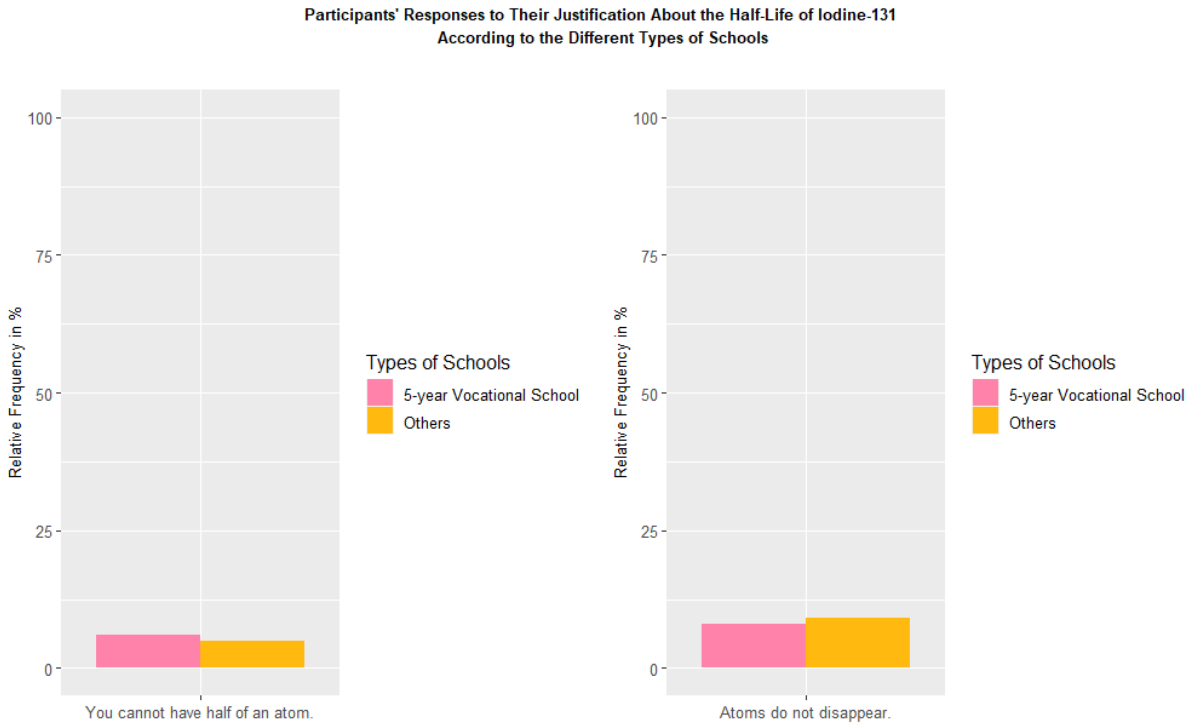


*Figure 50: Participants' Responses to Their Justification About the Half-Life of Iodine-131 Part 2, Source: Own Composition*

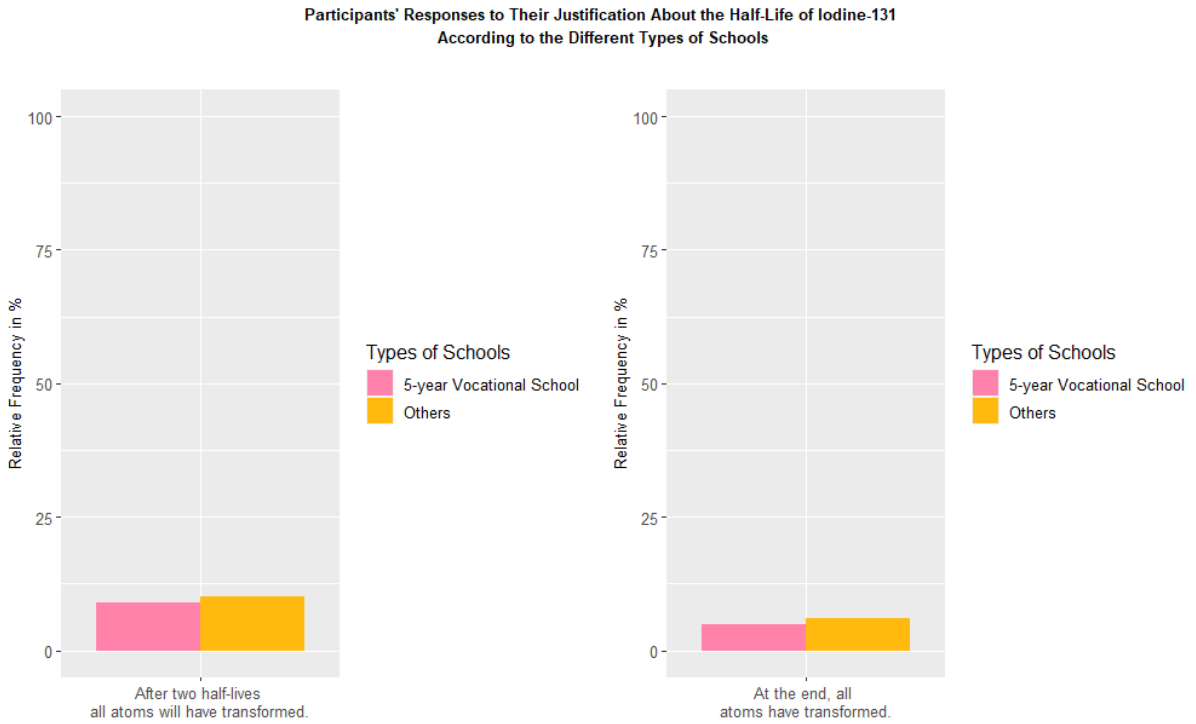


*Figure 51: Participants' Responses to Their Justification About the Half-Life of Iodine-131 Part 3, Source: Own Composition*

Figure 49, Figure 50 and Figure 51 show the participants' responses to their justification concerning Question 8. Approximately 80% of both school factor levels indicated in their answers to Question 8 that, "After the half-life half of the atoms will have transformed". Hence, most of the participants of both school types justified their answers from Question 8 appropriately. All other options were chosen by both factor levels with a relative frequency between approximately 5% and 11% each.

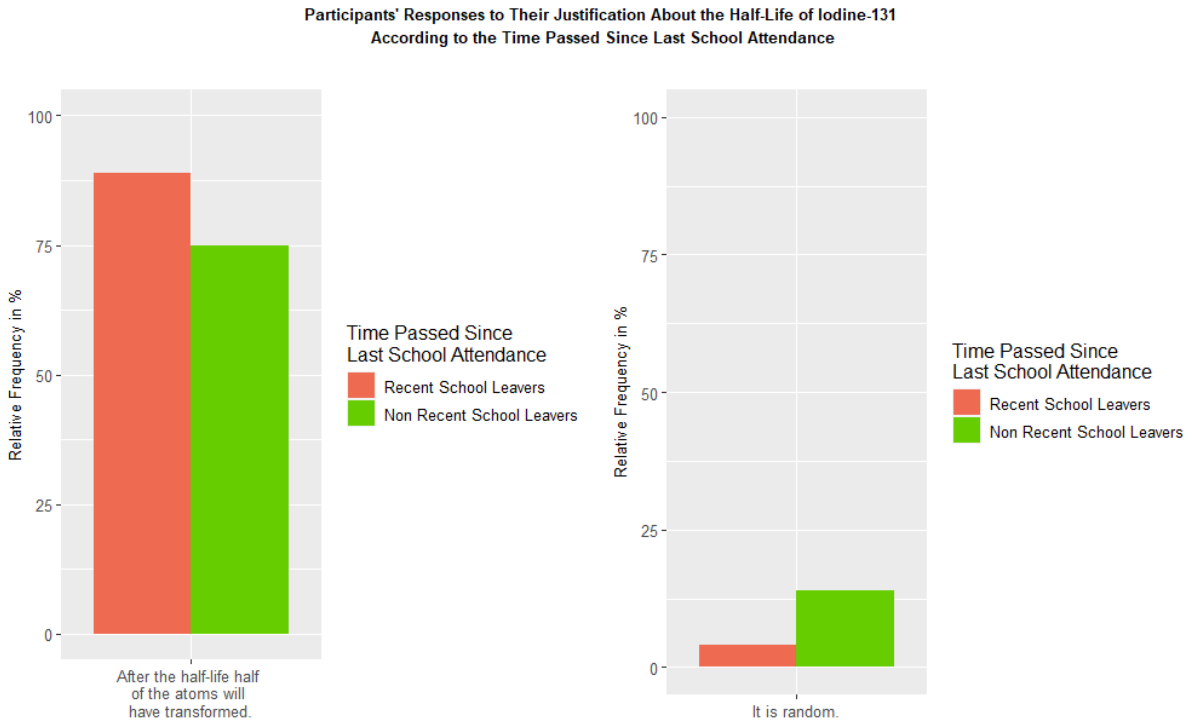


*Figure 52: Participants' Responses to Their Justification About the Half-Life of Iodine-131 Part 4, Source: Own Composition*

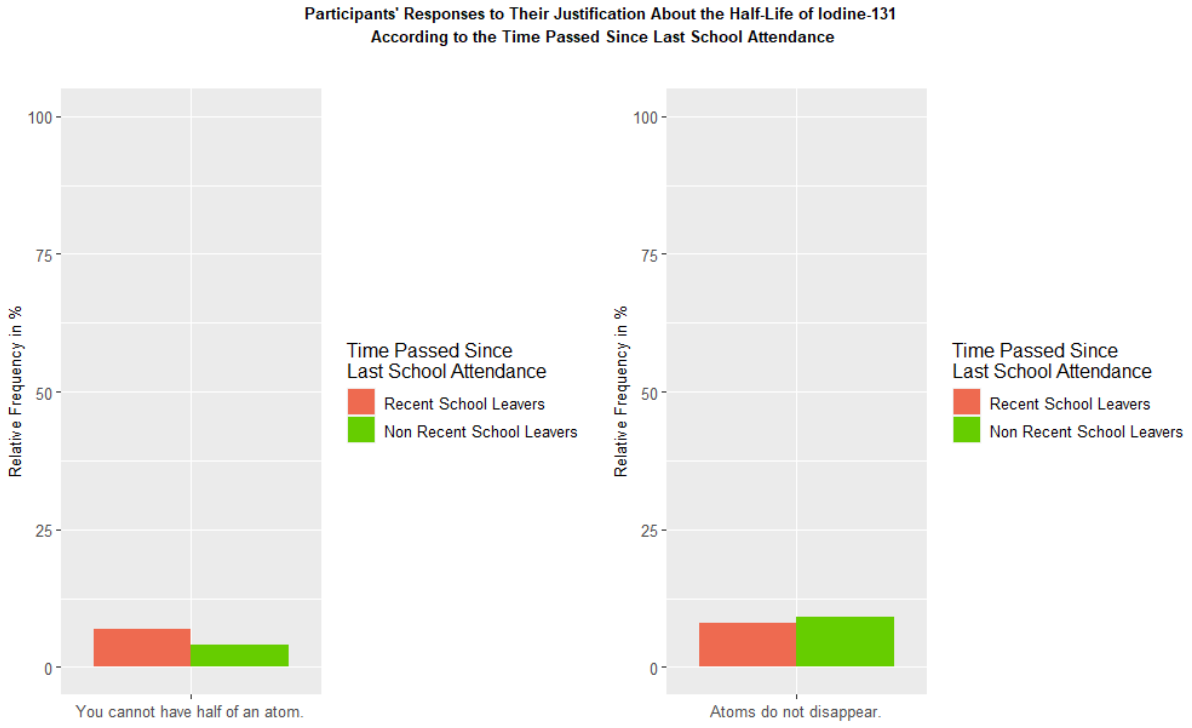


*Figure 53: Participants' Responses to Their Justification About the Half-Life of Iodine-131 Part 5, Source: Own Composition*

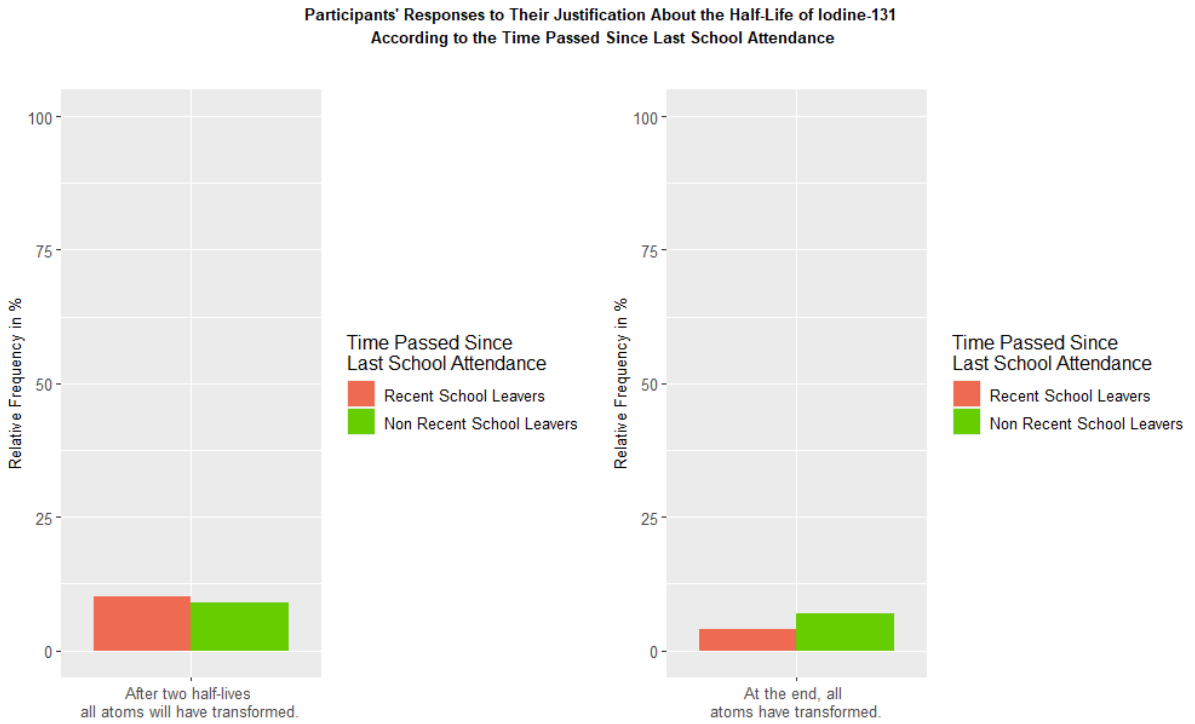


*Figure 54: Participants' Responses to Their Justification About the Half-Life of Iodine-131 Part 6, Source: Own Composition*

Figure 52, Figure 53 and Figure 54 present the justifications given by the participants to their answers to Question 8, in relation to the time passed since last school attendance. The correct option that "After the half-life half of the atoms will have transformed" was chosen by a relative frequency of approximately 85% by the "recent school leavers" and 75% by the "non recent school leavers". The difference between the relative frequency of the two factor levels is greater in the category of "time passed since last school attendance" (Figure 52) than in the factor of "types of schools" (Figure 49). With a relative frequency of approximately 15%, "non recent school leavers" think that the number of iodine-131 atoms which remain after one half-life "(…) is random". The "recent school leavers" considered this option correct with a relative frequency of approximately 5%. All other options were chosen from both factor levels with a relative frequency of approximately 5% to 13% each.

## Question 10 - The Sealed Closet

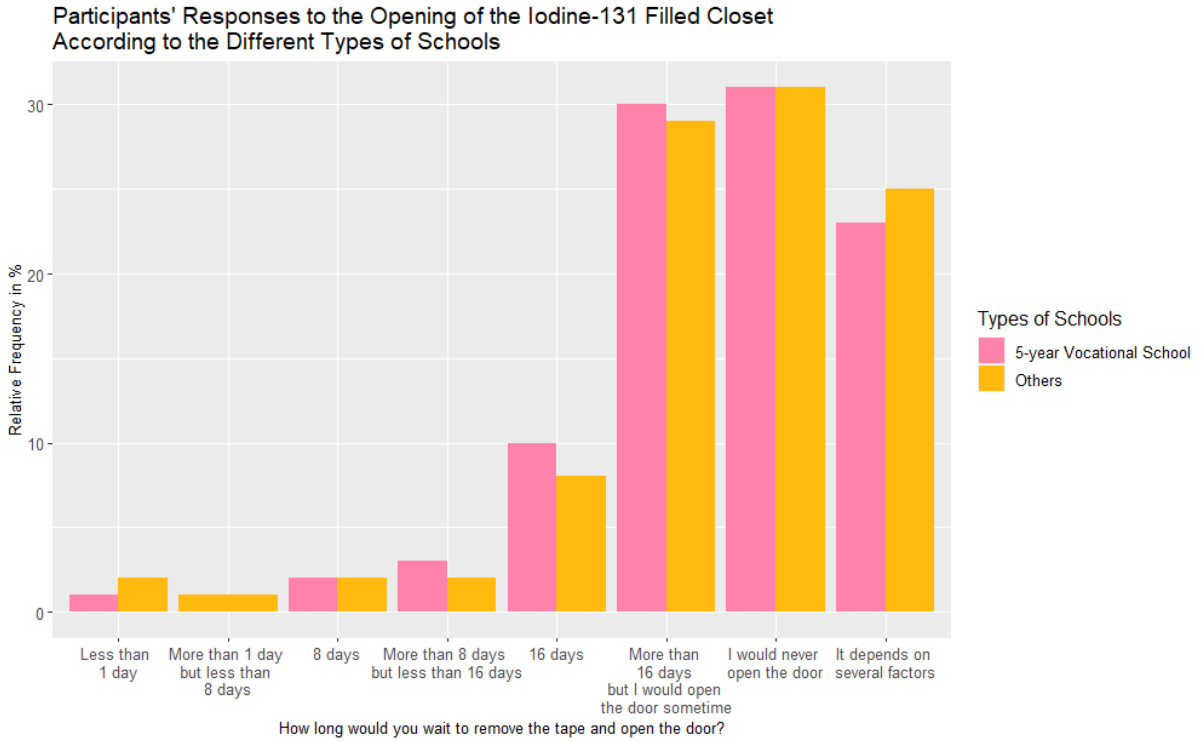


*Figure 55: Participants' Responses to the Opening of the Iodine-131 Filled Closet Part 1, Source: Own Composition*

In Figure 55 the participants' answers to when to open the iodine-131 filled closet are presented according to the types of schools. The three options "more than 16 days but I would open the door sometime", "I would never open the door" and "it depends on several factors" were all popular selections. The distribution between these three options does not even differ within a relative frequency of 10% for both factor levels.

The option with the next highest relative frequency is "16 days". 10% of the "5-year vocational school" graduates think that they would open the closet after "16 days". The participants of the other schools considered this option to be correct with a relative frequency of 8%. The remaining options are only chosen by a relative frequency of less than or equal to 3%, whereas the option "More than 1 day but less than 8 days" was only chosen by the participants of the factor level "others".

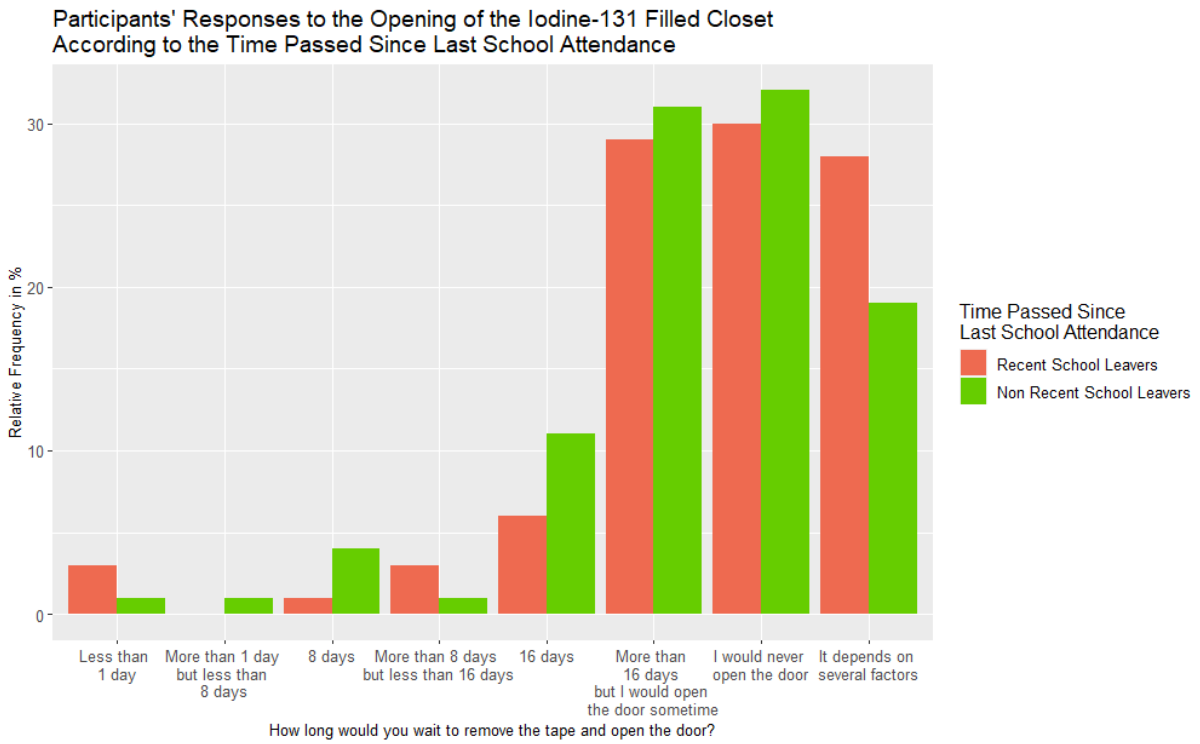


*Figure 56: Participants' Responses to the Opening of the Iodine-131 Filled Closet Part 2, Source: Own Composition*

The participants' answers to when to open the iodine-131 filled closet according to the time passed since last school attendance are seen in Figure 56. As in the previous Figure 55, the largest relative frequencies are distributed here between three responses. It is particularly striking that the "non recent school leavers" have a smaller relative frequency than the "recent school leavers" for one of the correct answers "it depends on several factors" (approximately 10%). The "non recent school leavers" have a relative frequency of 11% for the option "16 days", whereas only 6% of the "recent school leavers" considered this option correct. All remaining options are chosen by both factor levels with a relative frequency of less than 5% each.

## Question 11 - Justification of the Sealed Closet

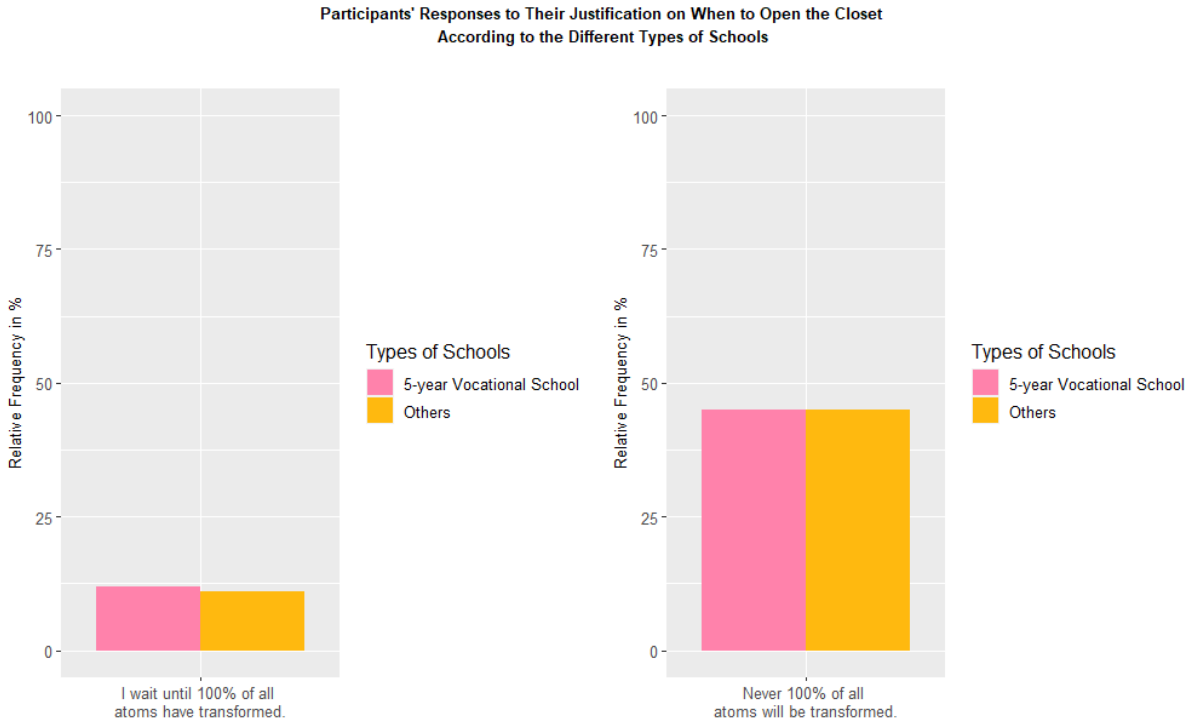


*Figure 57: Participants' Responses to Their Justification on When to Open the Closet Part 1, Source: Own Composition*

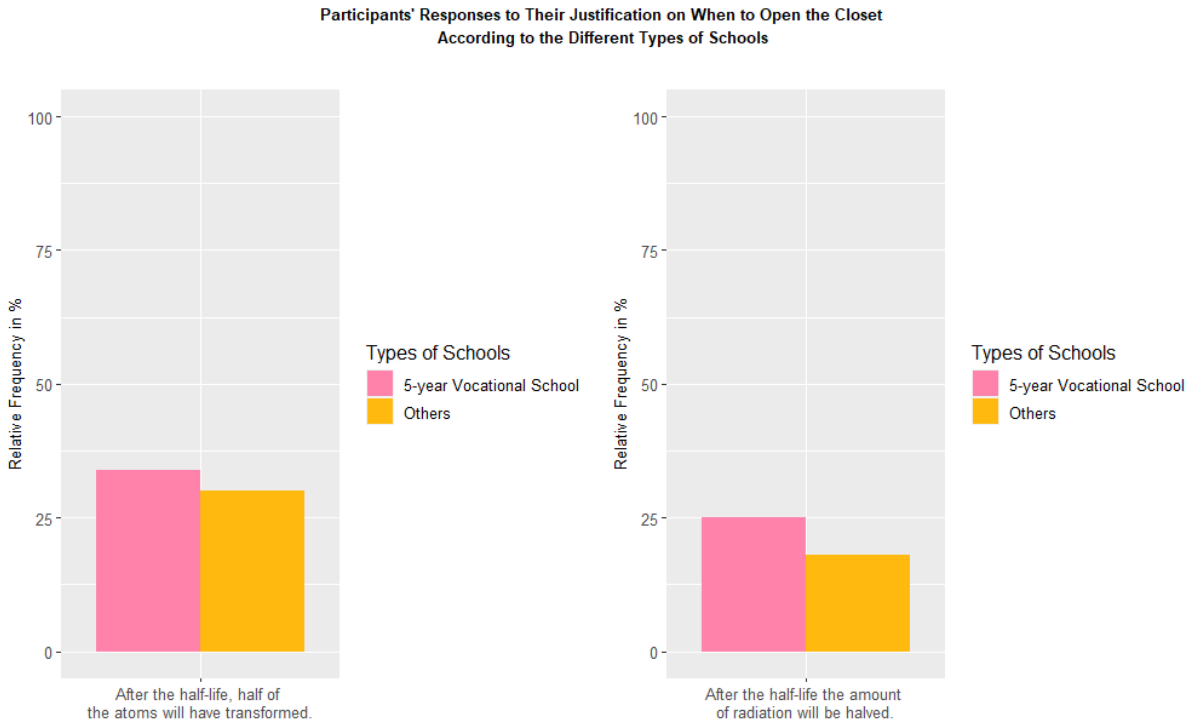


*Figure 58: Participants' Responses to Their Justification on When to Open the Closet Part 2, Source: Own Composition*

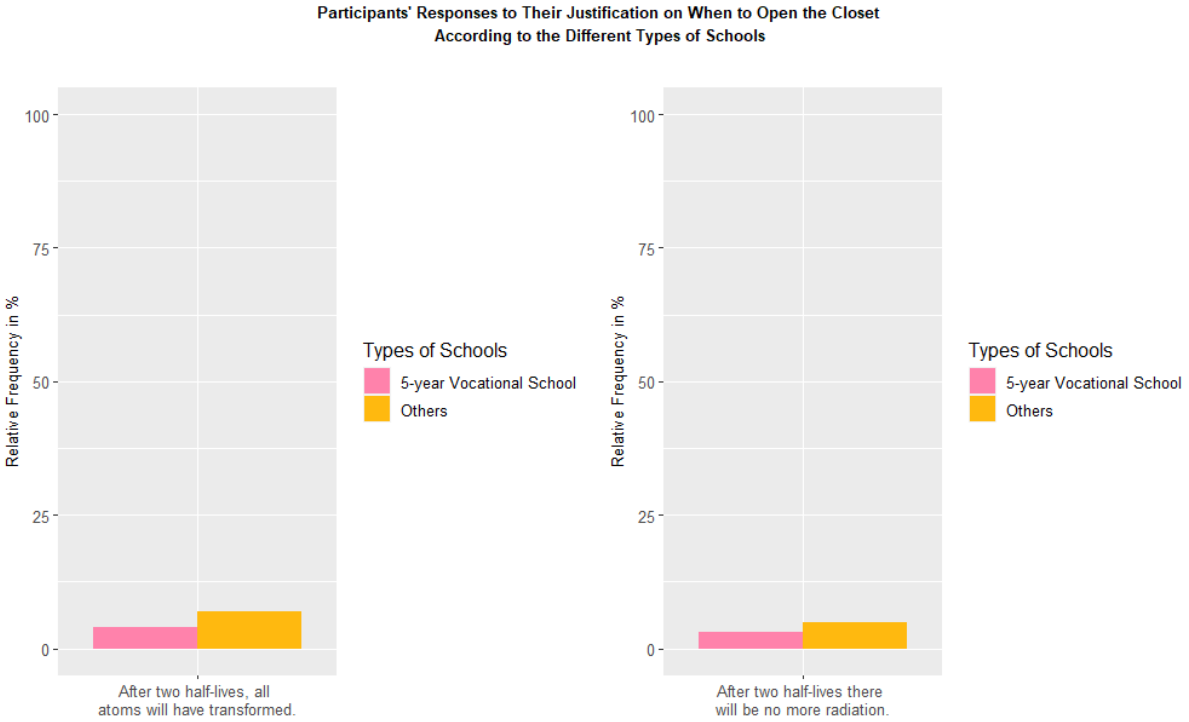


*Figure 59: Participants' Responses to Their Justification on When to Open the Closet Part 3, Source: Own Composition*

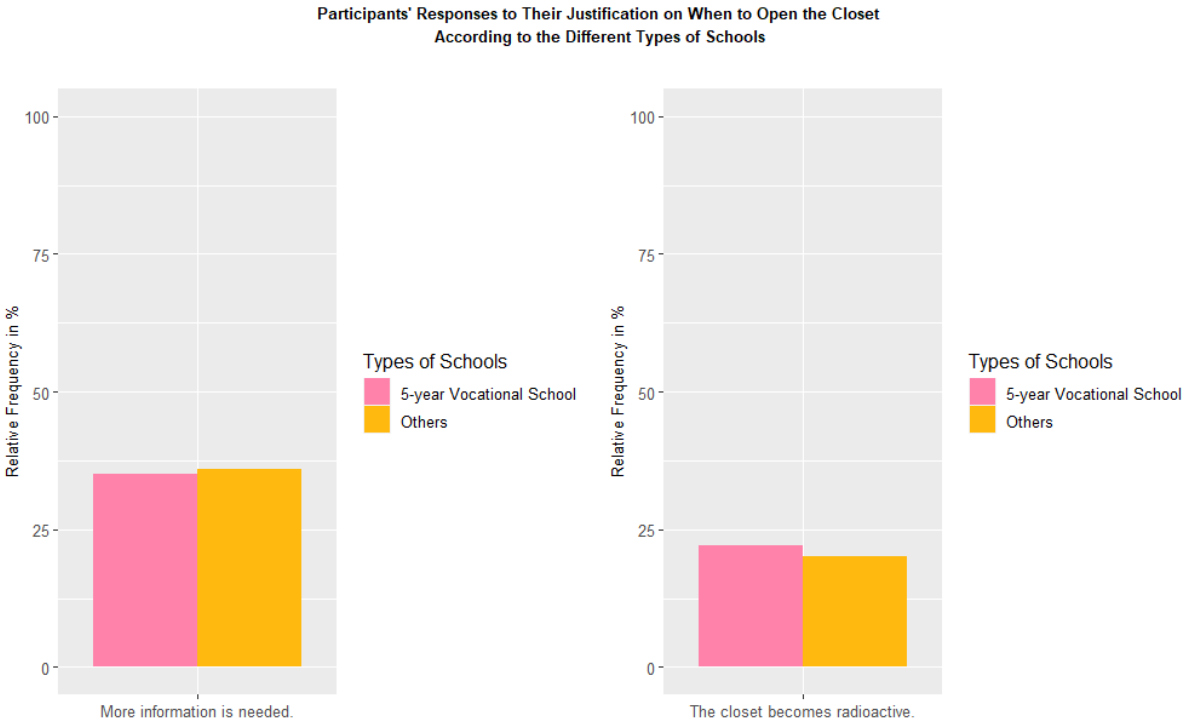


*Figure 60: Participants' Responses to Their Justification on When to Open the Closet Part 4, Source: Own Composition*

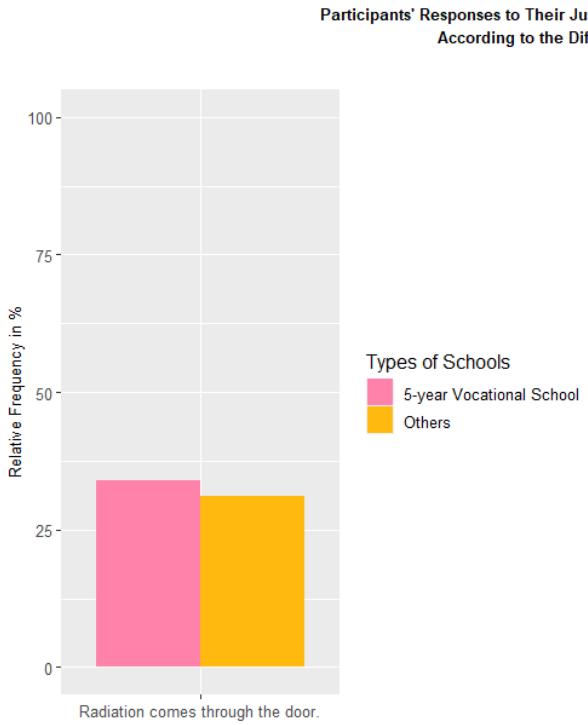


*Figure 61: Participants' Responses to Their Justification on When to Open the Closet Part 5, Source: Own Composition*

Figure 57, Figure 58, Figure 59, Figure 60 and Figure 61 show the participants' justification on their previous answers when to open the closet according to the types of schools. Based on the distribution among the different options, the members of both factor levels were not sure about their justification in Question 10. None of the given options reached the 50% mark. The most chosen option is "Never 100% of all atoms will be transformed", which was considered correct by both factor levels with a relative frequency of approximately 40%. The options "After the half-life, half of the atoms will have transformed", "More Information is needed" and "Radiation comes through the door" were chosen by the participants of both factor levels with a relative frequency of 25% to 40%. The remaining options were chosen by a relative frequency of less than or equal 25% by both factor levels. The differences between the options chosen by the "5-year vocational school" and "other" factor levels are very small.

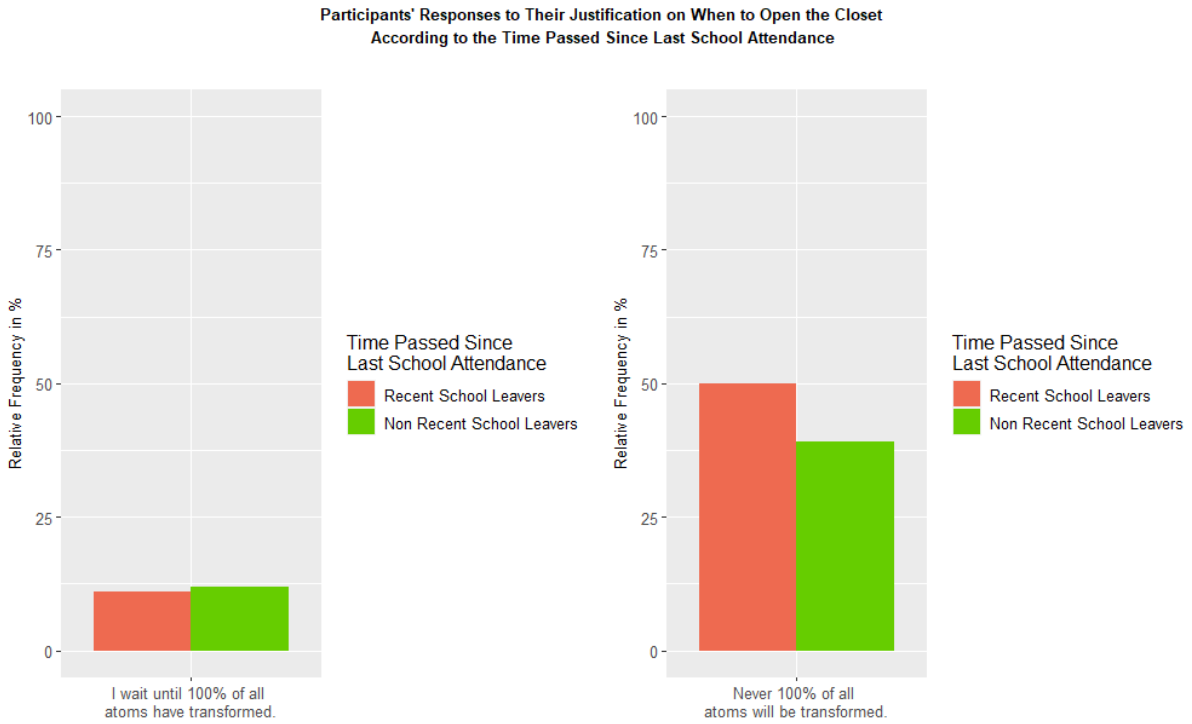


*Figure 62: Participants' Responses to Their Justification on When to Open the Closet Part 6, Source: Own Composition*

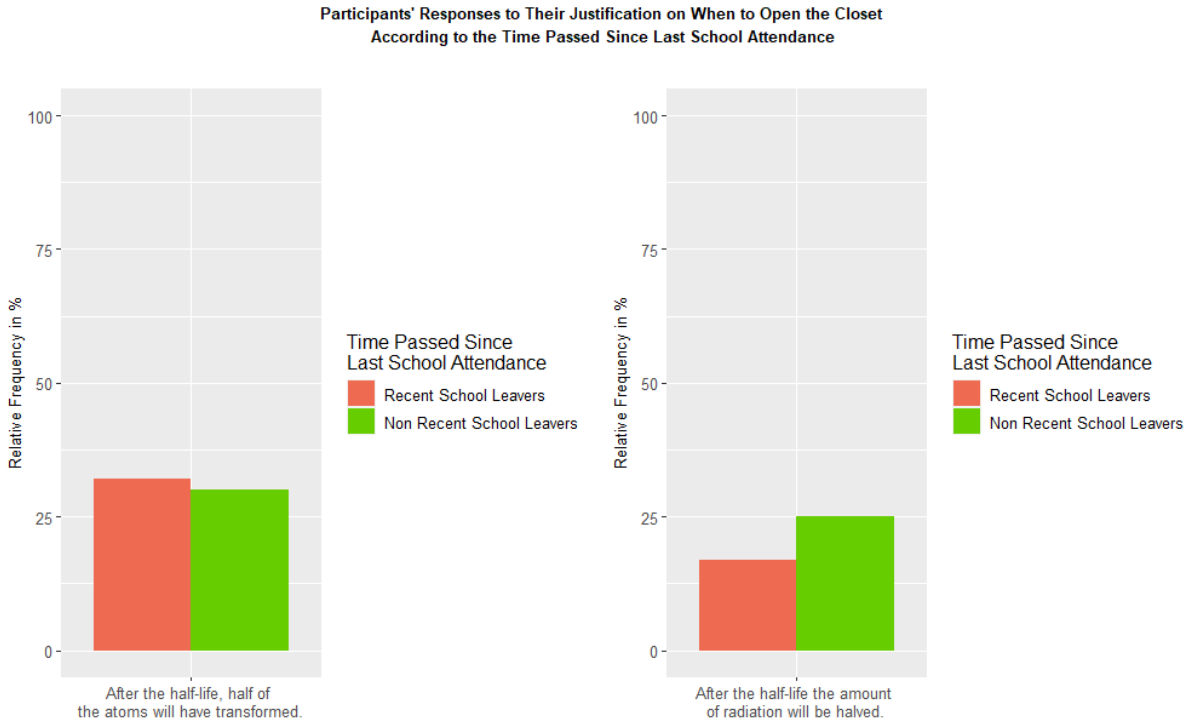


*Figure 63: Participants' Responses to Their Justification on When to Open the Closet Part 7, Source: Own Composition*

*Figure 64: Participants' Responses to Their Justification on When to Open the Closet Part 8, Source: Own Composition*

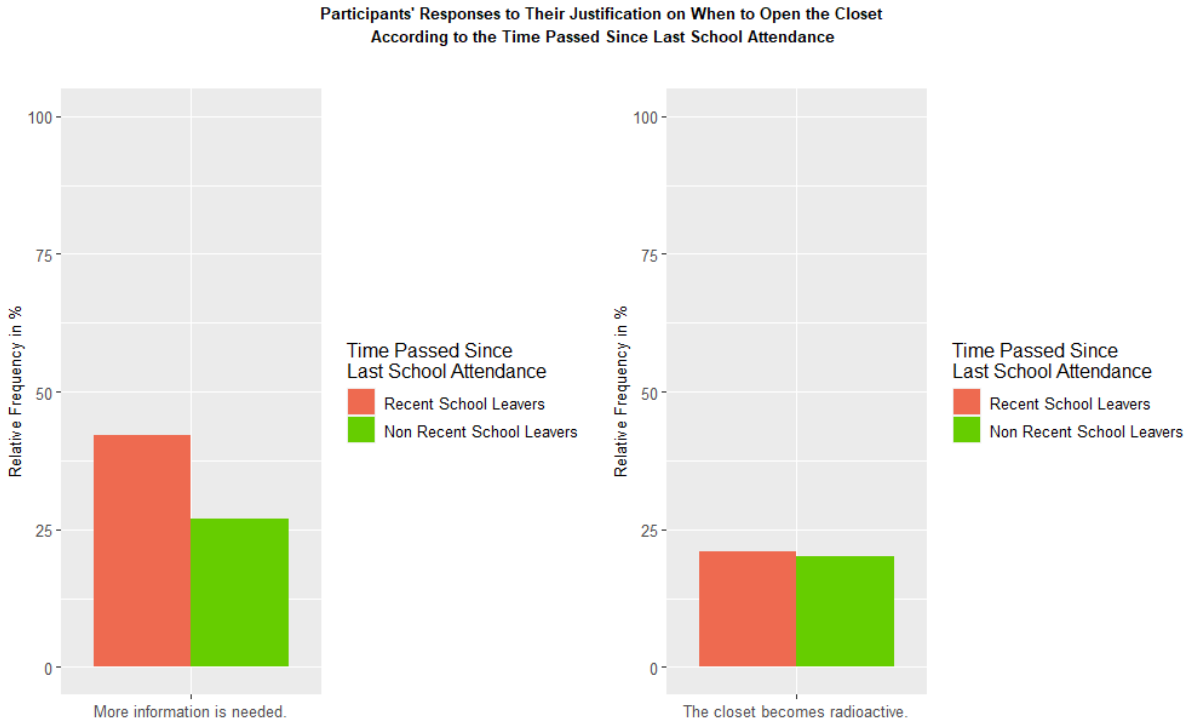


*Figure 65: Participants' Responses to Their Justification on When to Open the Closet Part 9, Source: Own Composition*

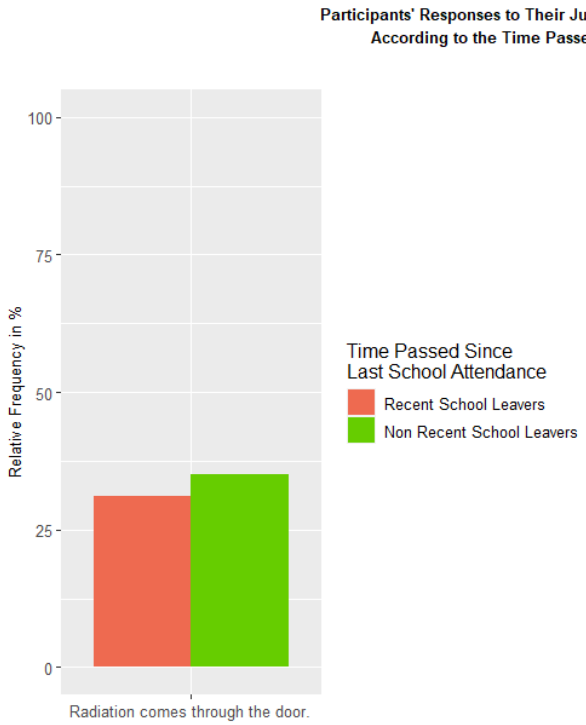


*Figure 66: Participants' Responses to Their Justification on When to Open the Closet Part 10, Source: Own Composition*

Figure 62, Figure 63, Figure 64, Figure 65, and Figure 66 show the participants' justification on their previous answers to when to open the closet according to the time passed since last school attendance. The most chosen option by both factor levels is that "Never 100% of all atoms will be transformed". The "recent school leavers" considered this option to be correct with a relative frequency of 50%, whereas the "non recent school leavers" reached a relative frequency of approximately 35% for this option. Especially in Figure 47, none of the "recent school leavers" has chosen the option that after one half-life there will be "0 atoms", which led them to the previously mentioned option in Question 11. The second most chosen option with a relative frequency of 40% by the "recent school leavers" is the correct answer that "More information is needed". The difference between "recent school leavers" and the "non recent school leavers" for this correct option is very high. The relative frequency of the factor level "non recent school leavers" is just over 25% for this option. The second most chosen option of the "non recent school leavers" is "Radiation comes through the door" which was chosen with a relative frequency of approximately 40%. "Recent school leavers" chose this option with a relative frequency of 30%. "After the half-life, half of the atoms will have transformed" was chosen by a relative frequency of approximately 30% by both factor levels. All

other options were chosen by both factor levels by a relative frequency of less than or equal to 25%.

## Question 12 - Risk Management

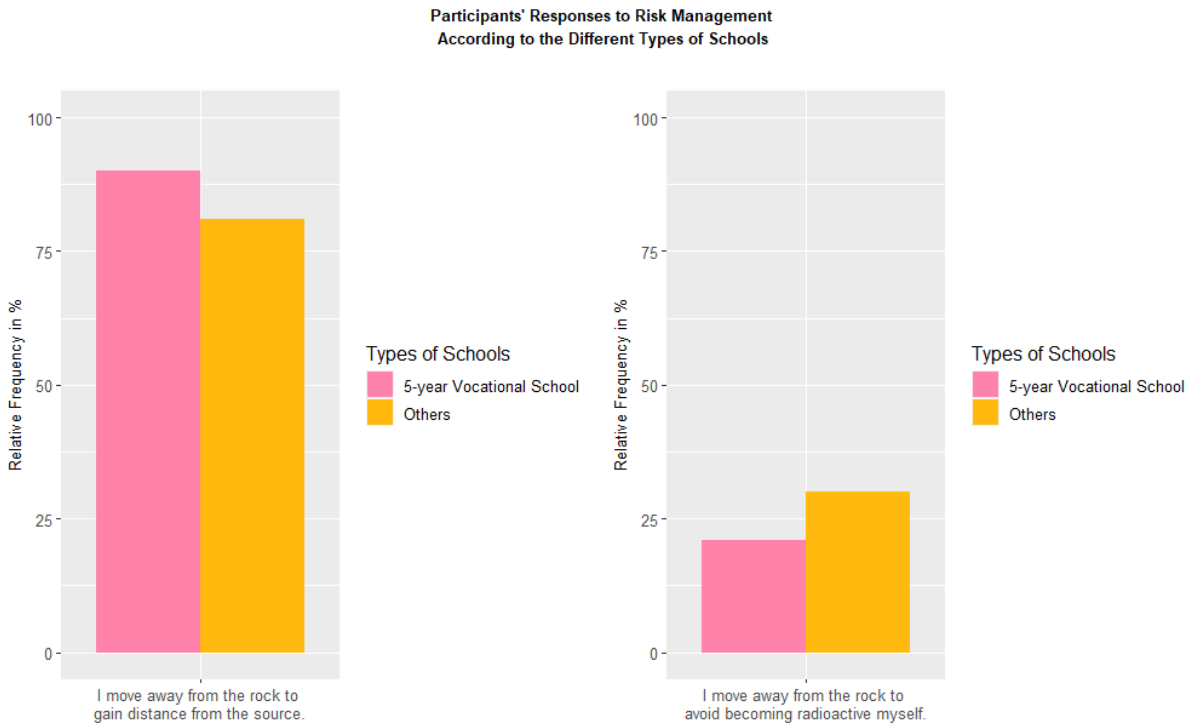


*Figure 67: Participants' Responses to Risk Management Part 1, Source: Own Composition*

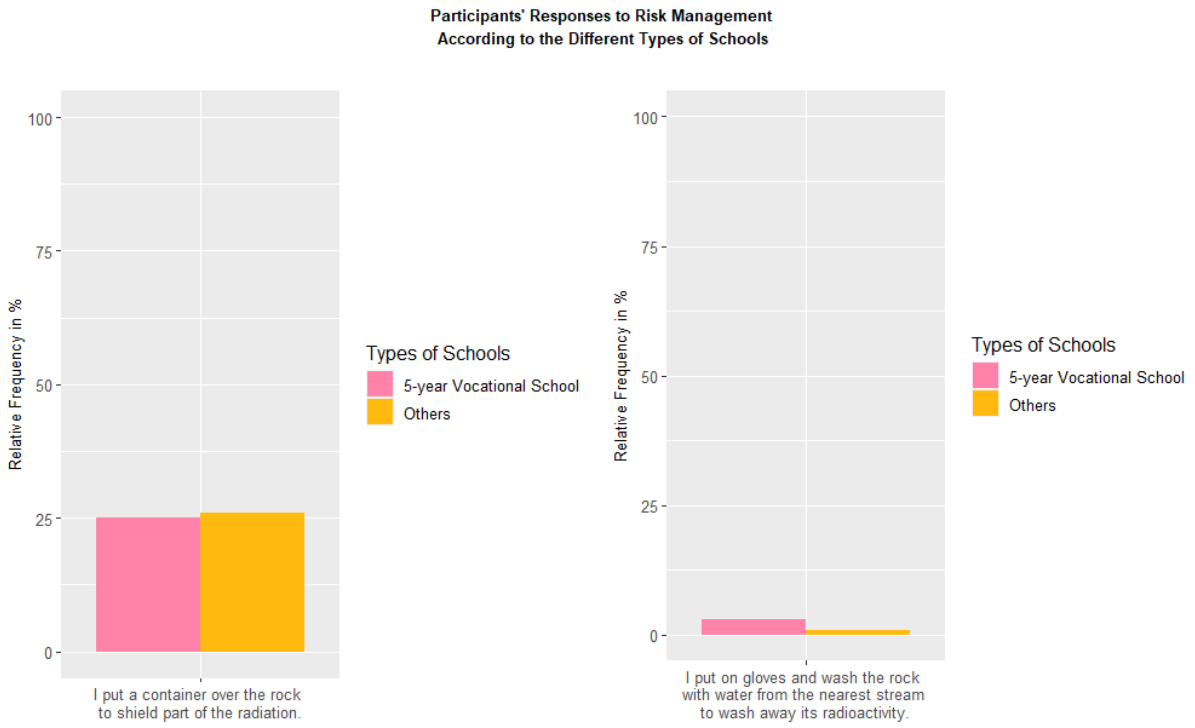


*Figure 68: Participants' Responses to Risk Management Part 2, Source: Own Composition*

Figure 67 and Figure 68 show what the participants would do after they find a radioactive rock in the Black Forest in Germany according to the different types of schools. More than 75% of both factor levels indicated that they would "gain distance from the source". Just over 25% of the factor level “others” would “move away from the rock to avoid becoming radioactive” themselves. The “5-year vocational school” participants considered this option to be correct with a relative frequency of just under 25%. The option to “put a container over the rock to shield part of the radiation” shows a relative frequency of approximately 25%. Almost none of the participants of both school types would “wash the rock (…) to wash away its radioactivity”.

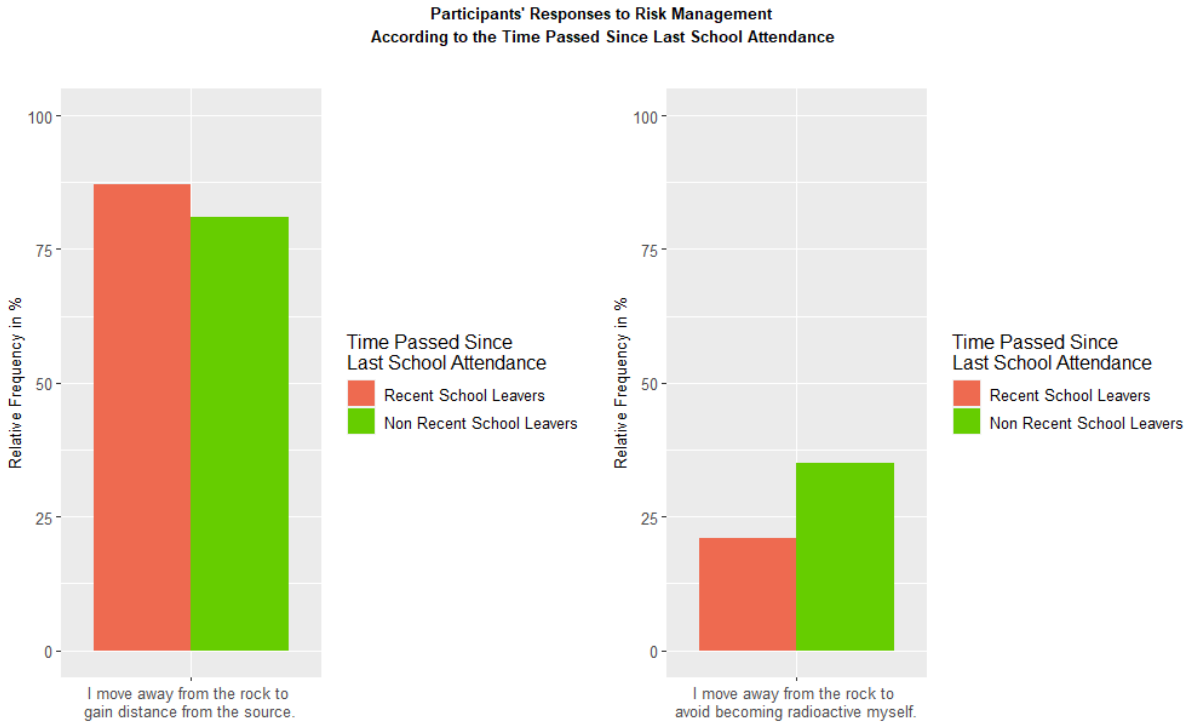


*Figure 69: Participants' Responses to Risk Management Part 3, Source: Own Composition*

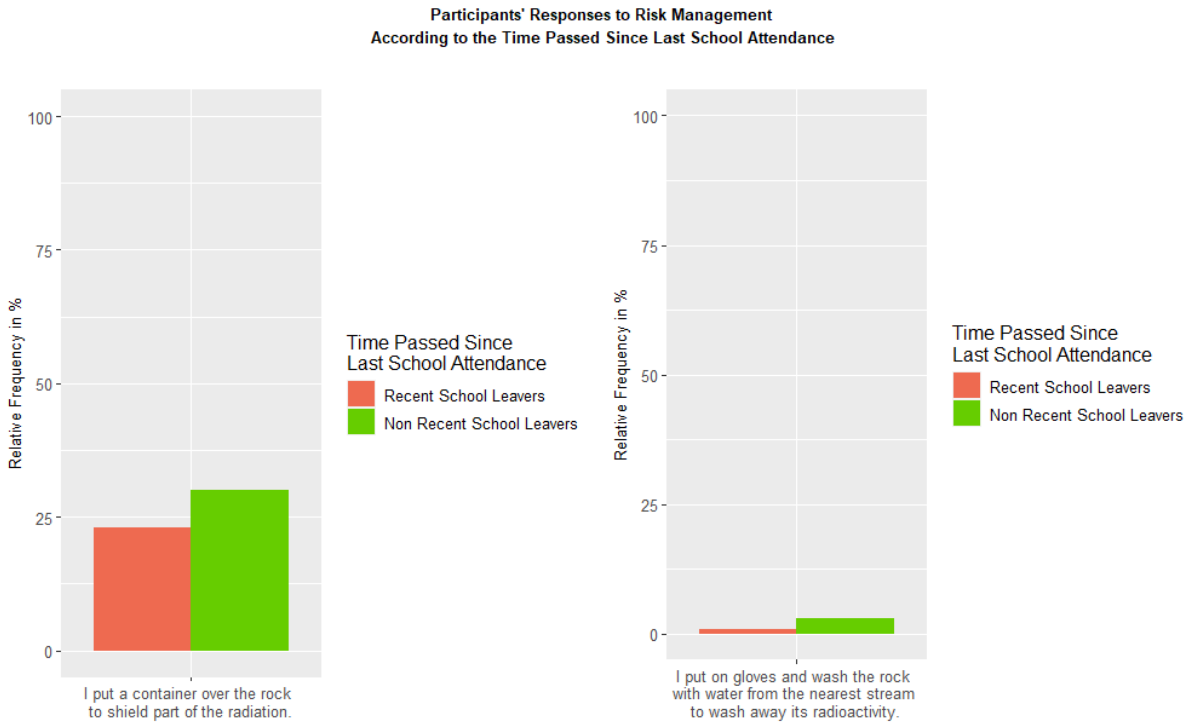


*Figure 70: Participants' Responses to Risk Management Part 4, Source: Own Composition*

Figure 69 and Figure 70 show the participants' responses to what they would do if they found a radioactive rock in the Black Forest in Germany, depending on the time since graduation. All participants, regardless of the classification of recency of leaving school, would "move away from the rock to gain distance from the source". Both factor levels have a relative frequency of over 75% but the relative frequency of the "recent school leavers" is higher. With a relative frequency of approximately 30% for each option, "non recent school leavers" also consider the two options "I move away from the rock to avoid becoming radioactive" and "I put a container over the rock to shield part of the radiation" to be correct. The agreement of "recent school leavers" for these two options was under 25% each. The option chosen least often was "I put on gloves and wash the rock with water from the nearest stream to wash away its radioactivity".

## Question 13 - Irradiating a Kiwi

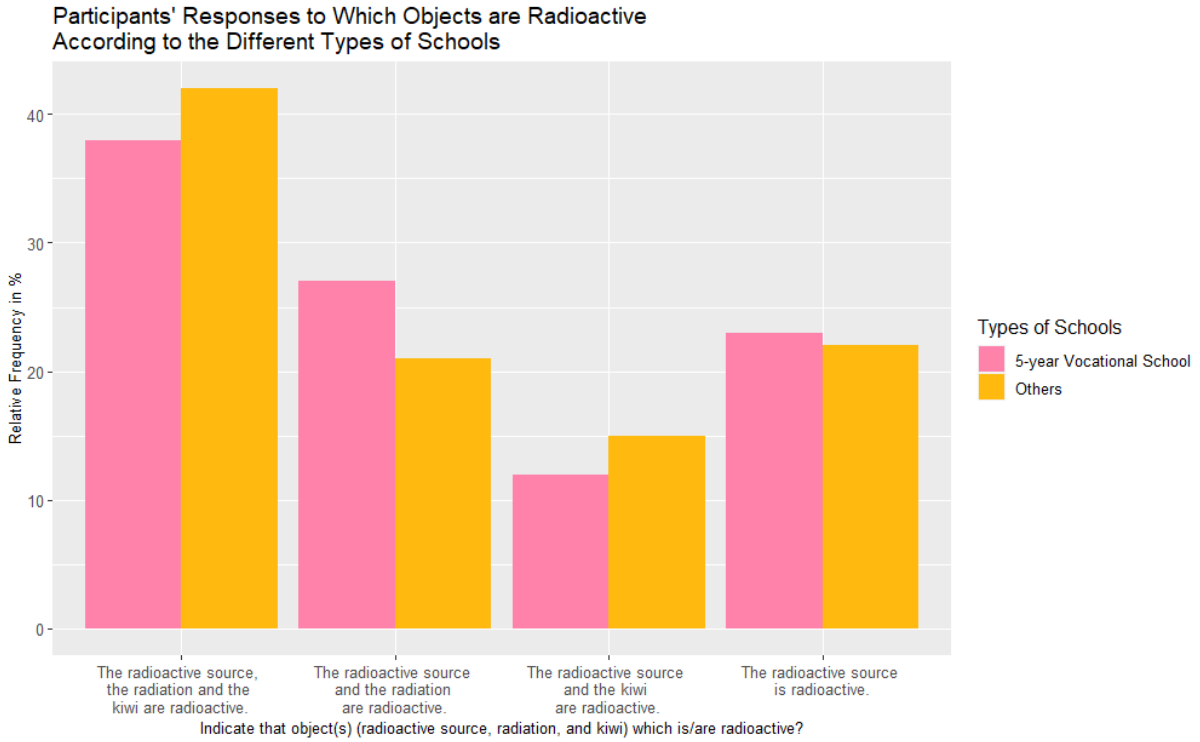


*Figure 71: Participants' Responses to Which Objects are Radioactive Part 1, Source: Own Composition*

Figure 71 shows the participants' responses to which objects they believe to be radioactive when irradiating a kiwi with a radioactive source in relation to the different types of schools. The majority of the participants of both school types have decided that "the radioactive source, the radiation and the kiwi are radioactive". Approximately 26% of the "5-year vocational school" graduates and 21% of the other types of school participants chose that "the radioactive source and the radiation are radioactive". The option that was chosen least often by both factor levels was that "the radioactive source and the kiwi are radioactive". Solely less than or equal to 15% considered this option to be correct. The correct option that "the radioactive source is radioactive", was chosen by the graduates of the "5-year vocational school" with a relative frequency of 23% and the other school types reached a relative frequency of 22% for this option.

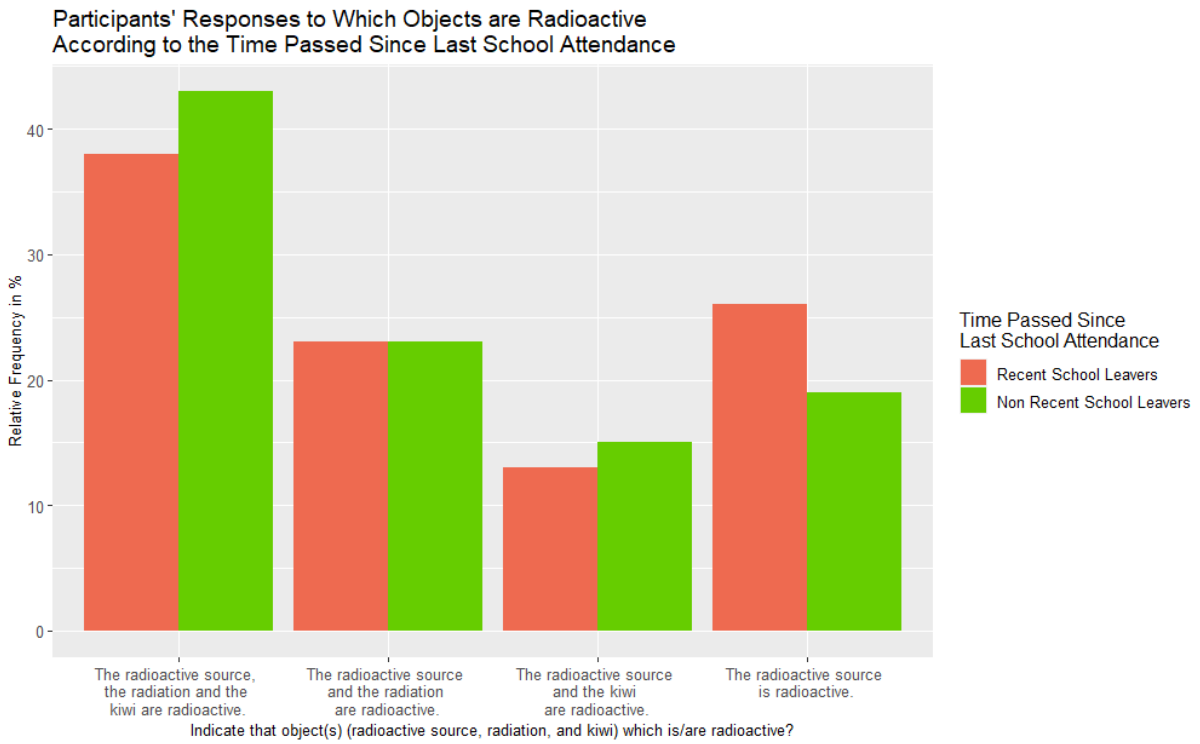


*Figure 72: Participants' Responses to Which Objects are Radioactive Part 2, Source: Own Composition*

Figure 72 shows the participants' responses to which objects are radioactive while irradiating a kiwi with a radioactive source in relation to the time passed since last school attendance. As one can see from the y-axis in Figure 71, it only reaches approximately 45% too. From this, one can see that almost none of the participants within the individual factor levels were sure in their answers.

With a relative frequency of more than 40%, the "non recent school leavers" have chosen at Question 13 that "the radioactive source, the radiation and the kiwi are radioactive". This option was also chosen by a comparatively high relative frequency of the "recent school leavers", namely 38%. The option "the radioactive source and the radiation are radioactive" was chosen by the participants of both factor levels with a relative frequency of 23%. "The radioactive source and the kiwi are radioactive" is the option which was chosen the least often. This option only reached a relative frequency of less than or equal to 15%.

The correct option that only "the radioactive source is radioactive" was chosen by the "recent school leavers" with a relative frequency of 26% and from the "non recent school leavers" with a relative frequency of 19%. This is not a very high percentage considering that this is the correct answer.

Question 14 - Removing the Radioactive Source

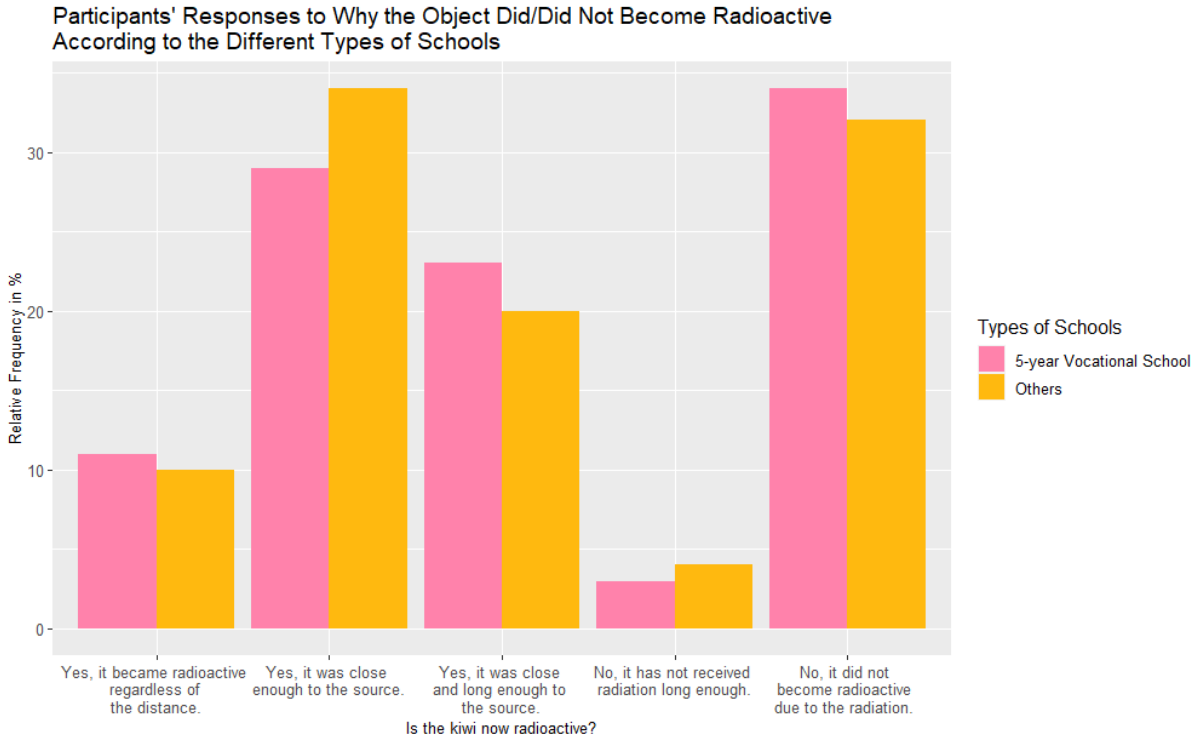


*Figure 73: Participants' Responses to Why the Object Did/Did Not Become Radioactive Part 1, Source: Own Composition*

Figure 73 presents the participants' responses as to why the kiwi did or did not become radioactive in relation to the types of schools. Comparing Figure 71 and Figure 73, neither of the factor levels shows a consistency in their answers. 50% of the "5-year vocational school" graduates said in Question 13 that the kiwi is not radioactive. After removing the source, only 37% of the participants of this school type still ticked that the kiwi did not become radioactive. The factor level "others" does not have a consistency in their answer either. While 57% of them state that the kiwi is not radioactive in Question 13, only 36% of them believe that the kiwi did not become radioactive in Question 14.

The most selected option by the factor level "others" was that the kiwi "was close enough to the source" and therefore, it became radioactive. 34% of the graduates of the factor level "others" have chosen this option. The "5-year vocational school" graduates chose this option with a relative frequency of 29%. The option "Yes, it was close and long enough to the source" was chosen by participants of the "5-year vocational school" with a relative frequency of 23% and by participants of the other school types by a relative frequency of 20%. The two remaining options "Yes, it became radioactive regardless of the distance" and "No, it has not received radiation

long enough” were chosen least often by both factor levels with a relative frequency of less than or equal to 11% each.

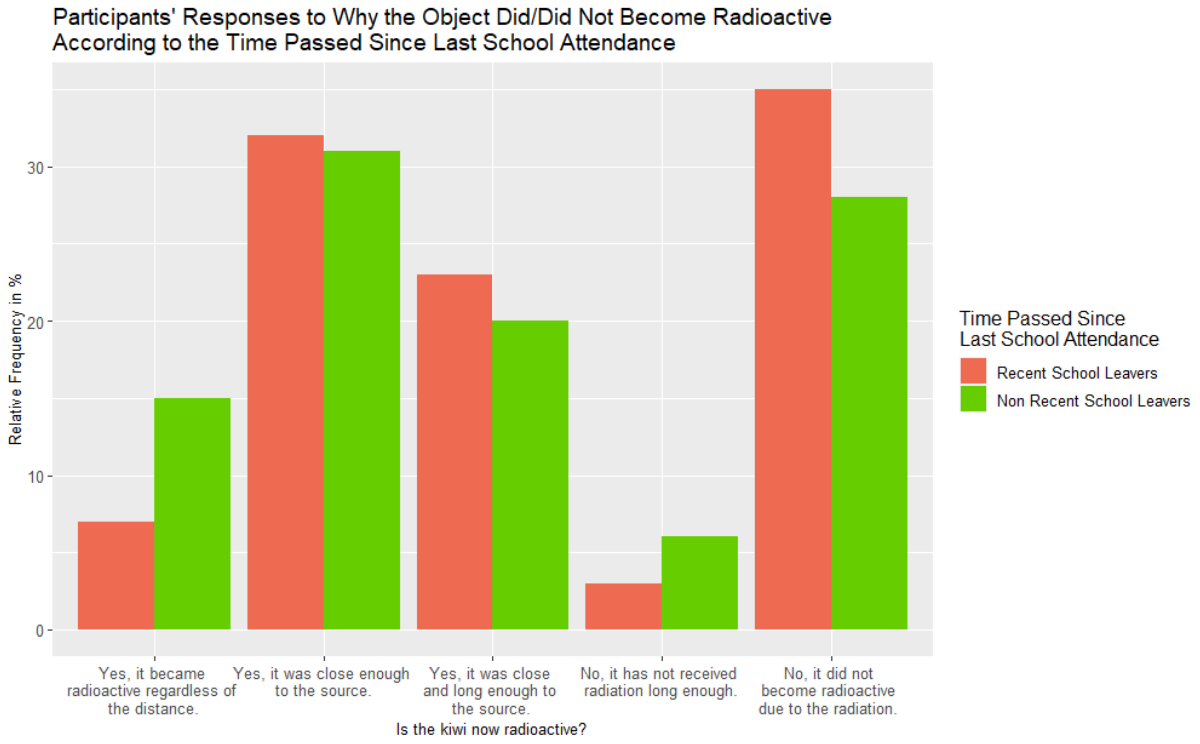


*Figure 74: Participants' Responses to Why the Object Did/Did Not Become Radioactive Part 2, Source: Own Composition*

Figure 74 presents the participants’ responses as to why the kiwi did or did not become radioactive in relation to the time passed since last school attendance. Comparing Figure 72 and Figure 74, the relative frequency for all factor levels shows an increase in identifying the kiwi as radioactive. From Question 13 to Question 14, the belief that the kiwi is radioactive increased for both factor levels with a relative frequency of 10% to 20%.

With a relative frequency of 35%, “recent school leavers” chose the correct option that the kiwi “did not become radioactive due to the radiation”. Only 28% of “non recent school leavers” considered this option to be correct. The option which was chosen most often with 31 %by the “non recent school leavers” was that the kiwi is radioactive because “it was close enough to the source”. The “recent school leavers” chose this option with a relative frequency of 32%. The third most chosen option by both factor levels is that the kiwi “was close enough to the source” and therefore, it become radioactive. The relative frequencies of both factor levels are 23% for “recent school leavers” and 20% for “non recent school leavers”. It is particularly striking that 15% of the “non recent school leavers” considered the option “yes, it became

radioactive regardless of the distance" whereas only 7% of the "recent school leavers" have chosen this option. The remaining option "No, it has not received radiation long enough" has a negligible relative frequency of less than 7% for both factor levels.

Question 15 - Generation of Radioactivity

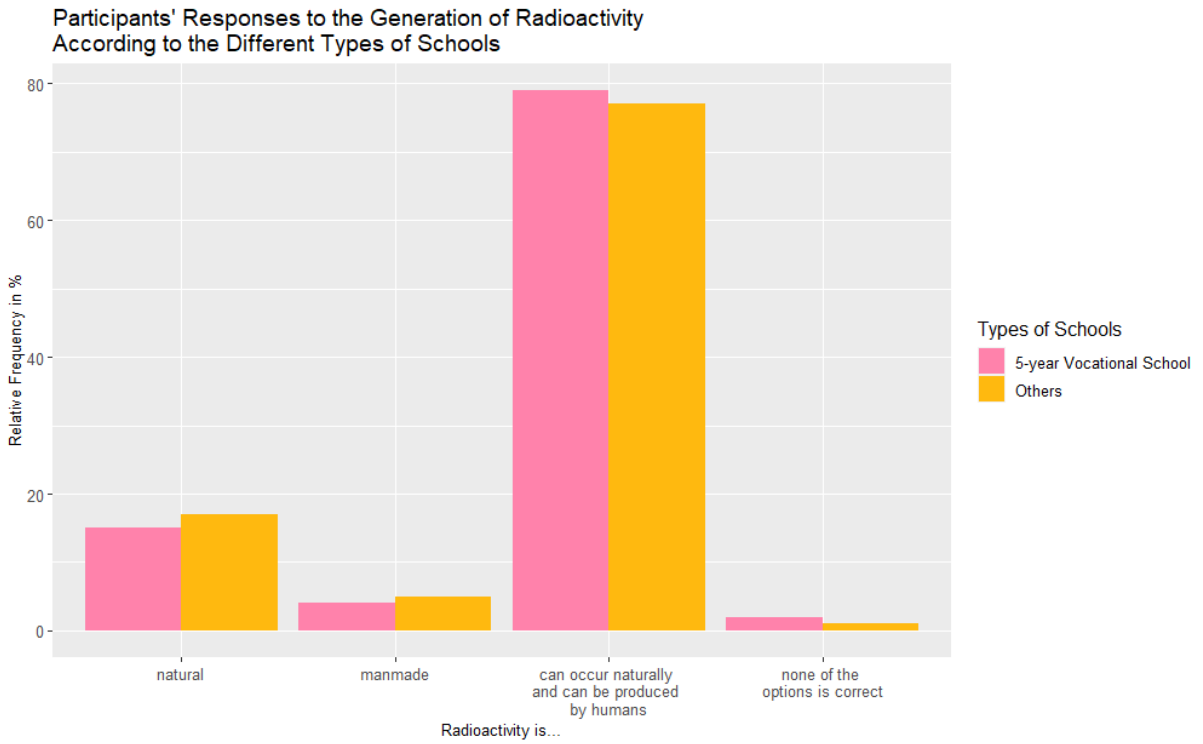


*Figure 75: Participants' Responses to the Generation of Radioactivity Part 1, Source: Own Composition*

The participants' responses to the generation of radioactivity in relation to the different types of schools can be seen in Figure 75. It is clear that the participants of every school type answered that radioactivity "can occur naturally and can be produced by humans". This option reached a relative frequency of 76% to 79% for both factor levels. With a relative frequency of approximately 18% the participants of the factor level "others" considered the option "natural" true, whereas 15% of the "5-year vocational school" graduates also chose this option. The remaining options that radioactivity is "manmade", respectively "none of the options is correct", only reached a relative frequency of less than or equal to 5% each.

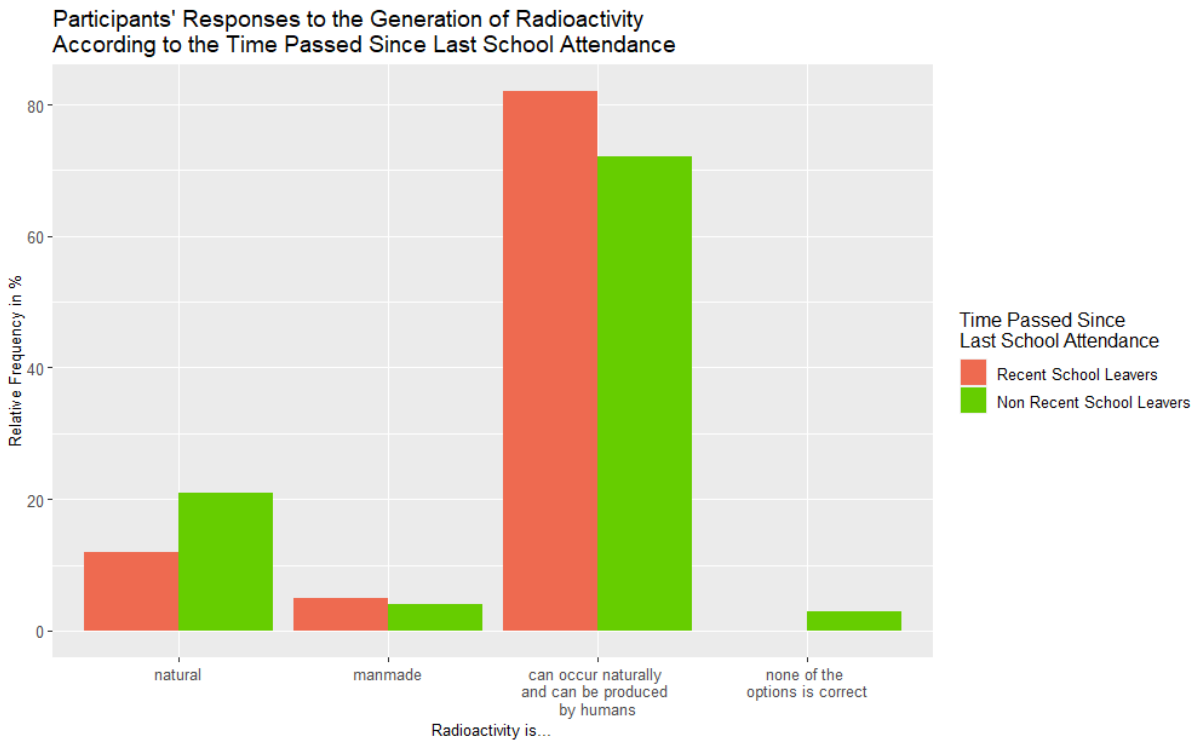


*Figure 76: Participants' Responses to the Generation of Radioactivity Part 2, Source: Own Composition*

Figure 76 presents the participants' responses to the generation of radioactivity classified in time passed since last school attendance. "Recent school leavers" chose the option radioactivity "can occur naturally and can be produced by humans" with a relative frequency of approximately 81%. 72% of the "non recent school leavers" chose this option. With a relative frequency of 21%, the "non recent school leavers" chose the option "natural". This answer was chosen by 12% of the "recent school leavers". The remaining options are chosen by a relative frequency of less than or equal to 5%, whereas the option "none of the options is correct" was not chosen at all by the factor level "recent school leavers".

Question 16 - Controllability of Radioactive Decay

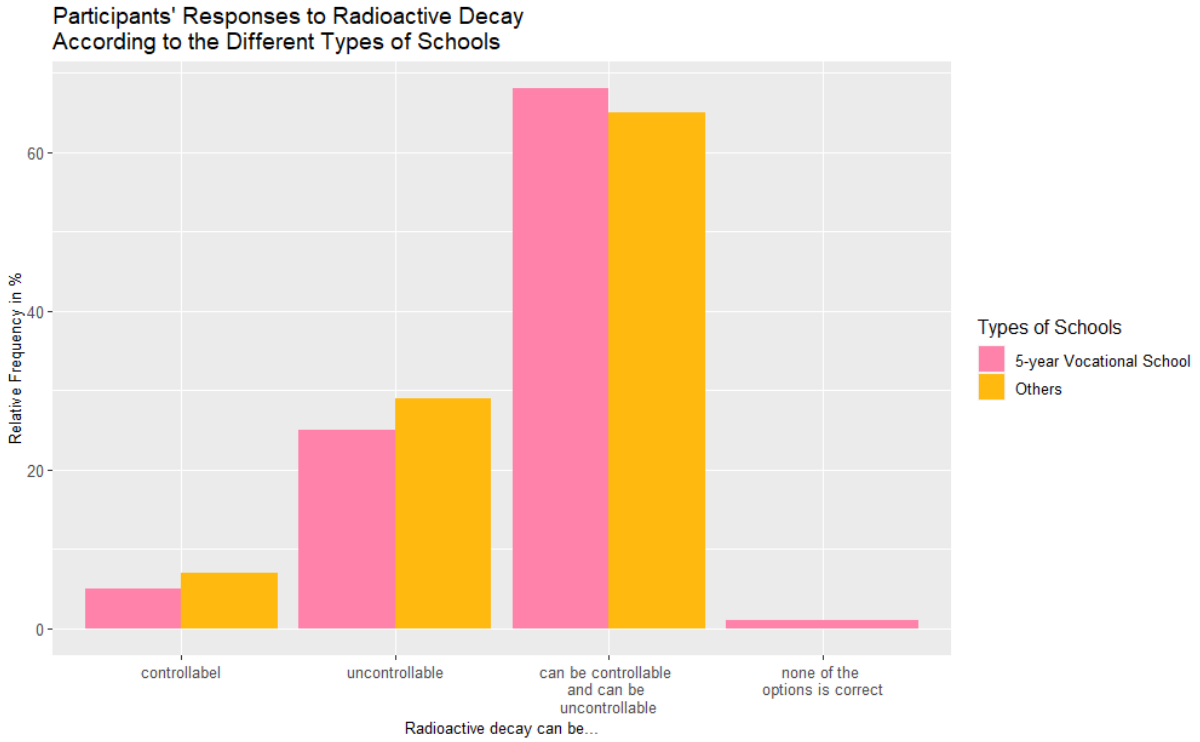


*Figure 77: Participants' Responses to Radioactive Decay Part 1, Source: Own Composition*

Figure 77 shows the answer of the participants from each school type, as to whether radioactive decay can be controllable and/or uncontrollable. The option “can be controllable and can be uncontrollable” was chosen by both factor levels with a relative frequency of more than or equal to 75%. The option “uncontrollable” was also chosen by both factor levels with a relative frequency of 25% to 29%. The two mentioned options were the ones, which were chosen the most. The remaining options, that the radioactive decay can be “controllable” or “none of the options is correct” were chosen with a relative frequency of less than 8% each. Additionally, the latter option was only chosen by a part of the participants who attended a “5-year vocational school”.

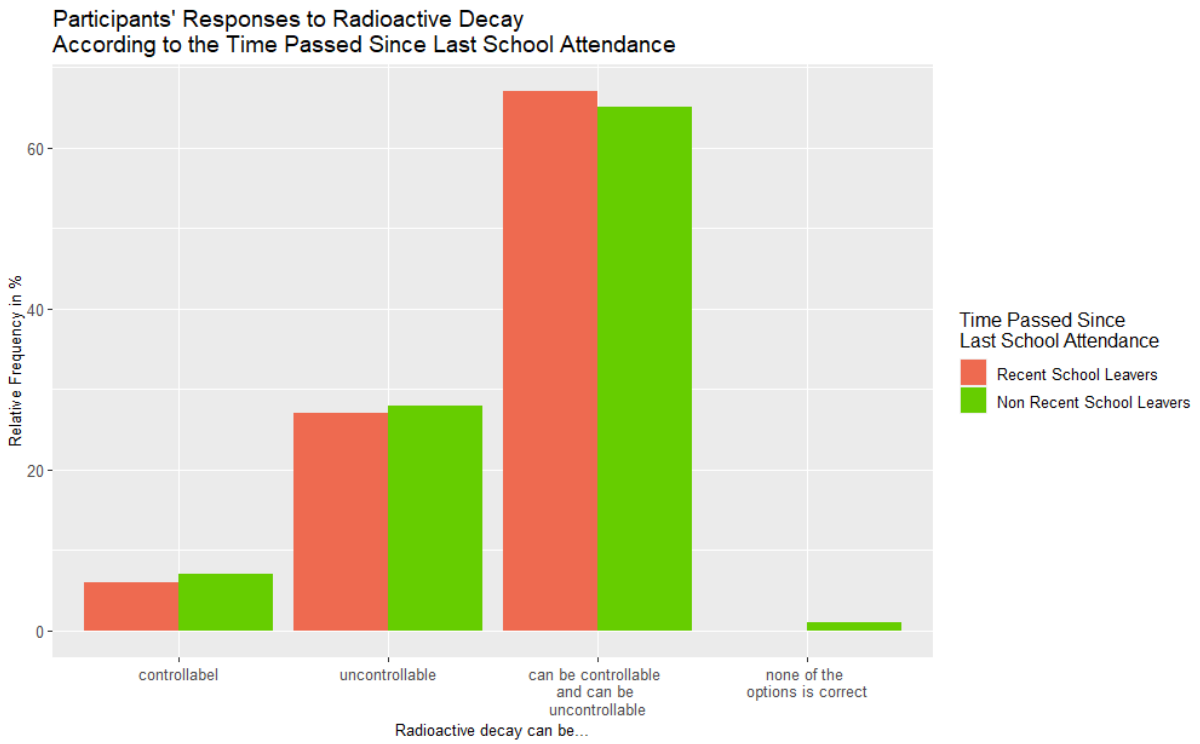


*Figure 78: Participants' Responses to Radioactive Decay Part 1, Source: Own Composition*

Figure 78 shows the participants' responses as to whether the radioactive decay is controllable and/or uncontrollable in relation to the time passed since last school attendance. More than 60% of the participants from each factor level have chosen that radioactive decay "can be controllable and can be uncontrollable". Only very few of the participants of both factor levels stated that the decay is "controllable". The option with the second most agreement from every factor level is that radioactive decay is "uncontrollable". The relative frequency concerning this option is between 28% and 29%. The option "none of the options is correct" was only chosen by the "non recent school leavers" with a relative frequency of only a few percent.

## Question 17 - Danger of Radioactivity for the Human Organism

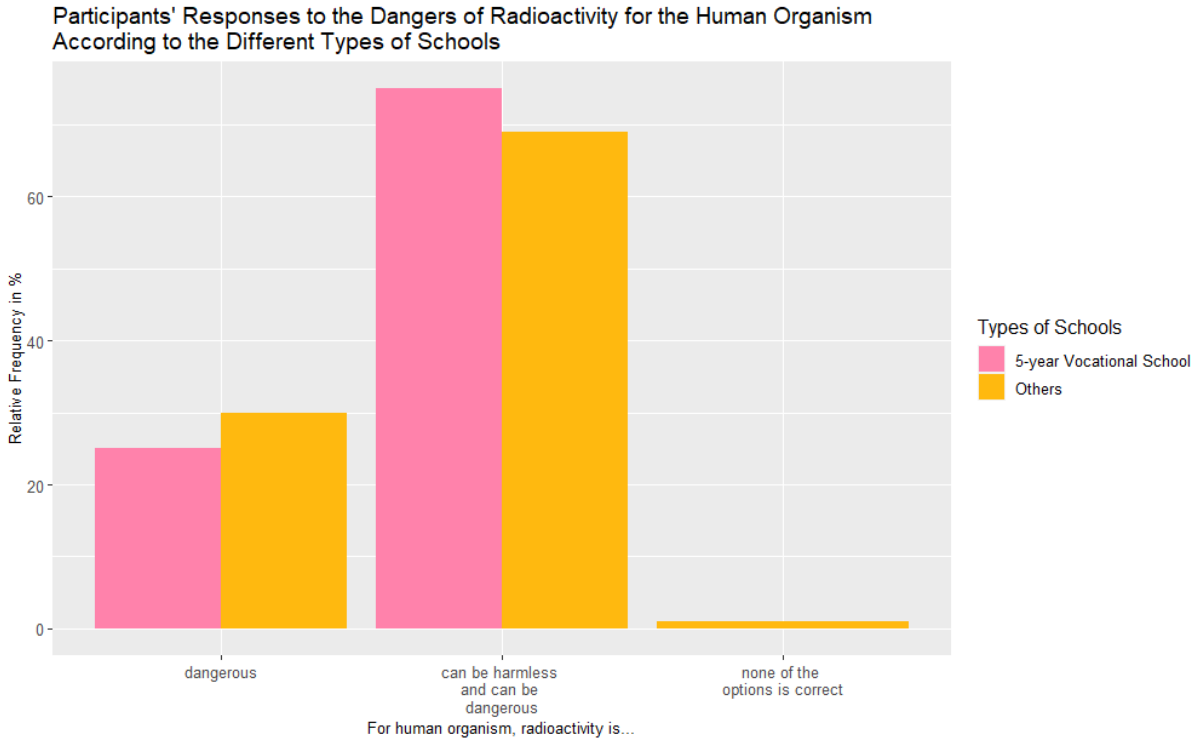


*Figure 79: Participants' Responses to the Dangers of Radioactivity for the Human Organism Part 1, Source: Own Composition*

The diagram (Figure 79) represents the participants' responses concerning the dangers of radioactivity for the human organism. The option "harmless" was not chosen by any of the participants (and hence does not appear on the x-axis). Participants from both school types considered the option "can be harmless and can be dangerous" to be correct. This option reached a relative frequency of 74% for the "5-year vocational school" graduates and 69% for the graduates of the factor level "others". These participants also chose the option "dangerous" with a relative frequency of 30%. This option was chosen by the "5-year vocational school" graduates with a relative frequency of 25%. "None of the options is correct" was only chosen by a few participants of the factor level "others".

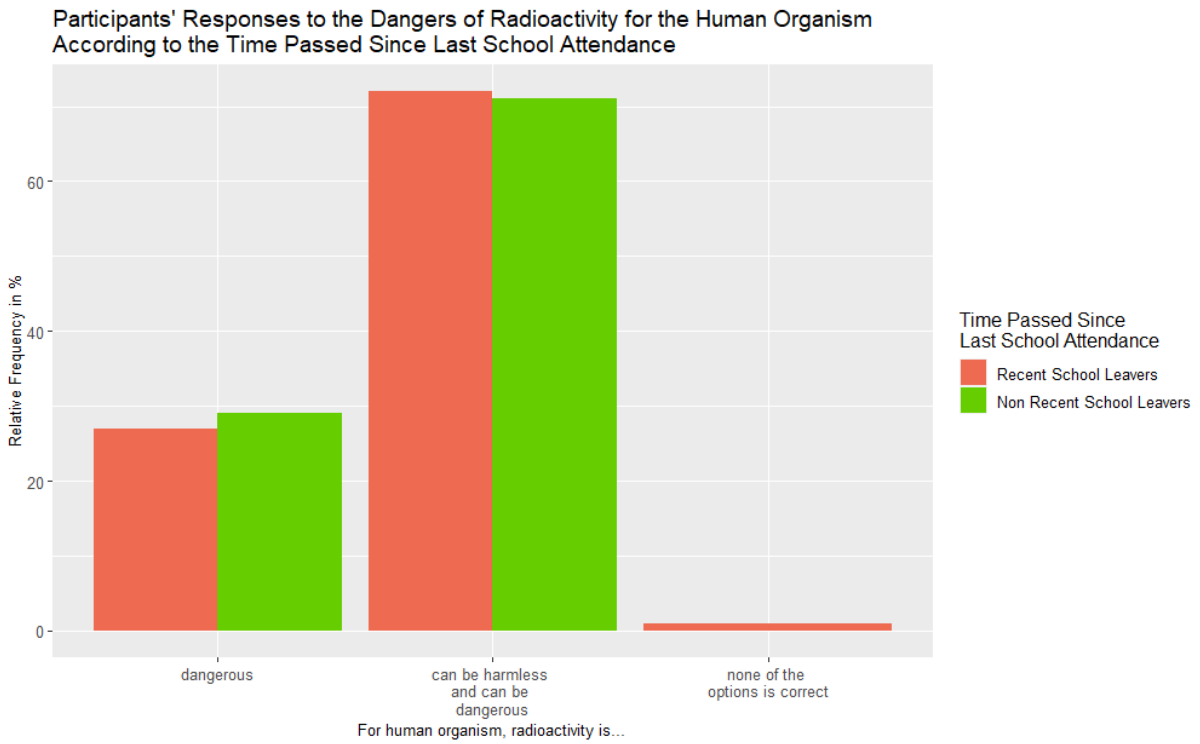


*Figure 80: Participants' Responses to the Dangers of Radioactivity for the Human Organism Part 2, Source: Own Composition*

Figure 80 shows the participants' responses to the dangers of radioactivity for the human organism. With a relative frequency of more than 70%, both factor levels consider the option "can be harmless and can be dangerous" to be correct. Additionally, a valid number of participants of both factor levels, namely 27% of "recent school leavers" and 29% of "non recent school leavers" chose the option "dangerous". Only a small percentage of "recent school leavers" chose the option "none of the options is correct".

## Question 18 - Airplane

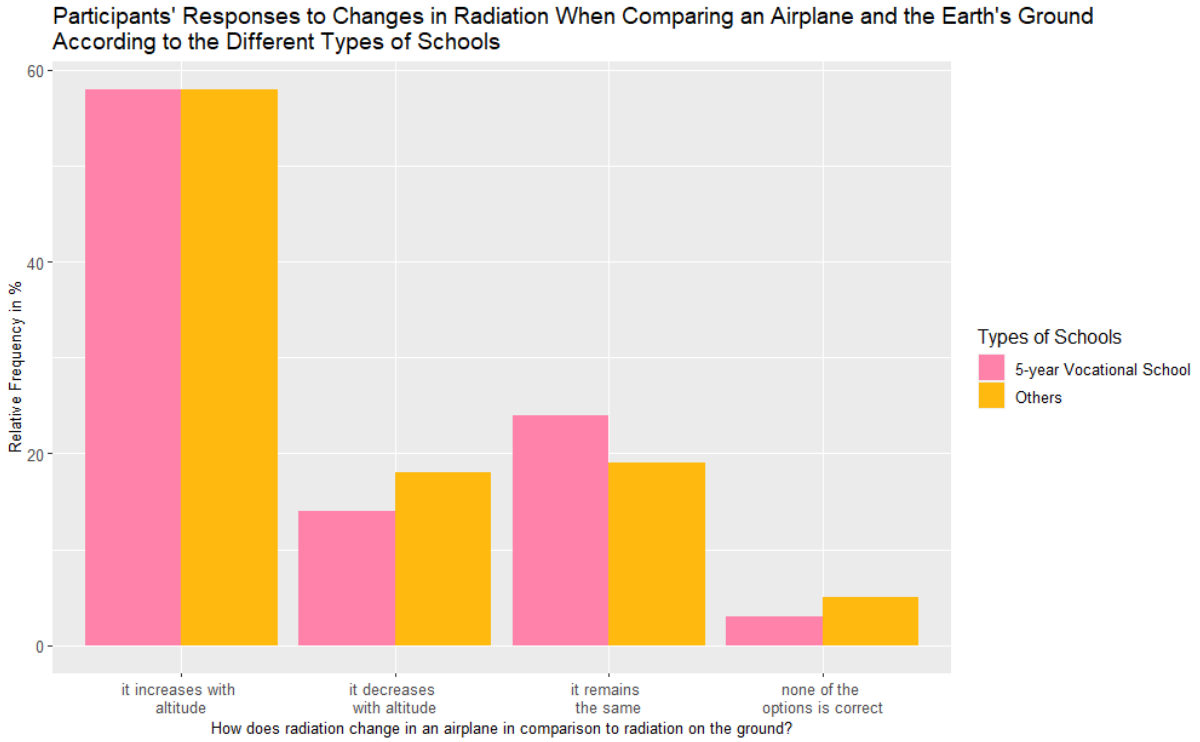


*Figure 81: Participants' Responses to Changes in Radiation When Comparing an Airplane and the Earth's Ground Part 1, Source: Own Composition*

Figure 81 displays the participants' responses to the possible changes in radiation when sitting in an airplane in comparison to when being on the ground in relation to the different types of schools. Participants of both school types selected the option "it increases with altitude" with a relative frequency of just under 60%. When comparing the factor levels "5-year vocational school" and "others", it is evident that more of the participants of the factor level "others" chose the option "it decreases with altitude" whereas more of the participants of the factor level "5-year vocational school" chose the option "it remains the same". The option "none of the options is correct" was chosen by a low relative frequency of less than or equal to 5% of each of the two mentioned factor levels.

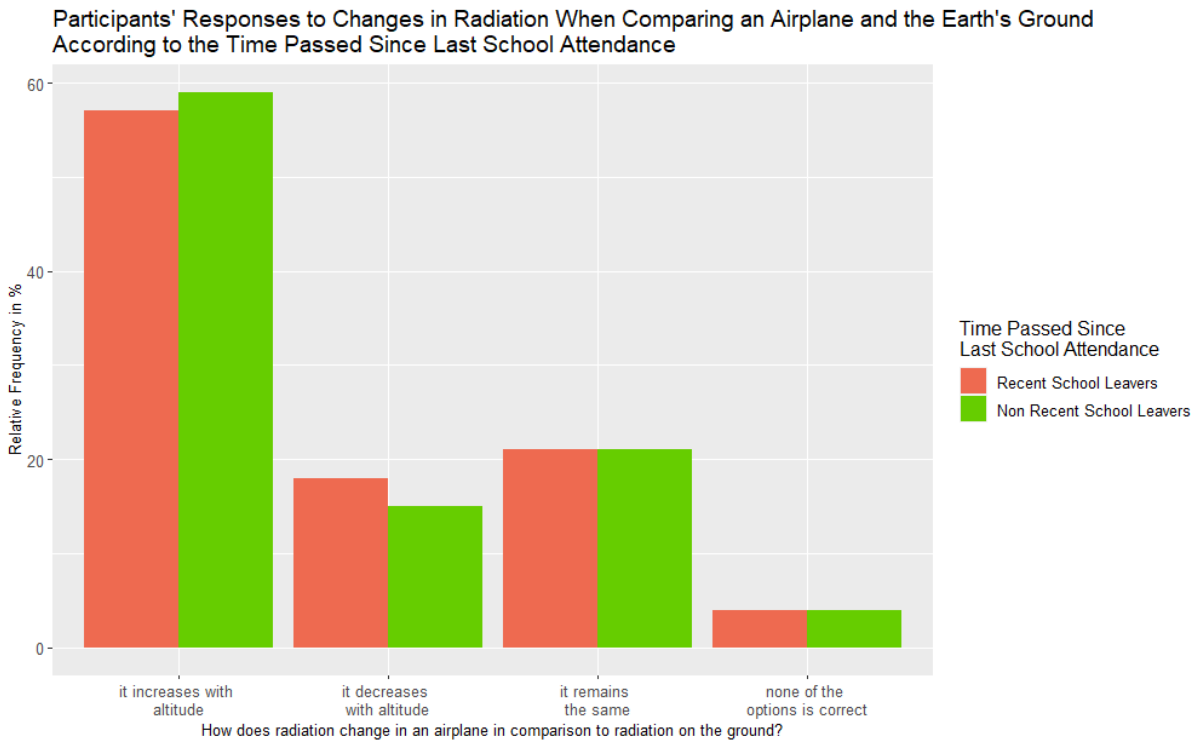


*Figure 82: Participants' Responses to Changes in Radiation When Comparing an Airplane and the Earth's Ground Part 2, Source: Own Composition*

Figure 82 shows the participants' responses to possible changes in radiation when sitting in an airplane in comparison to when being on the ground in relation to the time passed since last school attendance. The participants of both factor levels stated that radiation "increases with altitude" with a relative frequency of more than 55%. Additionally, more "recent school leavers" think that "it decreases with altitude". They reached a relative frequency of approximately 18% whereas the "non recent school leavers" reached a relative frequency of 15% for this option. The second-most chosen option is that "it remains the same" with a relative frequency of 21% for both factor levels. The option "none of the options is correct" reached a relative frequency of approximately 4% for both factor levels.

### 5.4.3. Results of the three-way ANOVA

The three-way ANOVA was applied by means of the statistic program RStudio. To be able to do an ANOVA, the participants were categorized into three different factors and two factor levels (Chapter 5.2.1). For instance, the categorization "time passed since school attendance" which consists of 9 options in the questionnaire, was regrouped into "recent school leavers" and "non recent school leavers". The participants who are in the factor level "recent school leavers" have attended school up to 10 years ago. Any other participant who has attended school more than 10

years ago, was classified into “non recent school leavers”. After regrouping in RStudio, the program created eight cases (see column “number of effect”) with the combination of all possible conditions. This can be seen in Table 16. (cf. R-Project, 2021)

*Table 16: Formation of the Factor Levels for the ANOVA, Source: Own Composition*

| Number of Effect | Chernobyl | Types of School | Time Passed | $n$ | Mean Value in Points | Standard Derivation in Points |
|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 31 | 11,00 | 2,70 |
| 2 | 2 | 1 | 1 | 53 | 10,00 | 2,39 |
| 3 | 1 | 1 | 2 | 28 | 8,37 | 2,89 |
| 4 | 2 | 1 | 2 | 34 | 9,40 | 2,23 |
| 5 | 1 | 2 | 1 | 47 | 10,40 | 2,87 |
| 6 | 2 | 2 | 1 | 93 | 9,80 | 2,76 |
| 7 | 1 | 2 | 2 | 31 | 8,84 | 3,32 |
| 8 | 2 | 2 | 2 | 69 | 8,57 | 3,39 |

The numbers in the column of the three independent variables are the same numbers as the participants who were divided into the factor levels in Chapter 5.2.1. As an example, the first row shows all the participants who have seen “Chernobyl” + went to a 5-year vocational school + are recent school leavers. $n$ describes the number of participants in each factor level. For effect 1 in Table 16, there are 31 participants with the respective conditions. The mean value of effect 1 is 11,00 points with a standard deviation of 2,70 points.

First, the conditions for the ANOVA were checked. With the D'Agostino test of skewness I proved that the data is distributed normally because the p-value of all tested variables is greater than 0,05 of the $\alpha$-error. Additionally, the data shows variance homogeneity since the p-value in the Bartlett test is also greater than 0,05. (cf. D’Agostino, 1970, p. 680; cf. Keating & Leung, 2010, p. 61)

After meeting these conditions, the three-way ANOVA was performed by means of the program RStudio. Table 17 shows the results. The first three samples are the main effects of every independent variable. Sample 4 to 6 are the interaction effects between each independent variable. Sample 7, indicating the main advantage of a three-way ANOVA compared to several two-way ANOVAs, shows if there is an

interaction between all three independent variables. DFn is the number of degrees of freedom of the numerator. It is calculated from the number of factor levels (Table 1) minus 1. Therefore, since each case consists of two factor levels, the DFn is 1. DFd is the number of degrees of freedom of the denominator, which is calculated from the total number of participants minus the effects. Here, there are 386 participants and 8 effects (Table 16), giving a DFd of 378. The F-value points out if there is a difference between the mean values of the respective factor level. The closer the F-value is to 1, the lower the mean difference. If there is a mean difference between the respective factor levels the F-value exceeds 1 by far. As already mentioned in the previous chapters, if the p-value is lower than 0,05, H0 is rejected. In addition to the p-value, the F-test checks whether the null hypothesis can be rejected. "$ges$" indicates the effect size (see Table 17). The higher the number, the larger the effect size and the more meaningful the result. The effect size for sample 1 is 0,056, which is denoted as medium effect. (cf. Backhaus et al., 2018, p. 194; cf. Bortz & Schuster, 2010, p. 270; cf. Cohen, 2008, p. 690; cf. *Effect Size in Statistics - The Ultimate Guide*, n.d.; cf. Fahrmeir et al., 2016, p. 266; cf. R-Project, 2021)

*Table 17: Implementation of the ANOVA, Source: Own Composition*

| Sample | Effect | DFn | DFd | F | p | p<.05 | ges |
|---|---|---|---|---|---|---|---|
| 1 | Time Passed | 1 | 378 | 22,281 | 3,32e-06 | * | 5,60e-02 |
| 2 | School Types | 1 | 378 | 1,387 | 2,40e-01 | | 4,00e-03 |
| 3 | "Chernobyl" | 1 | 378 | 1,126 | 2,89e-01 | | 3,00e-03 |
| 4 | Time Passed : School Types | 1 | 378 | 0,006 | 9,39e-01 | | 1,57e-05 |
| 5 | School Types : "Chernobyl" | 1 | 378 | 0,280 | 5,97e-01 | | 7,40e-04 |
| 6 | Time Passed : "Chernobyl" | 1 | 378 | 2,720 | 1,00e-01 | | 7,00e-03 |
| 7 | Time Passed : School Types : "Chernobyl" | 1 | 378 | 1,790 | 1,82e-01 | | 5,00e-03 |

In Chapter 5.2.1, the three null hypotheses were presented. These hypotheses only cover the main effects. Since there are three two-interaction effects and one three-interaction effect, four null hypotheses are added. All of them state that there is no difference between the independent variables which is why I do not list them individually. One example for Sample 7 (three-interaction effect) would be: Adults

have the same understanding of radioactivity regardless of the passing of time after graduation from school, whether or not they graduated from a 5-year vocational school and if they have seen the TV show “Chernobyl”. (cf. Fahrmeir et al., 2016, p. 266)

At first sight, it is remarkable that there is an asterisk in the column “$p < 0{,}05$” for sample 1. This asterisk shows that the p-value from the factor level “recent school leaver” compared to “non recent school leaver” is lower than 0,05. This is the only sample where the p-value is lower than the $\alpha$-error. Hence, the null hypothesis must be rejected. This means that there is a difference in the adults’ knowledge on radioactivity in relation to the passing of time after school. In addition, the F-value confirms that H0_1 must be rejected since the value 22,281 exceeds 1 by far. Every other main effect and interaction has a p-value greater than 5%, which means that the H0 is not rejected.

To sum up, there is a significant main effect of “recent school leavers” compared to “non recent school leavers” ($F = 22{,}281, df = 1, p < 0{,}05$). H0_1 is rejected and as a result, the alternative hypothesis, which states that there is a difference in the adults’ knowledge on radioactivity between “recent school leavers” and “non recent school leavers” is valid. There is no significant main effect on the adults’ knowledge on radioactivity if they have graduated from a 5-year vocational school or another type of school ($F = 1{,}387, df = 1, p > 0{,}05$). Hence, H0_2 is not rejected. If the participants have seen “Chernobyl” or if they have not seen “Chernobyl” ($F = 1{,}126, df = 1, p > 0{,}05$) does not show a significant main effect regarding their knowledge on radioactivity. Here, H0_3 is not rejected. In none of the interaction effects between the factors “time passed since last school attendance” and “different types of schools” ($F = 0{,}006,\ df = 1,\ p > 0{,}05$), “different types of schools” and “have or have not seen “Chernobyl”” ($F = 0{,}280, df = 1, p > 0{,}05$), and “time passed since last school attendance” and “have or have not seen “Chernobyl”” ($F = 2{,}720, df = 1, p > 0{,}05$) are significant main effects on the adults’ knowledge on radioactivity and the respective interactions. Hence, the null hypotheses are not rejected. There is also no significance within the three-interaction effect ($F = 1{,}790, df = 1, p > 0{,}05$), which combines all the independent variables, and the participants’ knowledge about radioactivity. Again, H0 is not rejected, and it can be concluded that there is no significant interaction of the three factors. (cf. Crosier et al., 2000, p. 337)

To illustrate the difference in means, a boxplot is used (Figure 83). In Figure 83, the types of schools and participants who have or have not seen “Chernobyl” are positioned on the x-axis, the test-points on the y-axis, and the values of “recent school leavers” respectively “non recent school leavers” are presented by means of boxplots. I chose this arrangement since I want to emphasize the difference between “recent school leavers” and “non recent school leavers” for various combinations of school attended and watching of the show “Chernobyl”. In Figure 83, the boxplots show the respective median and mean value, the dispersion using the interquartile range, the whiskers, and the outliers. The box (which represents the interquartile range) represents the values of the points where 50% of the participants are placed according to the respective factor. The median is represented by a horizontal line in the boxplot and states that 50% of the participants are above and 50% of the participants are below that line. The star-dot within the boxplot represents the mean value. Usually, the boxplot diagram does not show mean values but since the ANOVA compares whether there is a significant difference between mean values, I have included them in the diagram. Both ends of the whiskers point out the maximum and minimum points reached by the respective factor except of outliers. Outliers are represented by dots and are identified as such if they are larger or smaller than 1,5 times the interquartile range. Since a three-way ANOVA illustration by only one boxplot diagram would be too difficult to interpret, two two-way ANOVAs are placed side by side. (cf. Backhaus et al., 2018, pp. 166–167; cf. Bortz & Schuster, 2010, pp. 44–45; cf. Fahrmeir et al., 2016, pp. 44–45)

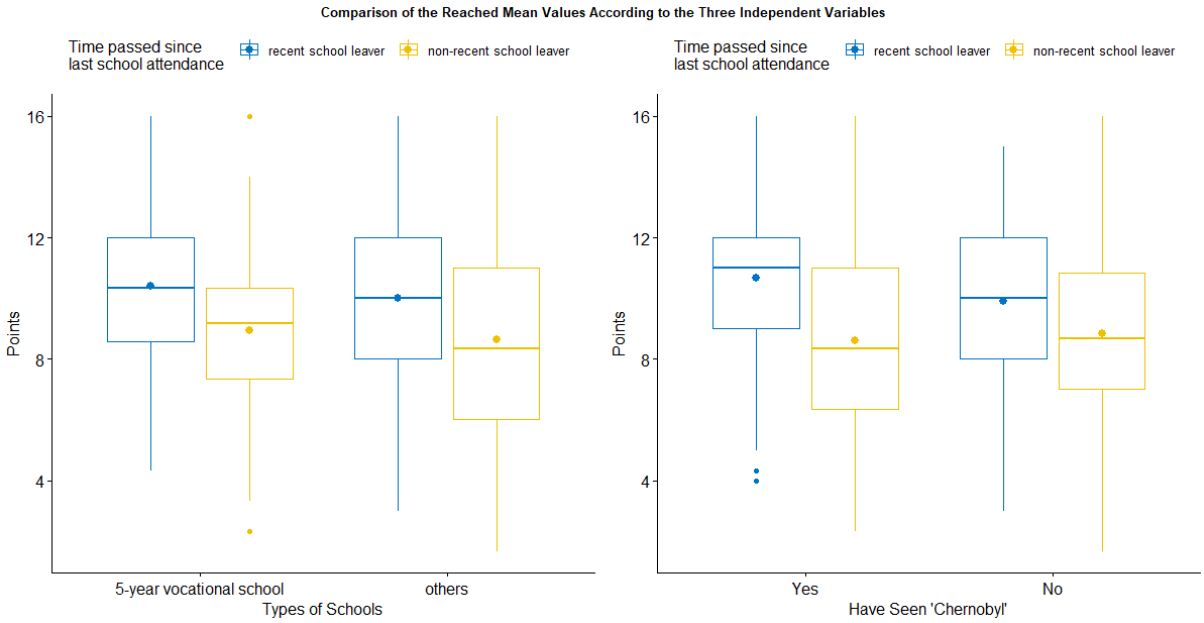


*Figure 83: Comparison of the Reached Mean Values According to the Three Independent Variables, Source: Own Composition*

Figure 83 shows the comparison of the reached mean values according to the three independent variables via a boxplot diagram. The colored boxplots represent the two factor levels of “time passed since last school attendance”, whereas the blue boxes indicate “recent school leavers” and the yellow boxes signify “non recent school leavers”. On the x-axis the independent variables “Types of Schools” and “Have Seen ‘Chernobyl’” are each represented in Factor 2 “Time Since Last School Attendance”. Since there is only a significant difference in the factor levels of “time passed since last school attendance”, I want to emphasize this factor. (cf. Fahrmeir et al., 2016, pp. 44–45)

The mean values of “recent school leavers” are always higher than the mean values of “non recent school leavers”. The mean value of “recent school leavers” is 10,16 points whereas the mean value of “non recent school leavers” is 8,76 points (Table 14). There is a clear difference between these two factor levels. Additionally, the medians of the blue boxes are always higher than the ones of the yellow boxes. This indicates that 50% of the “recent school leavers” participants reached higher points than the other “time passed since school attendance” factor level. (cf. Fahrmeir et al., 2016, pp. 44–45)

According to Table 16, Table 17, and Figure 83, it can be concluded that “recent school leavers” have a better knowledge on radioactivity than “non recent school

leavers”. In all other factors and interactions, there is no significant difference as indicated by the ANOVA.

### 5.4.4. Confirming or Rejecting the Hypotheses Based on the ANOVA

The null hypotheses have already been addressed using the results of the analysis. I would like to go back to the hypotheses presented in the beginning (H1, H2, H3 in Chapter 5.1.).

*H1: Adults who have graduated from school more recently know more about radioactivity than those who have graduated a longer period of time ago.*

Based on the above analysis and descriptions, this hypothesis (H1) can be confirmed. It has been shown that recent school leavers are more knowledgeable about radioactivity than those who have attended school more than 10 years ago.

*H2: Adults who have attended a 5-year vocational school have the highest understanding of radioactivity.*

With the help of the three-way ANOVA, this hypothesis can be rejected. The analysis of variance stated that there is no difference in the mean values of the two factor levels “types of schools”. Since the null hypothesis was retained and no differences are present, H2 can be rejected.

*H3: Adults who have seen the TV show “Chernobyl” have a better understanding of radioactivity.*

According to the implemented ANOVA, there is no advantage in watching “Chernobyl” in regard to the understanding of radioactivity. As for hypothesis H2, no difference was shown in the "Chernobyl" factor levels. Therefore, it can be claimed that hypothesis H3 is rejected.

# 6. Discussion and Outlook

This master's thesis is about the public's knowledge on radioactivity in Austria affected by the time passed since graduation and the type of school attended. The two research questions and the "question of interest" with the respective hypotheses were the foundation of this thesis. In order to answer the posed research questions, I created and administered a questionnaire. In this chapter, I will summarize the research findings. I will also discuss the difficulties which arose at various stages throughout the research project, as well as discuss positive experiences during the implementation. In the end, I will present an outlook on possible future research and limitations.

## 6.1. Answering the Research Questions and Hypotheses

In the following paragraphs, I will answer the research questions with the data gathered for this thesis which were analyzed by means of the three-way analysis of variance (in more detail in Chapter 5.4.3. and Chapter 5.4.4.). In doing so, I will confirm or reject the corresponding hypotheses I posed for these research questions. I will enrich this discussion by also comparing the mean values of the initial groups (i.e., Table 7, Table 12 and Table 15 from Chapter 5.4.2.).

<u>The following results were obtained for RQ1 and H1:</u>

*RQ1: How does understanding about radioactivity change with the passing of time after graduation from school?*

*H1: Adults who have graduated from school more recently know more about radioactivity than those who have graduated a longer period of time ago.*

Hypothesis H1 was confirmed by means of an ANOVA. The results show that those participants who have graduated from school more recently have a significantly higher mean value of points on the conceptual survey I created than those who have graduated a longer period of time ago. Hence, a person's understanding of radioactivity does change with the passing of time after school graduation. People who have graduated in the last 10 years have a better knowledge of radioactivity than people who have graduated more than 10 years ago. This trend also can be

seen in the survey items themselves (Chapter 5.4.2.). Out of 16 survey items, recent school leavers had a higher relative frequency of correct responses on 12 items than non-recent school leavers. The remaining four items (Q4 - What Makes a Measuring Device for Radioactivity Click/Beep?, Q16 - Controllability of Radioactive Decay, Q17 - Danger of Radioactivity for the Human Organism and Q18 - Airplane) were answered correctly by both factor levels in about equal percentages of relative frequency.

If we have a look at the research question RQ1 and the Table 12 in Chapter 5.4.2., the mean value of points is different for every single group. Those participants who have graduated within the last 6 to 20 years have a better knowledge on and understanding of radioactivity than those participants who have graduated within the last 5 years. Hence, the participants who have graduated from school most recently, have a lower high mean value in points than the ones who have graduated a longer period of time ago. When considering the standard deviation, the difference between the groups is minimized.

Moreover, there is no evidence of an above-average knowledge of radioactivity as a result of nuclear accidents such as Chernobyl or Fukushima. A student is assumed to be in school (excluding elementary school) between the ages of 10 and 18. The Chernobyl nuclear disaster occurred in 1986, so assuming above-average knowledge, participants who attended school approximately 27 to 35 years ago should have scored higher. If the time intervals "26 - 30" and "31 - 35" are considered, it can be seen that the mean values (Table 12) for these two areas are below the total mean value. Consequently, it is not possible to speak about the connection of the Chernobyl catastrophe during the school time with a higher knowledge.

If we consider the nuclear disaster in Fukushima that occurred in 2011, then it can be seen that this concerns the "recent school leavers". It is true that the recent school leavers scored better than the “non recent school leavers”. However, the fact that students during the time of Chernobyl did not similarly score higher suggests that retention of knowledge may play a larger role than special events-driven emphasis of content in the classroom. From my own experience, I was attending school at that time and there was no special focus on the event of Fukushima within the school.

Especially in regard to media coverage on Chernobyl, Lijnse et al. (1990, p. 69) report that scientifically incorrect terms are used. Consequently, people informed themselves about this event, but many misconceptions were developed in the process, e.g., the concept of a “radioactive cloud”. I want to highlight that the factor levels for the ANOVA were categorized in regards to Alsop (2001, p. 265) and that the formed hypothesis, and the ANOVA, just show results within this factor level formation. If the factor levels were categorized differently, other results could arise.

The following results were obtained for RQ2 and H2:

*RQ2: How does understanding about radioactivity depend upon the school graduated from?*

*H2: Adults who have attended a 5-year vocational school have the highest understanding of radioactivity.*

Since the null hypothesis regarding to H2 was not rejected (more in Chapter 5.4.3. and Chapter 5.4.4.), H2 must be rejected. H0_2 stated that there is no difference between the understanding of radioactivity and the different types of schools. Hence, H2 cannot be confirmed. Adults who have attended a 5-year vocational school do not have the highest understanding of radioactivity because the ANOVA does not state a significant difference between the two factor levels (“5-year vocational school” and “others”). Based on the research, the answer to RQ2 is that the type of school (divided into the two factor levels) does not influence the participant’s understanding of radioactivity.

When comparing the results of the ANOVA to the mean values of points of Table 7 in Chapter 5.4.2., the type of school with the highest mean value is the general secondary school closely followed by the 5-year vocational school. In addition, it must be noted that the HTL graduates (who are commonly assumed to be very technically gifted), comprising a subcategory of the 5-year vocational school, do not have the highest knowledge about radioactivity. This was shown with the help of Table 11. The participants of the individual school types within the category “5-year vocational school” all have a similar level of knowledge about radioactivity, except for the graduate of the HLFS. However, the mean value of the participant of the HLFS is not that meaningful since only one participant attended this school. Here, a larger

number of participants would be necessary to be able to examine the school types in more detail. The polytechnic school reached the lowest mean value. However, since only 4 people who have graduated from a polytechnic school finished this questionnaire, this mean value is not significant. The number of participants in this group does not represent the population.

In an attempt to answer research question RQ2 solely based on Table 7, it can be concluded that those people who have graduated from a school with a “Matura” (maturity exam) have a better understanding of radioactivity than those who do not have a “Matura” and consequently, who have attended school for a shorter period of time. When considering the standard deviation, the differences between the different types of schools (except the polytechnic school) are small. Nevertheless, there is a chance that a different formation of the factor levels could lead to different results in an ANOVA.

The following results were obtained for the “Question of Interest” and H3:

*Question of Interest*: *How does knowledge about radioactivity change after watching the TV series “Chernobyl”?*

*H3: Adults who have seen the TV show “Chernobyl” have a better understanding of radioactivity.*

Unlike the two research questions, for this question of interest and the respective hypothesis, there is only one possible group formation. As already shown in Chapter 5.4.4., H0_3 is not rejected which means that there is no difference in watching or not watching “Chernobyl” and having a better understanding of radioactivity (and H3 must be rejected). This conclusion is consistent with Table 15 in Chapter 5.4.2. It can be concluded that knowledge about radioactivity does not change after watching "Chernobyl" since adults who have seen the TV show “Chernobyl” do not have a better understanding of radioactivity.

## 6.2. The Participants

It must be noticed that 266 out of 386 participants are between 18 and 35 years old. This could be due to the fact that this reflects my own age group. The requests for participating in this research were mainly posted on diverse social media platforms.

My age group is particularly prevalent on such social media platforms, so this could be another reason why this group is so strongly represented.

Regarding presence of the different types of schools, only four participants had attended a polytechnical school. This is a very small number but as already mentioned, the groups respectively factors are newly formed into factor levels to perform the ANOVA. It should also be noted that four individuals can not represent the fraction of polytechnic school graduates in the population but since I cannot control the received data and this type of school is not the focus of the hypotheses, the data of this group was treated like all others. Crossing them out or putting the participants into other types of schools would have falsified my data.

The participants were not asked about the region in which they live. Additionally, to the already asked demographics, it would be interesting to consider this factor since Austria has areas with different radon gas concentrations. Nevertheless, according to a conceptual study of Alsop (2001, p. 263. 278) recent school leavers who are living in an area where the radon gas concentration is higher do not know more about the concepts of radioactivity compared to recent school leavers who are not living in such an area. Those who live in areas with high radon gas concentrations are simply more knowledgeable about the measures to take to avoid health hazards. Therefore, I do not expect participants to have a higher knowledge of radioactivity because of the radon region in which they live.

Although I mentioned in the covering letter of explanation that every participation in this research is important and no one should feel bad if he/she can't answer the question, 249 participants interrupted the questionnaire. I have heard from a few that they have abandoned the questionnaire because it was too difficult for them, or they had no interest in this topic. I am of the opinion that this topic has scared off many participants, which is why they decided to cancel their participation in the questionnaire.

## 6.3. Conduct of the Questionnaire

As already mentioned in Chapter 5.3.1., the questionnaire was created with the online platform SoSci. Since I set the presetting that every question must be answered, I have no missing data. Within the first 24 hours, more than 200 participants filled out the questionnaire. Participation dropped off abruptly after that.

This is consistent with the situation described by Gilham (2008, p. 47), that within the first ten days one reaches half of the total number of participants.

In the first 24 hours, I also received seven e-mails. In those emails, people asked me to provide additional websites where they could inform themselves further on radioactivity. A lot of them also asked me how I came up with this topic and why. It can therefore be concluded that there is definitely an interest in this topic. Mostly, people wanted to know the solution to the questionnaire's questions. Of course, I did not provide the correct answers since I wanted to prevent my research from being falsified. However, I pointed out that they can contact me again in a few weeks to talk about it. In any case, I have heard that not knowing the correct answer has created a feeling of discomfort and incompleteness for them.

In the questionnaire, the participants were asked to provide a statement about their emotions towards radioactivity. The results of this question are shown in Figure 84 for the different types of schools and in Figure 85 for the time passed since last school attended. The factor levels seen in the figures are in the same as those used with the ANOVA analysis.

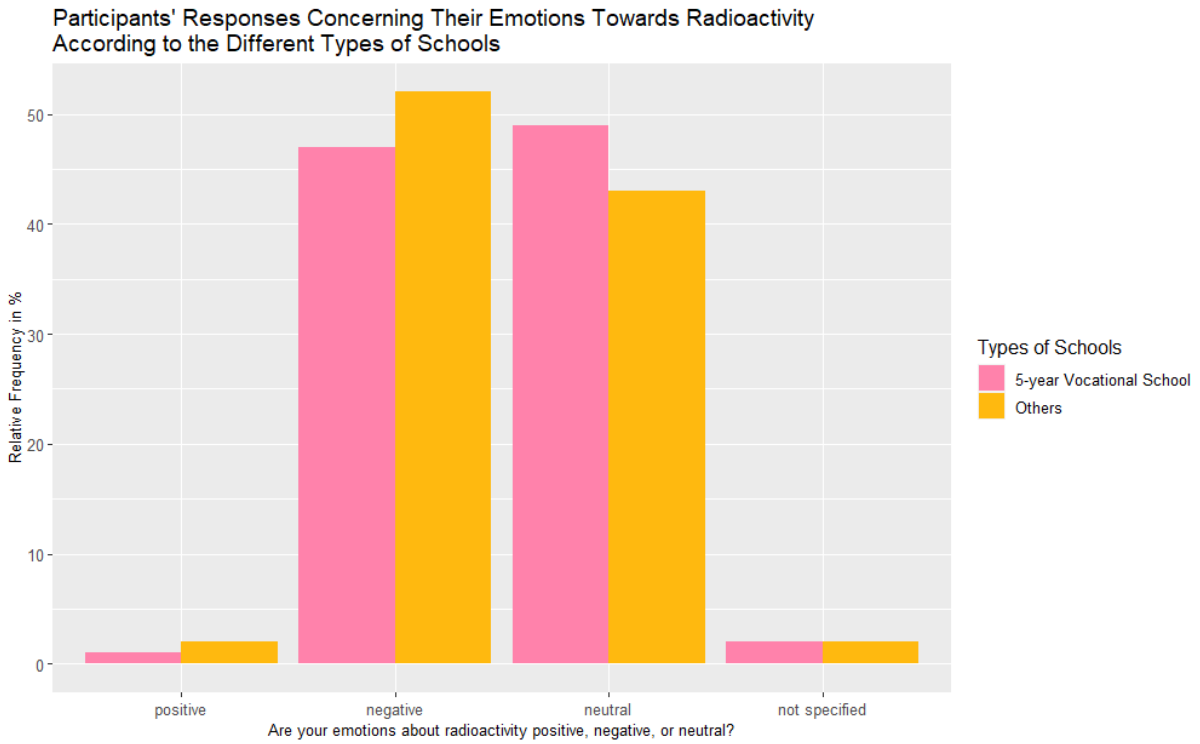


*Figure 84: Participants' Responses Concerning Their Emotions Towards Radioactivity Part 1, Source: Own Composition*

Figure 84 shows that the options "negative" and "neutral" were selected most frequently. The options were chosen approximately equally often. More participants

of the “5-year vocational school” stated that their emotions about radioactivity are “neutral”. This option reached a relative frequency of just under 50% for this factor level. The graduates of the remaining types of schools reached a relative frequency of 43% for this option. The most chosen option with approximately 52% by the factor level “others” was “negative”. The option “negative” was chosen by the “5-year vocational school” graduates with a relative frequency of 46%. The options “positive” and “not specified” were chosen by the participants of all factor levels with a negligible relative frequency of less than or equal to 3%.

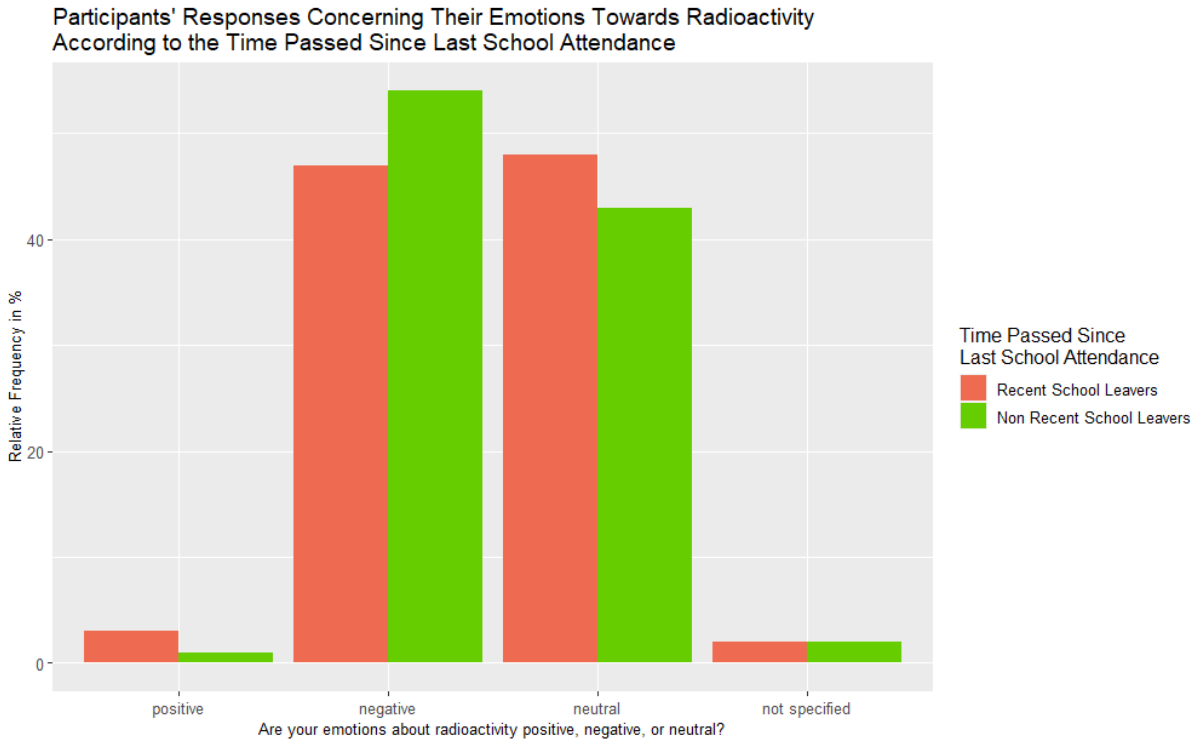


*Figure 85: Participants' Responses Concerning Their Emotions Towards Radioactivity Part 2, Source: Own Composition*

Figure 85 also shows the emotional tendency from all participants. But this time, it is classified in regard to the time passed since last school attendance. The emotions towards radioactivity are approximately equally distributed for “recent school leavers” among the options “negative” and “neutral”. These two bars show a relative frequency of approximately 47% each. “Non recent school leavers” were most likely to experience “negative” emotions about radioactivity. Their relative frequency for this option is approximately 55% whereas 42% of this factor level state that their emotions are “neutral”. The remaining options “positive” and “negative” were chosen by a very small number from both factor levels.

I was really surprised by the equal distributions in Figure 84 and Figure 85 towards the two options “neutral” and “negative” regarding their emotion about radioactivity. In accordance with to Hull, Janksy, and Hopf (2020, p. 58) as well as Morales and Tuzón (2020, p. 8-13), I thought that most of the participants experience negative emotions towards radioactivity. Surprisingly, a valid number of participants have indicated that their emotions towards this topic are neutral.

Additionally, I asked if the participants had a hard time completing the tasks and, if they did so, why. Figure 86 and Figure 87 show the given options regarding this question within both cases and their respective factor levels. Figure 88 shows their justification on why they did have a hard time in answering the questions.

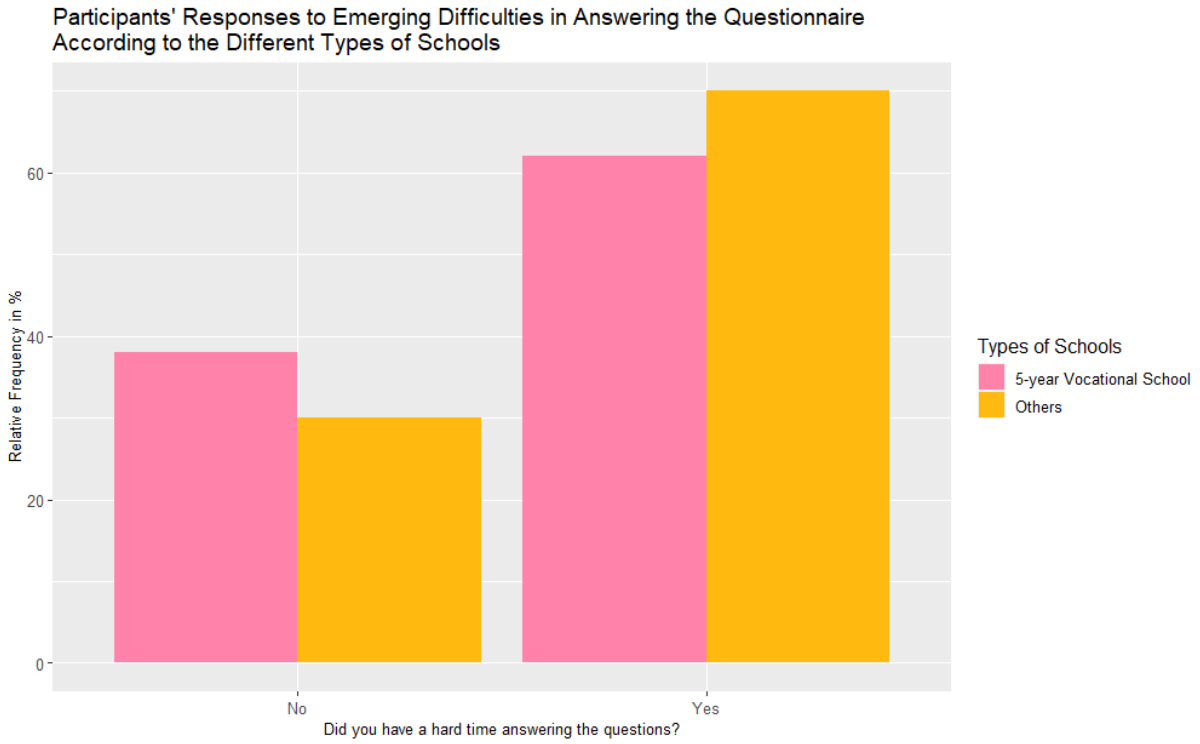


*Figure 86: Participants' Responses to Emerging Difficulties in Answering the Questionnaire Part 1, Source: Own Composition*

The majority of the participants of every type of school had a hard time answering the questions indicated by the relative frequency of more than 60%. Nevertheless, when comparing the two factor levels with each other, more “5-year vocational school” participants chose that they did not have a hard time answering the questions indicated by a relative frequency of just under 40%. The participants of the other types of schools reached a relative frequency of 30% for the option “No”. Since the ANOVA stated that there is no difference between the knowledge of radioactivity

between these two factor levels, it seems that the participants of the “5-year vocational school” are more confident about their knowledge of radioactivity.

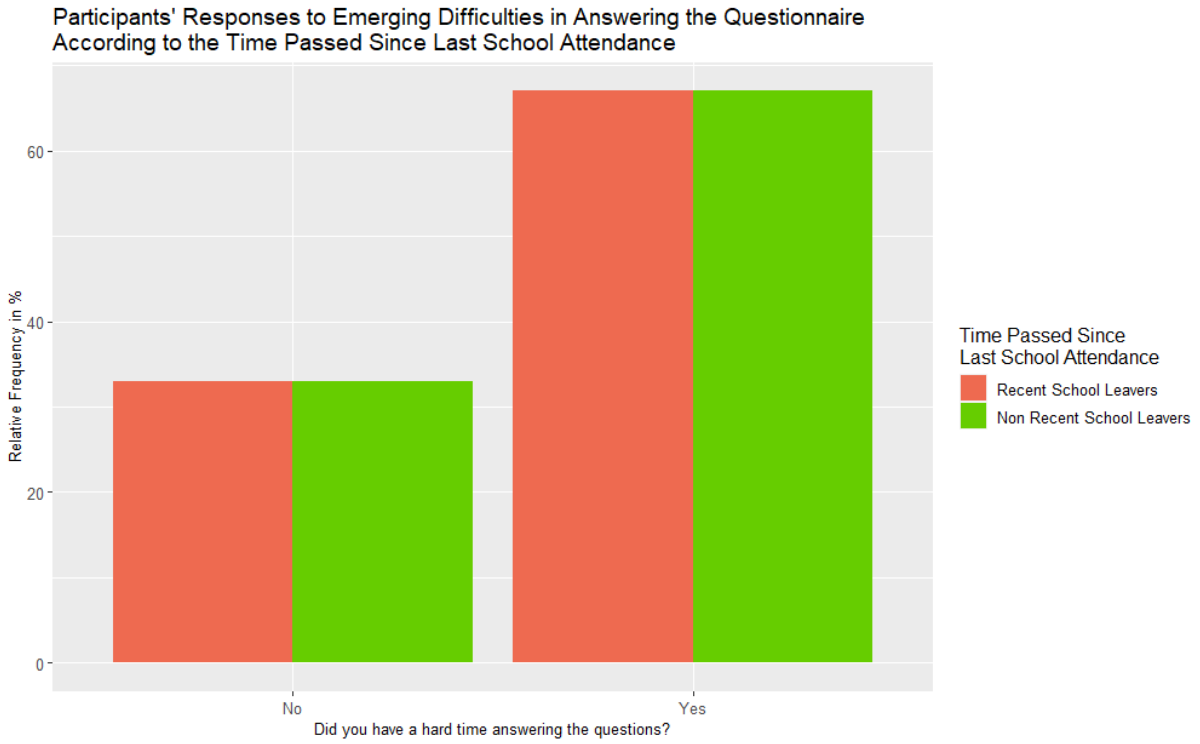


*Figure 87: Participants' Responses to Emerging Difficulties in Answering the Questionnaire Part 2, Source: Own Composition*

Figure 87 shows the participants’ responses to emerging difficulties in answering the questionnaire according to the time passed since last school attendance. Here, it is also noteworthy that the majority of the participants had a hard time answering the questions indicated by a relative frequency of more than 60% for each factor level. Both factor levels (i.e., “recent school leavers” and “non recent school leavers”) reached an equal relative frequency for both options “No” and “Yes”. 32% of the participants of both factor levels stated that they did not have a hard time during the questionnaire.

Those who have answered that they had a hard time in answering the topic had to justify their answer in a free response field. I coded the given justifications. I classified every single answer to one of the main category-codes, which can be seen in Figure 88 on the y-axis. To find these main categories, I created an Excel table, dividing the answers by categories. Figure 88 shows that two categories are combined. This is because all 13 respondents who mentioned that "The topic is far away from everyday life" also discussed how they are "negatively afflicted" by radiation. An example of an answer to this would be: “im alltag radioaktivität generell als negativ und gefährlich

gilt und darüber hinaus wenig über die tatsächlichen vorgänge berichtet/geredet wird, da diese uns meistns nicht betreffen“, respectively translated in English: "in everyday life radioactivity is generally considered negative and dangerous and furthermore little is reported/talked about the actual processes, since these mostly do not concern us". The x-axis shows the number of mentions.

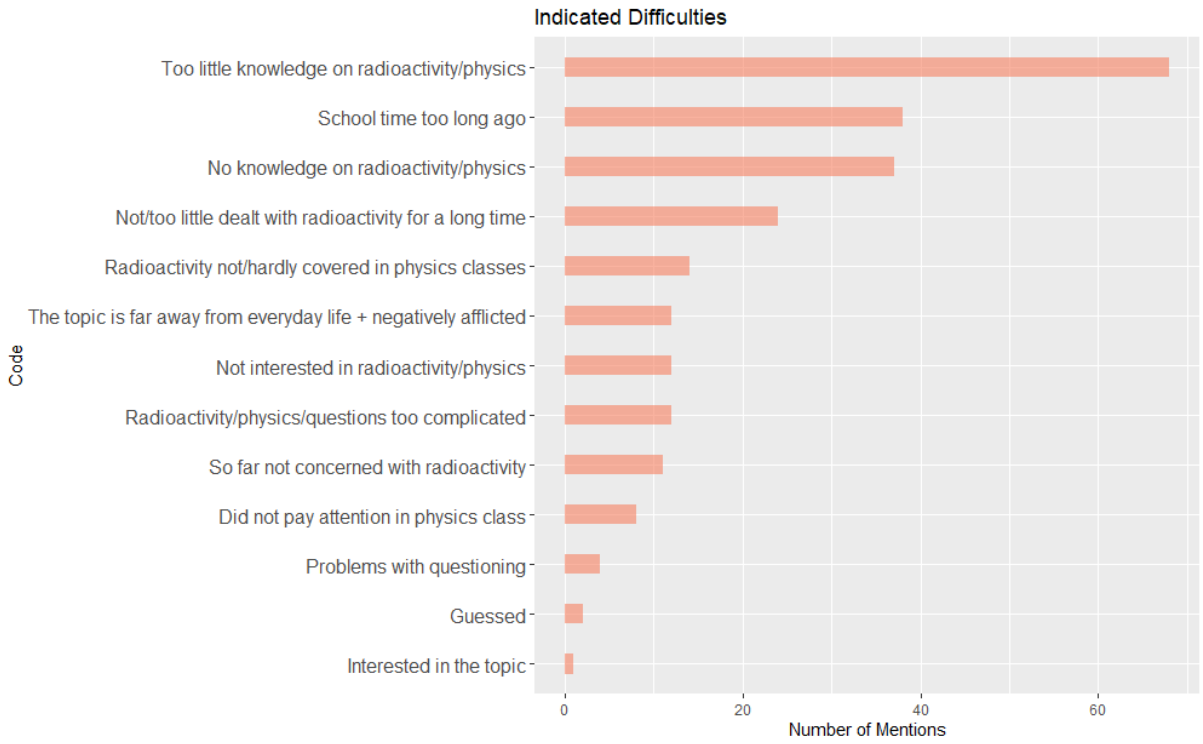


*Figure 88: Indicated Difficulties, Source: Own Composition*

258 participants stated that they had a hard time while answering the questions. Figure 88 shows the indicated difficulties. The number of mentions is 243. This is lesser than the 258 participants who stated that they had a hard time while answering the questions because 15 people entered a blank or a dot as a justification for why they had a hard time. These kinds of justifications are not represented in Figure 88.

The most mentioned reason why the participants had problems when answering the questions was that they have “too little knowledge about radioactivity, respectively physics”. This was mentioned by 68 participants. 38 participants also stated that their “school time is too long ago”. Hence, they cannot remember what they had learned in school. Additionally, a significant proportion of participants wrote that they do not have knowledge about radioactivity or physics at all. Approximately 25 participants stated that they had not dealt with radioactivity for a long time and 14 participants

wrote that they hardly or never covered the topic during physics classes. The codes “the topic is far away from everyday life + negatively afflicted”, “Not interested in radioactivity/physics” and “Radioactivity/physics/questions too complicated” were mentioned by 13 participants each. The selections of the code “the topic is far away from everyday life + negatively afflicted” reflects the answers for Question 4 in Chapter 5.4.2. This code was composed as shown in Figure 88, since these two terms were mentioned in combination by those participants. A lot of people view radioactivity negatively (as seen in Figure 84 and Figure 85) because they are not aware of the omnipresence of radioactivity. This is consistent with the findings in Question 4, that many people are not aware of ubiquitous radioactivity. 11 participants reported that they had not yet dealt with radioactivity. 8 participants mentioned that they did not pay attention in physics classes. Four participants had problems with the wording of the questions. Since they have provided their email address, I asked them about their difficulty concerning the formulation of the question. Three out of four participants replied to the email. One participant wrote that I did not distinguish between the different types of radiation in every single question. He/She (incorrectly) assumed that it would make a difference if the kiwi was irradiated by alpha particles, beta particles or gamma quanta. Another participant wrote in his/her email that Question 10 (the sealed closet) was not well formulated since there was not enough information provided. As the option “more information is needed” was a possible (and, in fact, the *correct answer* to Question 10), I could not follow this concern. Finally, the last person who replied to my email criticized that in Question 4, I did not distinguish whether or not the measurement was conducted before or after a nuclear accident. This concern only serves as further proof that people are not aware of the omnipresence of radioactivity. Another code is that the participants “guessed”. Since only four people mentioned this, it does not affect the results of this research. One person wrote that he/she is not familiar with the topic but would love to hear more about it. He/She also mentioned that this questionnaire has sparked his/her interest.

## 6.4. Discussion of the Single Questions

In addition to the already presented results in Chapter 5.4.2., I want to underline here the item responses which reflect the assumptions justifying the survey design

discussed in Chapter 5.3.1., the present students' conceptions already found in literature (Chapter 5.3.3.) and personal thoughts.

Question 4 - What Makes a Measuring Device for Radioactivity Click/Beep?

Question 4 asks what optional objects would trigger a lick from a measuring device for radioactivity. The results of these questions are not surprising. Almost everybody who participated in the research, regardless of the formed factors, had the opinion that concrete walls, in the rooms where X-rays are performed, would make a measuring device for radioactivity click. Since this was already discussed in articles of Millar et al. (1990, p. 339), the result regarding this question was expected. It confirmed the statement made by Millar et al. about the misbelief that walls are becoming radioactive after an X-ray treatment was performed in the room.

In the pilot stage of the questionnaire, someone said to me that this question is absolutely clear for him/her (and the respondent answered correctly). His/her reasoning was, that his/her teacher put a counter on the table, turned it on and it started clicking immediately without holding anything near the device. I think without having seen such a demonstration at some point in one's life, this question is very hard to answer. From this, I conclude that people are unaware of the ubiquity of radioactivity.

Question 5 - Definition of Radioactivity

Question 5 asks the participants to tick the correct definition for radioactivity. Although most people recognized the correct definition of radioactivity, a non-negligible proportion stated that "Radioactivity is the radiation emitted by a nucleus (…)". This students' conception, stated by Eijkelhof and Millar (1988, p. 37), Lijnse et al. (1990, p. 74) and Millar et al. (1990, p. 338), must be taken very seriously by teachers at school. This phrase is commonly found in mass media. Following the expert round, one teacher ticked that "Radioactivity is the radiation emitted by a nucleus (…)". As already mentioned in Chapter 5.3.3., some course books, but also teachers, use the term "radioactive radiation". I confronted him/her with this statement and why he/she considered this to be true. He/she replied that this is a society-used term and that is why he/she uses it. Although this term is often used, it is still incorrect and should not be used in my opinion. If students use this term from the beginning, and have built upon their own physical construct (which can occur as

students' conceptions), it will be even more difficult to teach them about the actual properties of radioactivity. This would be an example of the origin of students' conceptions induced by language as described by Schecker et al. (2018, p. 12) (more in Chapter 4.1.). Therefore, it is important to use the correct term and not the socially popular term from the beginning, and, in the case of an already existing students' conception, to build a good learning environment to work on it as early as possible.

Question 6 - Types of Radiation Emitted from Nuclei When Radioactive Materials Decay

In addition to checking the types of radiation, Question 6 also serves to check whether the participants take this questionnaire seriously or give arbitrary answers. Since the majority of participants of all factors considered the three correct answers to be true and did not choose the invented term "Theta radiation" as the correct answer, it can be concluded that this questionnaire was filled out with care.

Question 7 - Definition of Half-Life

Most of the participants knew the correct definition of half-life. This was very surprising when considering the article from Lijnse et al. (1990, p. 71)), as I expected more people to believe that "The half-life (…) is the period '*in which the isotope loses its radioactivity'* (Lijnse et al. 1990, p. 71) (…)". This term was chosen by each factor with a relative frequency of less than 25%. When explaining why the participants had problems answering the questions, one participant replied that apart from the questions on half-life, the questionnaire was difficult. The questions about half-life were not that difficult for the participant because he/she had additionally learned about this subtopic in math classes.

Question 8 - Decay of a Sample of Iodine-131

In Question 8 i and 8 ii, the participants were tested to see if they could correctly apply the concept of the half-life in an example. This worked out very well since more than 75% of the participants of each factor level of the factors "types of schools" and "time passed since last school attendance" chose the correct answer. Some of them were not able to state how many iodine-131 atoms are remaining after two half-lives. They considered "0 atoms" to be correct. To sum up, some participants of all factors were able to give the correct answer after one half-life but not after two half-lives.

Although the majority of participants gave the correct answer, there is a remarkable difference between "recent school leavers", who provided correct answers more often than "non-recent school leavers".

It is particularly striking in the given answer, that the amount of remaining iodine-131 atoms after two half-lives was rising. The relative frequency for the option “100 million atoms” was higher after two half-lives than after one half-life. One explanation could be that they rather answered how many atoms have already decayed instead of how many atoms have not decayed yet.

Question 9 - Justification of the Iodine-131 Example

To answer this question, the participants had to state their justification for their answers in Question 8. Again, more than 75% of the participants of every factor gave the correct answer. All the other options were mentioned with a negligible relative frequency.

Question 10 and Question 11 - The Sealed Closet

Question 10 asks the participants when they would open the door of an iodine-131 filled closet. Question 10 and Question 11 showed significantly more distribution across the individual answers than the other items. As already mentioned, one participant wrote that he/she had problems especially with these two questions. The option “I would never open the door” was chosen the most often by participants from every factor. The participants who have chosen this option have an impractical fantasy of avoiding ionizing radiation altogether. Furthermore, the fear about the unstoppable and eternal radioactivity, respectively radiation, is greater than “*the idea about half-life being active or dangerous time*” (Hull et al., 2021a). Additionally, some participants told me that they would open the door immediately if something very important was in it. This statement indicates that they do not think about health hazards at all. The most chosen option to justify their answer to Question 10 is the option that “Never 100% of all atoms will be transformed”. Although this is consistent with the mathematical model of radioactive decay, it is also consistent with Alsop's (2000) finding that students see radioactivity as “*quintessentially eternal and never stopping*” (Alsop, 2001, p. 271). I had the impression that participants attempted to tick a correct statement as if Question 11 was an isolated question, rather than what the rationale was for their answer to Question 10. This was especially the case with

the option “After the half-life, half of the atoms will have transformed”, which many respondents selected despite choosing that they would never open the closet (that is, this “reason” is not actually related to their answer on the previous item).

Question 12 - Risk Management

Question 12 asked what the participants would do if they found a radioactive rock in a forest. Almost all of the participants of all factors would move away from the source. For some of them, the reason why they would move away is to gain distance to the rock, while the others would move away to not becoming radioactive themselves. The second option was mostly chosen by the factor level “others” and “non recent school leavers”. This answer clearly implies an undifferentiated view on irradiation and contamination. Ionizing radiation is dangerous for the human body, but when there is no contact with the radioactive substance, the human standing next to the source will not become radioactive. (cf. Prather & Harrington, 2001, p. 90)

The option “I would put a container over the rock to shield part of the radiation” was not chosen as often as I expected. Although this is considered to be a correct answer, only 25% of the participants of each factor have chosen this option. One of the participants asked me what the container is made of. Maybe, if I had written “I would put a steel container over the rock to shield part of the radiation”, the participants would be more likely to select this answer as correct. It obviously depends on what the container is made of, but regardless of the material, the container would definitely shield α radiation, since this type of radiation can be stopped by a sheet of paper. The question I asked, was whether it is necessary to put a container over the radioactive rock. As putting a container over a radioactive source would not be a wrong action, this option is considered to be correct as well. (cf. Grupen & Rodgers, 2016, p. 65; cf. Millar et al., 1990, pp. 339–340; cf. Millar & Gill, 1996, p. 31)

Only a negligible number of participants of every factor chose the option “I put on gloves and wash the rock with water from the nearest stream to wash away its radioactivity”. In consideration of the undifferentiated view of the participants regarding irradiation and contamination, the little relative frequency of every factor at this option surprised me. One participant filled out the questionnaire next to me and justified his/her thinking after ticking this option: he/she would wash the rock because

in every movie in which a nuclear disaster happens, the persons “in the white clothes washed each other with a high pressure cleaner”. (cf. Lijnse et al., 1990, p. 76)

Question 13 and Question 14 - Irradiating a Kiwi + Removing the Source

Question 13 and Question 14 ask whether the participants know that ionizing radiation is not radioactive and that a kiwi cannot be made radioactive by irradiation. When looking at the answers given to Question 13, it can be said that the participants are not aware of these facts. The highest reached relative frequency for this question is 43% for the option that “the radioactive source, the radiation and the kiwi are radioactive”, which indicates that less than half of the participants within every factor are of the same opinion. This was the most chosen option. Since most participants correctly stated the definition of radioactivity in Question 5, I am surprised that more than 60% of each factor stated that radiation itself is radioactive. It is particularly striking that the participants of every factor are not consistent in their answers. The assumption that the kiwi is radioactive increased from Question 13 to Question 14. This could be due to the wording of the answers. The correct answer to Q14 is that the kiwi will not become radioactive because radiation cannot make something radioactive. This response was chosen by 34% of respondents. In comparison, on Q13, a total of 51% of respondents gave answers indicating the view that the kiwi is not radioactive. It may be that the specific context about time and distance in Q14 persuaded a number of respondents to abandon their stance that the kiwi does not become radioactive. It should further be noted that about half of the 51% respondents on Q13 saying that the kiwi is not radioactive DID say that the radiation is radioactive, resulting in only 26% answering the prompt correctly. (cf. Johnson & Maidl, 2014, p. 9, cf. 2014; cf. Prather & Harrington, 2001, p. 92)

One person reasoned that the answers to the individual questions were too similar when asked what he/she had difficulties in when filling out the questionnaire. Question 14 could be affected by this observation. Likewise, the undifferentiated view regarding irradiation and contamination could lead to uncertainty on the part of the participants.

Question 15 - Generation of Radioactivity

Question 15 which asks whether radioactivity is natural, manmade or both, was not a major challenge for the participants. The majority had no difficulty with this question.

Question 16 - Controllability of Radioactive Decay

The participants of all factors did not have problems in answering Question 16. Since there was disagreement in the expert round between two options for this question, it was decided that both answers were correct. These are the options that the radioactive decay “can be controllable and can be uncontrollable” and “uncontrollable”. The question here is if one observes a single atom or a greater number of atoms. If one looks at a single atom, one cannot make a statement of when exactly the atom is going to decay. For example, a task in the article “Student Understanding of Emergent Aspects of Radioactivity” from Hull and Hopf (2020, pp. 23-27) asks: if one is watching a single atom with a half-life of 4 days, when he/she should start to watch the atom to see the decay process. Although many students give an answer in terms of half-life (observing the atom around the day of half-life), that is incorrect, as the half-life does not predict when a single atom will decay. Fission of a single atom is a random process; half-life provides information on when half the number of radioactive substances will have decayed only when there are a large number of atoms in that substance. To sum up, when observing a single atom, it cannot be predicted when it will decay, and this will therefore happen “uncontrollable”. But having a greater number of defined atoms and controlled conditions, it is possible to give a statement about how many atoms will have decayed after a certain time.

As there are two out of four options correct, the number of correct answers is relatively high for this single-choice question.

Question 17 - Danger of Radioactivity for the Human Organism

The answers given to Question 17 were expected. In this question, the participant should give a statement if radioactivity is dangerous for the human organism. One quarter of the participants of all factors stated that radioactivity is “dangerous” for the human organism. The relative frequency of all factors at this option is between 20% and 30% each. Are these participants, who stated that radioactivity is dangerous for the human organism, aware of background radiation? The option “can be harmless and can be dangerous” is the correct option. People should always have in mind that destroying a tumor with radioactivity can be dangerous for the human organism, but “*the healthy tissue will recover more easily than the cancerous tissue will*” (Grupen &

Rodgers, 2016, p. 22). Hence, according to Grupen and Rodgers (2016, pp. 65, 67, 180, 181) if someone can get well through medical applications with the help of radioactivity, it is more dangerous *not* to resort to this aid than to take the health risk upon oneself. None of the participants stated that radioactivity is “harmless”.

Question 18 - Airplane

Question 18 asks how radiation changes when comparing the position of an airplane and the earth’s ground. Most of the participants chose the option that “it increases with altitude”. This option is considered to be correct but if one looks at it more closely, it first decreases with altitude and then increases with altitude. This is due to the fact that the radiation originating from the earth’s surface is decreasing with altitude (terrestrial radiation) but then, secondary radiation ensures that radiation increases again (cosmic rays). Hence, a response of “none of the above” was coded as “correct”. However, based upon the answers of the experts in the expert panel, I also coded the selection of “it increases with altitude” as correct. The second most chosen option by all factors is that radiation “remains the same”, which is not correct.

If I had to recreate this question again, I would ask how the radiation changes when an airplane increases its altitude because it has to fly over a storm. In this case, the terrestrial radiation does not have to be taken into account and the correct answer is irrefutably “increases with altitude”.

## 6.5. Results Drawn from the Conducted Questionnaire

Since there are a lot of questions in the questionnaire, I want to summarize my results by means of bullet points. Each bullet point is described in greater detail in Chapter 5.3.3., Chapter 5.4.2. and Chapter 6.3. Those questions, which were the base of the statements, are mentioned in brackets. Additionally, in two of the three factors (“types of schools” and “have or have not seen the TV series ‘Chernobyl’”) there are no differences in the mean values based on the implemented ANOVA. Hence, I formulate the following statements in general terms. If there is a serious difference in the factor levels of “time passed since last school attendance”, it will be mentioned.

- The majority of participants are not aware of ubiquitous radioactivity. (*Question 4 - What Makes a Measuring Device for Radioactivity Click/Beep?*)

- The majority of participants think that concrete walls of rooms in which X-rays are performed are radioactive. (*Question 4 - What Makes a Measuring Device for Radioactivity Click/Beep?*) (cf. Millar et al., 1990, p. 339)

- The definition of radioactivity is clear for more than half of the participants of every factor (*Question 5 - Definition of Radioactivity*), but they cannot apply this knowledge to an example (*Question 13 - Irradiating a Kiwi*). For example, half of the “non recent school leavers” thought that the radiation itself is radioactive.

- The three types of radiation (i.e., α, β, γ) are known to most participants. (*Question 6 - Types of Radiation*)

- The definition of half-life is known to most participants (*Question 7 - Definition of Half-Life*). They are also able to state the correct number of remaining atoms after one half-life (*Question 8 - Decay of a Sample of Iodine-131*). However, some stated that after two half-life there will be zero atoms.

- A sizable proportion (approximately 32%) of the respondents tend to identify radioactivity, respectively radiation, as unstoppable and eternal. (*Question 10 - The Sealed Closet*) (cf. Alsop, 2001, p. 271)

- The majority of participants do not distinguish between irradiation and contamination. They are afraid of getting radioactive after irradiation and believe that radiation itself is radioactive (*Question 4 - What Makes a Measuring Device for Radioactivity Click/Beep?, Question 12 - Risk Management, Question 13 - Irradiating a Kiwi* and *Question 14 - Removing the Radioactive Source*).

- The majority of participants are aware of the fact that radioactive decay “can be controllable and can be uncontrollable”. They are also aware that radioactivity “can be harmless and can be dangerous” for the human organism. (*Question 16 - Controllability of Radioactive Decay* and *Question 17 - Danger of Radioactivity for the Human Organism*)

- The emotions regarding radioactivity are negative to neutral. More participants of the “5-year vocational school” and “recent school leavers” tend to have neutral emotions than participants from other types of schools and

"non recent school leavers". For the remaining factor levels, the emotions tend to be rather negative. (*Question 19 - Emotions*)

- More than half of all participants did have a hard time answering the questions. The most mentioned reasons were: "too little knowledge on radioactivity/physics", "school time too long ago" and "no knowledge on radioactivity".

## 6.6. Limitations

The research of this master's thesis is affected by a few limitations. One of them is that the participants are neither homogeneous in school nor in age. As mentioned in Chapter 6.2., most of the participants are of my age i.e., in their twenties. This may be due to the fact that this questionnaire was posted online and thus reached this kind of age group. Furthermore, the questionnaire was posted online due to corona, which in turn means that the target group tends to be younger.

In addition, many participants have attended a general secondary school or a 5-year vocational school. This could be due to the fact that the survey was only available online on diverse social media platforms which is used more frequently by younger persons. Probably more younger persons attended these schools and graduate with a "Matura".

I was also able to have a look at where the participants interrupted the questionnaire. Most participants ended the questionnaire at Question 8, where they have to state the remaining number of atoms after one, respectively two, half-lives. Apparently, some participants were deterred by the fact that they had to "calculate" something.

## 6.7. Recommendations for Further Research

Since the research for this master's thesis is based on two factor levels for each factor, it would be interesting to have a closer look on each "type of school" and every "time passed since last school attendance" group on their own. To be able to perform this, additional data should be collected from the respondents in all subgroups since some subgroups do not have enough participants to find significant results, particularly the polytechnic school and HLFS. Additionally, the factor levels could be reformed which could lead to other results in the ANOVA.

Another option for additional research would be to elaborate on the results of the respondents categorized as “experts” who were thus excluded from the research. These respondents were excluded because I assumed they would have an above-average knowledge of radioactivity. It would be interesting to test this assumption. If they indeed are above-average, it would be interesting to see on which items they perform better than average.

It would also be interesting to know if "recent school leavers" performed better because the knowledge they acquired in school was not that long ago or if there has been a change in the curriculum.

An additional option could be to find out if the knowledge on radioactivity depends on the duration of school attended. It can be investigated whether persons who have gone to school for a longer period of time have a greater knowledge about radioactivity than those who have gone to school for a shorter period of time.

Since the scoring system of the compiled questionnaire in this master’s thesis was evenly distributed with one point for each question, it would be interesting to assign different weighting factors for the different difficulty levels. This means that more points can be obtained for questions that are more difficult. Additionally, one of the questions (Q11) used in the survey validation interviews and in the first expert panel has not fulfilled the set requirement. Nevertheless, I used Question 11 since this question was already validated in prior research by the authors Hull and Hopf (2020). I also decided to award one point for this question since it shows that the participants in question have an extensive knowledge of radioactivity and have earned this point. In further research, it should be considered whether no points should be awarded for this question and to use this question to check misconceptions.

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# 10. Appendix

## 10.1. Abstract English

Talking about physics remains to be an unpopular topic in general. This may be due to the fact that a lot of adults do not remember anything they have learned at school. This master's thesis provides insight into adults' understanding of radioactivity in relation to the type of school they attended and their time since graduation. Using an online questionnaire composed of three main parts (theoretical part, pre-existing misconceptions, "*Inquiry into Radioactivity*" (Johnson, 2014)), data was collected from individuals with Austrian school-leaving qualifications. Based on the answers of 386 participants, a three-way ANOVA was performed, and it was found that there is a difference in knowledge about radioactivity between recent school leavers and non-recent school leavers. All other groups formed (i.e., school types, have seen "Chernobyl") show no significant difference. The definitions (e.g., radioactivity, half-life) were correctly stated but could not be applied in an example. In addition, the confusion between irradiation and contamination remains, as was already known from the literature.

## 10.2. Abstract German

Über Physik zu sprechen, ist im Allgemeinen immer noch ein unbeliebtes Thema. Das mag daran liegen, dass sich viele Erwachsene nicht mehr an das erinnern, was sie in der Schule gelernt haben. Diese Masterarbeit gibt einen Einblick in das Verständnis von Radioaktivität bei Erwachsenen in Abhängigkeit von der Art der besuchten Schule und der Zeit seit dem Schulabschluss. Mit Hilfe eines Online-Fragebogens, der sich aus drei Hauptteilen zusammensetzt (theoretischer Teil, bereits bekannte SchülerInnenvorstellungen, "*Inquiry into Radioactivity*" (Johnson, 2014)), wurden Daten von Personen mit österreichischem Schulabschluss erhoben. Basierend auf den Antworten von 386 TeilnehmerInnen wurde eine dreifaktorielle ANOVA durchgeführt. Es wurde festgestellt, dass es einen Unterschied im Wissen über Radioaktivität von jenen Teilnehmern gibt, welche kürzlich bzw. vor längerem die Schule abgeschlossen haben. Alle anderen gebildeten Gruppen (d. h. Schultypen, haben "Tschernobyl" gesehen) weisen keinen signifikanten Unterschied auf. Die Definitionen (z. B. Radioaktivität, Halbwertszeit) wurden zwar richtig

angegeben, konnten aber in einem Beispiel nicht angewendet werden. Außerdem bleibt die Verwechslung zwischen Bestrahlung und Kontamination bestehen, wie bereits aus der Literatur bekannt war.

## 10.3. Questionnaire German

**The Public's Knowledge on Radioactivity in Austria Affected by the Time Passed After Graduation and the Type of School Attended**

Deckblatt:
Diese Erhebung wird im Rahmen meiner Masterarbeit „*The Public's Knowledge on Radioactivity in Austria Affected by the Time Passed After Graduation and the Type of School Attended*" an der Universität Wien durchgeführt. Ziel ist es, das Wissen über Radioaktivität in Abhängigkeit von der Schulausbildung und der Zeit seit dem letzten Schulabschluss herauszufinden. Bekommen Sie kein schlechtes Gefühl, wenn Sie sich bei manchen Antworten nicht sicher sind. **Jeder beantwortete Fragebogen leistet einen großen Beitrag zu dieser Studie.**

Wer kann an dieser Befragung teilnehmen?

An dieser Befragung können alle Personen teilnehmen, welche z.B. über einen Pflichtschulabschluss, einen Abschluss einer Berufsschule, einen Abschluss einer allgemeinbildenden höheren Schule etc. verfügen.

Was muss ich tun?

Wenn Sie an dieser Befragung teilnehmen wollen, dann nehmen Sie sich bitte **10-15 Minuten** Zeit und füllen Sie den Fragebogen aus. Dieser Fragebogen ist **freiwillig** und **anonym**.

Wer erhält meine Daten und was passiert mit ihnen?

Ihre Daten werden gespeichert und ausschließlich zur Bearbeitung meiner Masterarbeit verwendet. Der Fragebogen ist **anonym**, es sind **keine personenbezogenen Daten** wie Name und Adresse anzugeben. Folglich können **keine Rückschlüsse** auf einzelne Personen gezogen werden. Ihre Daten werden **strikt vertraulich** behandelt.

An wen kann ich mich bei Fragen wenden?

Bei Fragen wenden Sie sich bitte an mich:
Eva Holzinger, BEd
a01404074@unet.univie.ac.at

Ich würde mich über Ihre Teilnahme und der damit verbundenen Unterstützung freuen.
Ich bedanke mich im Voraus und verbleibe mit freundlichen Grüßen

Eva Holzinger

Zustimmungserklärung

Ich habe die Informationen gelesen und verstanden. Hiermit erkläre ich mich, diesen Fragebogen freiwillig durchzuführen und bin mit der Verwendung meiner Daten für die interne Auswertung im Rahmen der Masterarbeit „The Public's Knowledge on Radioactivity in Austria Affected by the Time

Passed After Graduation and the Type of School Attended“ einverstanden. Ich bin mir bewusst, dass ich die Befragung jederzeit - ohne Angaben von Gründen - abbrechen kann.

---

1) Ich habe die Information gelesen, verstanden und stimme zu.
   * ich stimme zu
   * ich stimme nicht zu

---

2) Haben Sie in Ihrem Beruf Kontakt mit ionisierender Strahlung? Wenn ja, geben Sie bitte Ihren Beruf an.
   A) Ja, _____
   B) Nein

3) Haben Sie die Fernsehserie „Chernobyl“ gesehen?
   A) Ja
   B) Nein

4) Sie sehen nun eine Reihe von Begriffen. Kreuzen Sie alle Begriffe an, bei welchen ein Messgerät für Radioaktivität klicken würde.
   Mehrfachantwort möglich.
   A) Smartphone
   B) Umgebungsluft
   C) Ein Schulkind
   D) Betonwände in der Rezeption eines Krankenhauses
   E) Betonwände eines Krankenhausraumes, in dem Röntgenaufnahmen gemacht wurden
   F) Betonwände eines Schulgebäudes
   G) Zigarettenrauch
   H) Sonnenlicht
   I) Popcorn aus der Microwelle
   J) Banane

5) Geben Sie die Definition von Radioaktivität aufgrund folgender Aussagen an. Mehrfachantwort möglich.
   A) Radioaktivität geht nie mit einem Atomkernzerfall einher. Es beschreibt lediglich die Energieabgabe in Form von ionisierender Strahlung.
   B) Radioaktivität ist die fluoreszierende Eigenschaft von Atomen. Radioaktive Stoffe leuchten immer in Dunkelheit.
   C) Radioaktivität ist die Freigabe von Energie in Form von ionisierender Strahlung, nachdem ein instabiler Atomkern zerfallen ist.
   D) Radioaktivität ist die von einem Atomkern ausgesendete Strahlung. Diese Strahlung ist für den menschlichen Organismus sehr gefährlich.

6) Nennen Sie die Arten von Strahlung, die beim Zerfall radioaktiver Stoffe von Atomkernen ausgesendet werden.
   Mehrfachantwort möglich.

A) Radiowellen
B) Alphastrahlung
C) Gammastrahlung
D) Betastrahlung
E) Thetastrahlung

7) Kreuzen Sie die richtigen Aussagen über die Halbwertszeit an.
Mehrfachantwort möglich.
A) Die Halbwertszeit ist für alle Elemente gleich.
B) Die Halbwertszeit gibt jene Zeit an, in der sich jeweils die Hälfte der ursprünglich vorhandenen Atomkerne in andere Atomkerne umwandeln.
C) Halbwertszeiten gibt es nur im Nanosekunden-Bereich.
D) Die Halbwertszeit ist jene Periode, in welcher der Stoff seine Radioaktivität verliert. Danach ist der Stoff nicht mehr radioaktiv.

8) Iod-131 ist ein Beispiel eines radioaktiven Atoms. Es hat eine Halbwertszeit von 8 Tagen. Stellen Sie sich vor, dass es zu Beginn 100 Millionen Iod-131-Atome gibt. Wieviel Iod-131 wird sich nach … noch nicht umgewandelt haben?

... i. 8 Tagen? ii. 16 Tagen?

i) ... nach 8 Tagen?

A) 100 Millionen Atome

B) 50 Millionen Atome

C) 0 Atome

D) 100 Millionen ODER 0 Atome

E) 65,5 Atome

ii) ... nach 16 Tagen?

A) 100 Millionen Atome

B) 25 Millionen Atome

C) 0 Atome

D) 100 Millionen ODER 0 Atome

E) 32,8 Atome

9) Erklären Sie kurz, wie Sie zu Ihren Antworten (zu Fragen 8ai - 8aii) gekommen sind. Kreuzen Sie alle Aussagen an, welche Sie zu dieser Antwort geführt haben.
Mehrfachantwort möglich.

A) Nach der Halbwertszeit werden sich die Hälfte der Atome umgewandelt haben

B) Es ist zufällig

C) Man kann keine Hälfte eines Atoms haben

D) Atome verschwinden nicht

E) Nach zwei Halbwertszeiten haben sich alle Atome umgewandelt

F) Zum Schluss haben sich alle Atome umgewandelt

10) Iod-131 ist ein Beispiel eines radioaktiven Atoms. Es hat eine Halbwertszeit von 8 Tagen. Stellen Sie sich vor, dass Ihr Kleiderschrank irgendwie mit Iod-131 - Gas gefüllt wurde. Der Schrank ist so mit Klebeband versiegelt, dass das Gas nicht herauskommen kann. Sie stehen draußen vor dem Kleiderschrank, bewahren aber wertvolle Dinge im Schrank auf. Wie lange würden Sie warten bis Sie das Klebeband wegnehmen und die Tür öffnen?

A) Weniger als 1 Tag

B) Mehr als 1 Tag aber weniger als 8 Tage

C) 8 Tage

D) Mehr als 8 Tage aber weniger als 16 Tage

E) 16 Tage

F) Mehr als 16 Tage, aber ich würde die Tür irgendwann öffnen

G) Ich würde die Tür nie öffnen

H) Es hängt von verschiedenen Faktoren ab

11) Erklären Sie kurz, wie Sie zu Ihrer Antwort gekommen sind. Kreuzen Sie alle Aussagen an, die Sie zu dieser Antwort geführt haben.
Mehrfachantwort möglich.

A) Ich warte bis sich 100% aller Atome umgewandelt haben

B) Es werden sich nie 100% aller Atome umwandeln

C) Nach der Halbwertszeit werden sich die Hälfte der Atome umgewandelt haben

D) Nach der Halbwertszeit halbiert sich die Menge der Strahlung

E) Nach zwei Halbwertszeiten haben sich alle Atome umgewandelt

F) Nach zwei Halbwertszeiten gibt es keine Strahlung mehr

G) Mehr Information wird benötigt

H) Der Kleiderschrank wird radioaktiv

I) Strahlung kommt durch die Tür

12) Sie finden im Schwarzwald (Deutschland) ein unbekanntes Gestein. Ihr Messgerät für Radioaktivität schlägt bedenklich weit aus. Es könnte sich hier also um radioaktives Gestein handeln. Was machen Sie?
Mehrfachantwort möglich.
    A) Ich entferne mich von dem Gestein, um Abstand zur Quelle zu gewinnen.
    B) Ich entferne mich von dem Gestein, um nicht selbst radioaktiv zu werden.
    C) Ich stülpe einen Behälter über das Gestein, um einen Teil der Strahlung abzuschirmen.
    D) Ich ziehe Handschuhe an und wasche das Gestein mit Wasser des nächsten Baches ab, um seine Radioaktivität abzuwaschen.

13) Vor Ihnen liegt folgender Versuchsaufbau, welcher in der Abbildung zu sehen ist. Die Abbildung zeigt eine radioaktive Quelle. Von dieser wird Strahlung ausgesendet (welche in dieser Skizze nicht gezeigt wird). Diese Strahlung trifft auf eine Kiwi. Die radioaktive Quelle und die Kiwi sind 2 cm voneinander entfernt.

Versuchsaufbau:

*Abbildung 1: Versuchsaufbau*

Geben Sie jenes Objekt/jene Objekte (radioaktive Quelle, Strahlung und Kiwi) an, welches/welche radioaktiv ist/sind? (eine Antwort ist möglich)

    A) Die radioaktive Quelle, die Strahlung und die Kiwi sind radioaktiv.
    B) Die radioaktive Quelle und die Strahlung sind radioaktiv.
    C) Die radioaktive Quelle und die Kiwi sind radioaktiv.
    D) Die radioaktive Quelle ist radioaktiv.

14) Die radioaktive Quelle wird nach 24 Stunden entfernt. Ist die Kiwi jetzt radioaktiv?
    A) Ja, die Kiwi ist durch die Strahlung radioaktiv geworden - unabhängig von der Distanz.
    B) Ja, die Kiwi ist durch die Strahlung radioaktiv geworden, weil sie nah genug an der Quelle war.
    C) Ja, die Kiwi ist durch die Strahlung radioaktiv geworden, weil sie während des Experiments lange genug neben der Quelle war.
    D) Nein, die Kiwi ist durch die Strahlung nicht radioaktiv geworden, weil sie, um radioaktiv zu werden, eine längere Dauer neben der Strahlungsquelle verweilen müsste.
    E) Nein, die Kiwi ist durch die Strahlung nicht radioaktiv geworden, weil die Strahlung Objekte nicht radioaktiv macht.

15) Radioaktivität ist:
    A) Natürlich
    B) Von Menschen erzeugt
    C) Kann natürlich auftreten und kann vom Menschen erzeugt werden

D) Keine der Antwortmöglichkeiten ist richtig

16) Der radioaktive Zerfall ist:
   A) Kontrollierbar
   B) Unkontrollierbar
   C) Kann kontrollierbar und kann unkontrollierbar sein
   D) Keine der Antwortmöglichkeiten ist richtig

17) Radioaktivität ist für den Menschen:
   A) Ungefährlich
   B) Gefährlich
   C) Kann gefährlich und kann ungefährlich sein
   D) Keine der Antwortmöglichkeiten ist richtig

18) Wie verändert sich die Strahlung in einem Flugzeug im Vergleich zum Boden?
   A) Sie nimmt mit der Höhe zu
   B) Sie nimmt mit der Höhe ab
   C) Sie bleibt gleich
   D) Keine der Antwortmöglichkeiten ist richtig

19) Sind Ihre Emotionen bezüglich Radioaktivität positiv, negativ oder neutral?
   A) Positiv
   B) Negativ
   C) Neutral
   D) Keine Angabe

20) In welchen der folgenden Schultypen haben Sie ihren höchsten Abschluss absolviert?
   A) Pflichtschule
   B) Polytechnische Schule
   C) Allgemeinbildende höhere Schule
   D) Berufsschule
   E) Berufsbildende mittlere Schule
   F) Berufsbildende höhere Schule

21) Welche der folgenden Schultypen haben sie besucht (wenn Ihr Schultyp nicht dabei ist, geben sie diesen bitte im leeren Feld an):

AHS:

   A) Gymnasium
   B) Realgymnasium
   C) Wirtschaftskundliches Realgymnasium
   D) (leere Zeile)

Berufsbildende mittlere Schule:

   A) TMS
   B) HAS

C) FSWB
D) FM
E) HF
F) FS
G) LFS
H) BSPA
I) FW/EWF
J) Fachschule für pädagogische Assistenzberufe
K) Schule für Gesundheits- und Krankenpflege
L) (leere Zeile)

Berufsbildende höhere Schule:

A) HTL
B) HAK
C) HLM
D) HBLA
E) HLF
F) HLW
G) HLFS
H) BAfEP
I) BASOP
J) (leere Zeile)

22) Wie lange ist ihre Schulzeit her?
A) 0 - 5
B) 6 - 10
C) 11 - 15
D) 16 - 20
E) 21 - 25
F) 26 - 30
G) 31 - 35
H) 36 - 40
I) 40 +

23) Wenn Sie noch in die Schule als Schüler:in gehen, in welcher Schulstufe (in Jahren) sind Sie? Wenn nicht, lassen Sie die Zeile bitte frei. (z.B. die 6. Schulstufe entspricht der 2. Klasse Unterstufe)

_____ (freie Zeile für Schulstufe)

24) Geben Sie Ihr biologisches Geschlecht an.
A) Männlich
B) Weiblich
C) Divers

25) Zu welcher dieser Alterskategorien gehören Sie?
A) 17 oder jünger

B) 18 - 25
C) 26 - 35
D) 36 - 45
E) 46 - 55
F) 56 oder älter

26) Haben Sie sich bei der Beantwortung der Fragen schwergetan? Wenn ja, begründen Sie ihre Antwort.
A) Ja, weil _____
B) Nein

27) Woher stammt Ihr Wissen über Radioaktivität?
Mehrfachantwort möglich.
A) Fernsehen (z.B. Serie Chernobyl)
B) Zeitungen
C) Schule
D) Internet
E) (freie Zeile)

<u>Für darüberhinausgehende Informationen:</u>

Wenn Sie so freundlich wären, mit mir über dieses Thema im Detail zu sprechen, geben Sie bitte am Ende des Fragebogens gerne ihre E-Mail-Adresse an. In diesem Fall erklären Sie sich dazu bereit, vertiefende Informationen auf Ihren Fragebogen zu geben. In diesem Fall interessieren mich die Beweggründe Ihrer Antworten. Sie können diese Zeile aber auch gerne **freilassen**!

Wenn Sie sich bereit erklären, Ihren Fragebogen mit mir näher im Detail zu besprechen, geben Sie bitte hier Ihre E-Mail an. Bei Ablehnung kann diese Zeile freigelassen werden. **Dies ist freiwillig!**

_____

(Die letzte Seite des Fragebogens listet alle Quellen, welche zur Erstellung des Fragebogens herangezogen wurden, auf.)

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## 10.4. Questionnaire English

**The Public's Knowledge on Radioactivity in Austria Affected by the Time Passed After Graduation and the Type of School Attended**

Cover Sheet:
What is the purpose of this survey?

This survey is conducted in the context of my master's thesis "The Public's Knowledge on Radioactivity in Austria Affected by the Time Passed After Graduation and the Type of School Attended" at university Vienna. The aim is to find out the knowledge about radioactivity depending on the type of school attended and the time passed after graduation. Don't get a bad feeling if you are not sure about some answers. Every questionnaire answered makes a great contribution to this study.

Who can participate in this survey?

All persons can take part in this survey who, for example, have a compulsory school leaving certificate, a leaving certificate from a vocational school, a leaving certificate from a general secondary school, etc.

What do I have to do?

If you would like to participate in this survey, please take 10-15 minutes and complete the questionnaire. This questionnaire is voluntary and anonymous.

Who receives my data and what happens to it?

Your data will be stored and used exclusively for processing my master's thesis. The questionnaire is anonymous, no personal data such as name and address are to be provided. Consequently, no conclusions can be drawn about individual persons. Your data will be treated strictly confidential.

Who can I contact with questions?

If you have any questions, please contact me:
Eva Holzinger, BEd
a01404074@unet.univie.ac.at

I would be pleased about your participation and the associated support. I thank you in advance and remain with kind regards

Declaration of consent

I have read and understood the information. I hereby declare that I have voluntarily completed this questionnaire and agree to the use of my data for internal evaluation as part of the master's thesis "The Public's Knowledge on Radioactivity in Austria Affected by the Time Passed After Graduation and the Type of School Attended". I am aware that I can cancel my survey at any time - without giving reasons.

1) I have read, understood, and agree to the information.
* I agree
* I do not agree

---

2) Do you have contact with ionizing radiation in your job? If yes, please indicate your profession.
    C) Yes, _____
    D) No

3) Have you seen the television series „Chernobyl“?
    C) Yes
    D) No

4) You will now see a series of terms. Tick all the terms for which a measuring device for radioactivity would klick/beep.
   Multiple answers possible.
    A) Smartphone
    B) Ambient air
    C) A school child
    D) Concrete walls in the reception room of a hospital
    E) Concrete walls in a room where x-rays are performed in a hospital
    F) Concrete walls of a school building
    G) Cigarette smoke
    H) Sunlight
    I) Popcorn from a microwave oven
    J) Banana

5) Give the definition of radioactivity based on the following statements. (Multiple answers possible)
    A) Radioactivity is never accompanied by atomic nuclear decay. It only describes the release of energy in the form of ionizing radiation.
    B) Radioactivity is the fluorescent property of atoms. Radioactive substances always glow in darkness.
    C) Radioactivity is the release of energy in the form of ionizing radiation. It happens after an unstable atomic nucleus decays.
    D) Radioactivity is the radiation emitted by an atomic nucleus. This radiation is very dangerous for the human organism.

6) Name the types of radiation emitted from nuclei when radioactive materials decay. (Multiple answers possible)
    E) Radio waves
    F) Alpha radiation
    G) Gamma radiation

H) Beta radiation
I) Theta radiation

7) Tick the correct statements about the half-life.
Multiple answers possible
E) The half-life is the same for all elements.
F) The half-life is the time it takes for half of the original atomic nuclei to change into other atomic nuclei.
G) Half-lives exist only in the nanosecond range.
H) The half-life of a radioactive isotope is the period in which the isotope loses its radioactivity. During this period, the isotope is dangerous. After that period, the isotope is no longer radioactive or dangerous.

8) Iodine-131 is an example of a radioactive atom. It has a half-life of 8 days. Imagine that there are 100 million iodine-131 atoms at the beginning. How much iodine-131 will not have transformed after ...?
... i. 8 days? ii. 16 days?

i) ... After 8 days? (one answer option)

A) 100 million atoms

B) 50 million atoms

C) 0 atoms

D) 100 million OR 0 atoms

E) 65.5 atoms

ii) ... after 16 days? (one answer option)

A) 100 million atoms

B) 25 million atoms

C) 0 atoms

D) 100 million OR 0 atoms

E) 32.8 atoms

9) Briefly explain how you arrived at your answers (to questions 8ai - 8aii). Tick all the statements which led you to this answer.
Multiple answers possible.

A) After the half-life half of the atoms will have transformed

B) It is random

C) You cannot have half of an atom

D) Atoms do not disappear

E) After two half-lives all atoms will have transformed

F) At the end, all atoms have transformed

10) Iodine-131 is an example of a radioactive atom. It has a half-life of 8 days. Imagine that your closet has somehow been filled with iodine-131 gas. The closet is sealed with tape so that the gas cannot get out. You are standing outside the closet, but you keep valuable things in the closet. How long would you wait to remove the tape and open the door?

A) Less than 1 day

B) More than 1 day but less than 8 days

C) 8 days

D) More than 8 days but less than 16 days

E) 16 days

F) More than 16 days but I would open the door sometime

G) I would never open the door

H) It depends on several factors

11) Briefly explain how you arrived at your answer. Tick all the statements that led you to this answer.
Multiple answers possible.

A) I wait until 100% of all atoms have transformed.

B) Never 100% of all atoms will be transformed.

C) After the half-life, half of the atoms will have transformed.

D) After the half-life the amount of radiation will be halved

E) After two half-lives, all atoms will have transformed.

F) After two half-lives there will be no more radiation

G) More information is needed

H) The closet becomes radioactive

I) Radiation comes through the door

12) You find an unknown rock in the Black Forest (Germany). Your measuring device for radioactivity deflects alarmingly far. So, this could be a radioactive rock. What do you do?
Multiple answers possible.

A) I move away from the rock to gain distance from the source.
B) I move away from the rock to avoid becoming radioactive myself.

C) I put a container over the rock to shield part of the radiation.
D) I put on gloves and wash the rock with water from the nearest stream to wash away its radioactivity.

13) In front of you is the following experimental setup, which can be seen in the figure. You can see a radioactive source. Radiation is emitted from this source (which is not shown in this sketch). This radiation irradiates a kiwi. The radioactive source and the kiwi are 2 cm apart.

Experimental setup:

*Figure 2: Experimental setup*

Indicate that object(s) (radioactive source, radiation, and kiwi) which is/are radioactive? (Multiple answers are possible)

E) The radioactive source, the radiation and the kiwi are radioactive.
F) The radioactive source and the radiation are radioactive.
G) The radioactive source and the kiwi are radioactive.
H) The radioactive source is radioactive.

14) The radioactive source is removed after 24 hours. Is the kiwi now radioactive?
A) Yes, the kiwi became radioactive due to the radiation regardless of the distance.
B) Yes, the kiwi became radioactive due to the radiation because it was close enough to the source.
C) Yes, the kiwi became radioactive due to the radiation because it was close enough to the source for long enough during the experiment.
D) No, the kiwi did not become radioactive due to the radiation because in order to become radioactive it would have to receive radiation for a longer duration from the source.
E) No, the kiwi did not become radioactive due to the radiation because radiation does not make objects radioactive.

15) Radioactivity is:
E) natural
F) manmade
G) can occur naturally and can be produced by humans
H) none of the answer options is correct

16) The radioactive decay can be:
E) controllable
F) uncontrollable
G) can be controllable and can be uncontrollable

H) none of the answer options is correct

17) For human organism radioactivity is:
   E) harmless
   F) dangerous
   G) can be harmless and can be dangerous
   H) none of the answer options is correct

18) How does the radiation in an airplane change compared to the ground?
   A) it increases with the altitude
   B) it decreases with the altitude
   C) it remains the same
   D) None of the answer options is correct

19) Are your emotions about radioactivity positive, negative, or neutral?
   E) positive
   F) negative
   G) neutral
   H) not specified

20) In which of the following types of schools did you graduate with your highest degree?
   G) Compulsory school
   H) Polytechnic school
   I) General secondary school
   J) Vocational school
   K) 3-year vocational school
   L) 5-year vocational school

Depending on the type of school the respondents chose, there is a subcategory (except compulsory school, polytechnic school, and vocational school):

21) Which of the following types of schools did you attend (if your school type is not included, please indicate it in the blank field):

AHS:

   E) Gymnasium
   F) Realgymnasium
   G) Wirtschaftskundliches Realgymnasium
   H) (leere Zeile)

Berufsbildende mittlere Schule:)

   M) TMS
   N) HAS
   O) FSWB
   P) FM
   Q) HF
   R) FS

S) LFS
T) BSPA
U) FW/EWF
V) Fachschule für pädagogische Assistenzberufe
W) Schule für Gesundheits- und Krankenpflege
X) (leere Zeile)

Berufsbildende höhere Schule:

K) HTL
L) HAK
M) HLM
N) HBLA
O) HLF
P) HLW
Q) HLFS
R) BAfEP
S) BASOP
T) (leere Zeile)

22) a) How long ago were you in school?

A) 0 - 5
B) 6 - 10
C) 11 - 15
D) 16 - 20
E) 21 - 25
F) 26 - 30
G) 31 - 35
H) 36 - 40
I) 40 +

23) If you are still in school as a student, what grade level (in years) are you in? If not, please leave the line blank. (e.g., the 6th grade corresponds to the 2nd grade lower school)

_____ (free line for school level)

Demographics

24) Indicate your biological sex?

A) male
B) female
C) diverse

25) To which of these age categories do you belong?

G) 17 or younger
H) 18 - 25
I) 26 - 35

J) 36 - 45
K) 46 - 55
L) 56 or older

26) Did you have a hard time answering the questions? If yes, justify your answer.
C) Yes, because _____
D) No

27) Where does your knowledge about radioactivity come from?
Multiple answers possible.
F) Television (e.g. series Chernobyl)
G) Newspapers
H) School
I) Internet
J) (free line)

For information beyond that:

If you would be so kind as to talk to me about this topic in detail, please feel free to provide your e-mail address at the end of the questionnaire. In this case, you agree to provide more detailed information in response to your questionnaire. In this case I am interested in the motives of your answers. However, it is possible to **leave** this line blank!

If you agree to discuss your questionnaire with me in more detail, please enter your e-mail here. If you decline, this line can be left blank. **This is voluntary!**

_____

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