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ABSTRACT

In education context "*competency*" is an increasingly popular term. According to Eriksson *et al.* (2014) it can be defined as knowing "what to focus on in a given situation and how to interpret it in an appropriate, disciplinary manner" (p.168). In teaching particle physics various visualizations are used to illustrate abstract concepts, but little is known on what learners discern from such representations, even though everyday conceptions may be barriers to disciplinary discernment [7]. This diploma thesis is a report on a study involving the discernment of students and teachers. In total 174 participants with various backgrounds participated in a survey about two different visualizations concerning particle physics. A video about the structure of matter and a representation of a measurement with a pixel detector and corresponding user interface were analyzed. The study approach was interpretive-hermeneutic and category-based. The reference categories were the five *Levels of Discernment* which had been introduced for an astronomical representation in form of the *Anatomy of Disciplinary Discernment (ADD)* by Eriksson *et al.* (2014). There are two main analytical outcomes: Firstly, the conclusions of the study correspond to the *ADD*. This means that it is also valid for visualizations in particle physics. Secondly, the participants answers were used to give recommendations to improve the analyzed visualizations.

ABSTRACT IN GERMAN

Im Bildungskontext wird der Begriff „*Kompetenz*" immer populärer. Er beinhaltet zwei Aspekte: Kompetent ist jemand, der seinen Fokus auf das Wesentliche richtet und das Wahrgenommene auch auf wissenschaftlich angemessene Weise interpretiert [7]. Im Bereich der Teilchenphysik werden verschiedene Visualisierungen verwendet, um abstrakte Konzepte im Unterricht zu veranschaulichen. Doch was Lernende von solchen Repräsentationen wahrnehmen, wurde bisher noch nicht ausreichend untersucht. Dass es einer derartigen physikdidaktischen Forschung bedarf, ist auf Alltagskonzepte zurückzuführen, die Hindernisse für wissenschaftlich angemessene Wahrnehmung darstellen können. Im Rahmen der vorliegenden Diplomarbeit wurde eine Studie durchgeführt, die sich mit der Wahrnehmung von Schüler*innen, Studierenden und Lehrenden beschäftigt. Insgesamt nahmen 174 Teilnehmer*innen unterschiedlicher Bildungshintergründe an einer Umfrage über zwei verschiedene Visualisierungen im Bereich der Teilchenphysik teil. Zum einen wurde ein Video über den Aufbau der Materie und zum anderen die Repräsentation einer Messung mit einem Pixeldetektor und zugehöriger Benutzeroberfläche analysiert. Es handelte sich um eine qualitative Studie mit hermeneutisch-interpretativem Ansatz. Die Analyse erfolgte auf Basis von Kategorien, wobei die fünf *Levels of Discernment* als Vorbild herangezogen wurden. Diese waren in Form der *Anatomy of Disciplinary Discernment* von Eriksson *et al.* (2014) eingeführt worden. Es gibt zwei Hauptresultate der Studie: Einerseits entsprechen die analytischen Ergebnisse der *Anatomy of Disciplinary Discernment,* was verdeutlicht, dass dieses Modell auch auf Repräsentationen in der Teilchenphysik angewandt werden kann. Andererseits wurden die Antworten der Studienteilnehmer*innen verwendet, um Empfehlungen zur Verbesserung der analysierten Visualisierungen zu formulieren.

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0. Introduction

νομίζεται μὲν εἶναι καὶ δοξάζεται τὰ αἰσθητά, οὐκ ἔστι δὲ κατ' ἀλήθειαν ταῦτα, ἀλλὰ τὰ ἄτομα μόνον καὶ τὸ κενόν. ([13], p. 378)

One accepts and believes that the perceived objects exist in truth. Nonetheless, these do not really exist, but only the atoms and the empty space.

In ancient Greece natural philosophers have already though about the particular nature of matter. Leucippus and his student Democritus were the first to claim that matter is not continuous, but rather made up of "ἄτομα", undividable constituents, and "κενόν", empty space, in between as cited above.

2500 years later the assertions are similar, even though they have been slightly changed as a result of intense research. What is referred to as "atom" nowadays, is not the smallest possible unit. It rather is made up of the elementary particles as described in the Standard Model. However, this current way of thinking is very likely to be just one step of a large stairway. The composition of the universe evokes fascination, which connects the past with the future. Scientists from all over the world are currently elaborating different possibilities to extend the research conducted at the *Large Hadron Collider* (LHC), the world's largest and most powerful particle accelerator hosted by CERN. In this respect it is important to emphasize that research in particle physics does not end in itself but has a great impact on modern life. Technologies developed by scientists at CERN have various applications in medicine, e.g. contributions to cancer therapy, in telecommunication, e.g. development of the World Wide Web, and many others. In short, the fundamental principles of particle physics as well as their applications are worth learning.

Thus, there is the Physics Education Research facility "*S'Cool LAB*" on-site at CERN. High school students and teachers are invited to contribute to research projects by taking part in hands-on and minds-on particle physics experiments. In the framework of S'Cool LAB's learning activities and CERN's outreach efforts, many visualizations are produced to illustrate the abstract concepts of particle physics. However, although everyday conceptions may be barriers to disciplinary discernment, little is known on what learners discern from such visualization in particle physics. In contrast, discernment from visualizations in astronomy has recently been investigated by Eriksson *et al.* (2014) who introduced five *Levels of Discernment* in form of the *Anatomy of Disciplinary Discernment* (ADD).

The subject of this diploma thesis is, what students and teachers discern, when they engage with visualizations in particle physics. To answer this question, a qualitative study examining and evaluating a video about the structure of matter and the representation of a measurement with a pixel detector and corresponding user interface was planned and performed. The analysis was based on the five above-mentioned *Levels of Discernment* and resulted in recommendations for improving the analyzed representations.

This thesis is a report on the investigation process from the initial engagement with theoretical literature to the final analysis of the collected data. It is structured as follows:

Chapter 1 provides an overview of the literature encompassing learners and their discernment, representations and their affordances, as well as the relation between both aspects. Furthermore, a brief introduction to the content knowledge of particle physics is given.

In **chapter 2** the main research questions are outlined.

The analyzed representations are described in **chapter 3**. Their style and affordances in terms of particle physics as well as their applications at CERN are addressed.

Chapter 4 gives an overview of the methodology of the study. This encompasses the study approach, the data collection process including development and administering of the questionnaire, and the analysis approach.

Acquisition and specific characteristics of the different groups of participants are presented in **chapter 5**.

Chapter 6 focuses on quality issues and their implementation in the study. Furthermore, problems regarding reliability, validity, and bias in this study are discussed.

The analysis of the collected data is described separately for both visualizations in **chapter 7**. To enable the repeatability of the study, the content and analysis categories are defined and examples for each category are provided. Moreover, the results of the analysis are presented and interpreted and recommendations for improving the analyzed representations are given.

In **chapter 8** conclusions are drawn.

Sources and literature are listed in **chapter 9.**

Finally, the questionnaire in its initial and final version is appended in **chapter 10.** The appendix also contains a table that illustrates the interrater reliability.

1. THEORETICAL BACKGROUND

The overall aim of teaching is to transfer knowledge to learners. Media are means of knowledge transfer, and thus help to reach learning goals [16]. The term "*medium*" comprises a variety of means for teaching practice [16]. In the broadest sense the teacher is a medium as well [16]. However, in this thesis the term "*medium*" refers to non-personal means for knowledge transfer [16]. Media didactics is concerned with teaching by means of media and aims to provide a theoretical background as well as to recommend implementation possibilities [16]. It must not be confused with media education which itself is a teaching subject and intends to foster a reflective use of media [16]. In the following I engage with media according to media didactics.

When evaluating the potential of knowledge transfer intended by a certain sender (e.g., a teacher), the focus must be on the learners as receiver, the knowledge as message, and the representation as medium (see FIGURE 1). This chapter is divided into four subchapters: learners, representations, relation between learners and representations, and content knowledge of particle physics.

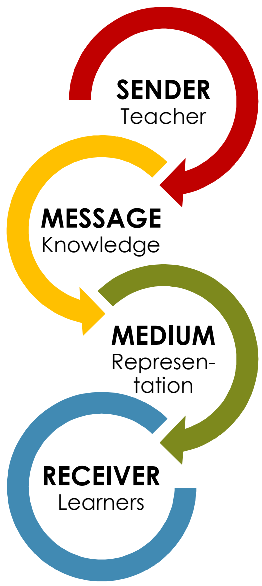

FIGURE 1: The teacher as sender wants to transfer a message, i.e. disciplinary knowledge, via a representation as medium to the learners as receiver.

1. A. Learners

Learners constitute the receivers of the knowledge transferred through the representation as a medium. Concerning the learners, there are two important aspects, which need to be considered: preconceptions and discernment.

1. A. 1. Preconceptions

Firstly, learners have diverse everyday conceptions, which are termed "*preconceptions*", before they engage with disciplinary representations. As these preconceptions tend to be inaccurate from a physics point of view, learners need to overcome them to achieve disciplinary knowledge. When teaching a specific topic, one needs to be aware of corresponding preconceptions. In the following the most common concerning particles, quantum objects and radiation are listed, since these topics relate to the visualizations analyzed in this thesis.

1. A. 1. 1. Preconceptions about particles

- **Macroscopic characteristics:** In general, learners tend to attribute macroscopic, everyday characteristics to elementary particles, e.g. color and shape [5]. Furthermore, they believe that elementary particles expand in case of temperature increase, and thereby the macroscopic object expands [9]. The preconception of macroscopic characteristics is also intensified by misleading teaching methods [9]. E.g., a common way of introducing the particular nature of matter is using the fragmentation principle [9]: At first, a macroscopic object (e.g., a sugar cube) is really divided into finer and finer fragments and then theoretically [9]. If learners follow this path, they are more likely to transfer properties of visible objects to submicroscopic particles [9].

- **Continuous versus particular nature of matter:** Furthermore, learners use a continuous rather than a particle model of matter for explaining everyday physics phenomena, unless it is offered as a reasonable explanation [36]. Then, most of them accept and use the particle model, although the acceptance varies for different age groups [36]. This means that middle school students are less likely to accept it compared to high-school students [36].

- **Empty space:** After introduction of the particle model, some learners tend to add it to their previous continuous model [36]. Misleading representations in schoolbooks reinforce this preconception (e.g., the representation of a glass filled with 'water' and H_2O-molecules) [36]. Therefore, learners struggle to believe that there is nothing between the particles and they do not accept the concept of empty space [36]. They rather believe that 'air' is between the particles of every solid or gaseous material, even between the air molecules themselves, or 'water' between H_2O molecules as mentioned above [5, 31]. Misleading wordings also reinforce these preconceptions (e.g., "Molecules are 'inside' the water." or "Quarks are 'inside' the proton.") [9]. Instead the wording "is made up of" should be used when talking about the composition of matter [9].

- **Constant motion:** In addition, the movement from the everyday concept of rest to the concept of constant motion of particles is challenging for learners [5]. They rather believe that after a while particles stop moving like macroscopic objects do [9].

- **Models versus reality:** Learners want to know how matter is composed in reality and are not satisfied with the model aspect of particle physics [9]. This attitude constitutes a learning obstacle, since models of the reality are the only way, in which one can talk about particle and quantum physics [25].

- **Planetary model of the atom:** The planetary model is the most common preconception about the structure of atoms [25]. In this model electrons are locatable all the time and move around the nucleus along circular paths, between which they can 'jump' by emitting or absorbing energy in form of a photon [25]. Learners neglect that electrons on circular paths are accelerated and would emit energy all the time [25].

- **Electron clouds, shells, and orbitals:** Besides the planetary model there are other common preconceptions. According to the cloud model, the atom is composed of a nucleus and a static electron cloud, i.e. the electron is thought of as 'smeared object' [25]. Some learners think that the atom is made up of thick continuous or thin outer shells, within which one cannot tell where the electron is [25]. The orbital model describes where the electrons are approximately locatable [25]. Often learners use various models simultaneously [25].

1. A. 1. 2. Preconceptions about quantum objects

- **Mass as most important property:** Learners take the mass of classical objects as its most important physical quantity and transfer this way of thinking to quantum objects [37]. Thus, they think that quantum objects can mainly be considered as particles because of their mass [37].

- **Permanent location property:** Learners tend to assign a location to particles all the time [37]. They only think that it may be difficult to measure the location (e.g., because the particles move too fast, due to the wave-particle-duality or the uncertainty principle) [37].

- **Particle and wave properties simultaneously:** A quantum object is as particle permanently locatable and at the same time surrounded by a wave which causes interference phenomena [37]. Besides, learners think that an electron, which makes up an atom, sits on a wave, and thereby moves up and down [25].

1. A. 1. 3. Preconceptions about ionizing radiation

- **Radioactivity is man-made:** Learners think that radioactivity is artificial and man-made [20]. It even goes as far as to consider any technical device or industry as radioactive source [20]. Furthermore, they neglect that we are surrounded by natural radioactive sources (e.g., in air or rock) and ionizing radiation in form of cosmic radiation all the time [20].

- **Radiation is dangerous:** Ionizing radiation (particle and electromagnetic radiation) is always dangerous from a learner's point of view [20]. It is only considered as less dangerous, if it is useful (e.g., X-rays used for medical purposes) [20]. Sometimes a dose argumentation is used, namely that radiation is not dangerous until a certain dose is exceeded [20]. Furthermore, the preconceptions of artificiality and danger are combined and hence, learners believe that any technical device or industry is a source of dangerous radiation [20].

- **Radioactive radiation:** "Radioactive radiation" is a common but misleading shortening for "ionizing radiation from radioactive materials" [20]. Thus, learners mix up the process of emitting radiation, *radioactivity*, with the ionizing radiation that is emitted [20]. Radiation is accordingly taken for the transportation of radioactive material [20].

1. A. 2. Discernment

Secondly, discernment is intertwined with the learner, as it is a combination of noticing something and reflecting on it [7]. Thereby meaning is constructed from a representation, which is part of the learning process [6].

Concerning visualizations, the most compelling aspects of the represented objects are very likely to attract most of the learners' attention so that other important issues may not be discerned [6]. Another factor must be considered when talking about discernment from visualizations: Many important aspects are not explicitly present and can therefore not be discerned immediately [6].

FIGURE 2: **Anatomy of Disciplinary Discernment** introduced by Eriksson *et al.* (2014a)

How the intended meaning of a representation may be discerned, is described by the *Anatomy of Disciplinary Discernment* (ADD), which was introduced by Eriksson *et al.* (2014) for an astronomical representation. Eriksson figured out that different people discern different aspects of the same representation since disciplinary discernment is dependent on experiences, knowledge, and educational background [7]. Thereby more attention is paid to disciplinary characteristics of a representation as the educational level increases [7]. As shown in FIGURE 2 there are five levels of discernment according to the ADD.

1. A. 2. 1. Non-disciplinary Discernment

The lowest level of the ADD is *Non-disciplinary Discernment*. Learners who are on this level mainly wonder what they notice without being able to identify what they see [7].

1. A. 2. 2. Disciplinary Identification

The first level of disciplinary discernment is *Identification.* In this category learners can recognize and name salient disciplinary objects, and therefore they tend to use phrases like 'That is …' [7].

1. A. 2. 3. Disciplinary Explanation

On the level of *Disciplinary Explanation* learners explain and interpret, *why* the objects are represented in a particular way using their disciplinary knowledge [7].

1. A. 2. 4. Disciplinary Appreciation

The level of *Disciplinary Appreciation* involves "analyzing and acknowledging the value of the disciplinary affordances of the representation" ([7], p.174).

1. A. 2. 5. Disciplinary Evaluation

The highest level of the ADD is *Disciplinary Evaluation.* Persons on this level analyze as well as criticize the representation due to their disciplinary knowledge [7]. In addition, "some of the descriptions in this category also include aspects related to using such a resource in the teaching practice of the discipline" ([7], p. 174f).

1. B. Representations

In general, one can distinguish between internal and external representations. The former means the mental model built by a learner regarding a certain learning content, whereas the latter includes texts, graphs or pictures [28]. Indeed, the way an empirical property is represented externally can have an impact on the internal representation built by the learner [16]. But the imaging process is complex and prone to error, since it is affected by the learner's individual perception and prior knowledge (see chapter 1. C. 2.) [16]. However, in the following the term "*representation*" only refers to external representations.

According to Kress *et al.* (2014) "*representation* focuses on what the individual wishes to represent about the thing represented" (p. 3). When teaching, representations are intended to be media to provide access to disciplinary knowledge for learners. There are various approaches to categorize media as described by Girwidz (2015a):

One can categorize media according to technical aspects [16]. In this respect, there is a distinction between *pre-technical* (e.g., book or chalkboard) and *technical media* (e.g., television set or radio) [16].

Furthermore, media can be classified according to cognitive psychology [16]. The corresponding categories refer to the senses that are addressed by the medium [16]. Thus, there are *visual, auditive*, *audiovisual,* and *haptic media* [16].

Finally, they can be categorized according to methodical aspects because there are various ways to imply them in a teaching unit [16]. E.g., a text can be read in plenum, discussed after it has been read individually or the learners can write a summary [16]. This methodical categorization is essential, since the way a medium is implied in the learning process is clinching for learning to take place [16].

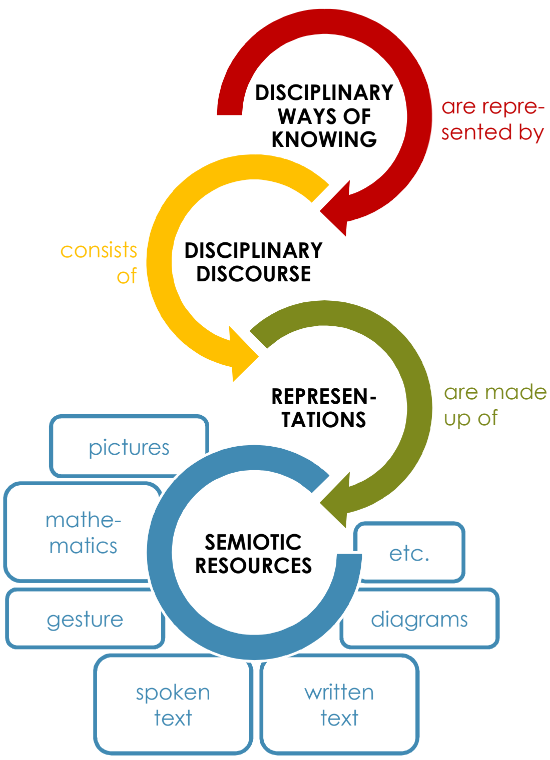

FIGURE 3: Examples for **semiotic resources** and how they are related to the disciplinary ways of knowing (after [5], p. 127)

However, as mentioned above to communicate within or outside the discipline representations are used as media. There are various semiotic resources which representations are made up of [6]. FIGURE 3 shows examples for semiotic resources and how they are related to the disciplinary ways of knowing. In this regard, it is important to note that the process of creating a representation is also referred to as *coding* [16].

Furthermore, two important aspects regarding representations need to be considered: There are several types of representations as well as various affordances of each representation.

1. B. 1. Types of representations

As mentioned above there are several types of representations with specific benefits and drawbacks in terms of knowledge transfer. In literature one can find various approaches to categorize them (see [1]).

In chemistry three types of representations are distinguished, which are also relevant in context of particle physics: macro, submicro and symbolic [28]. This is similar to the definition of Girwidz (2015a) who distinguishes between pictorial, analog and logical image [16].

Representations of the first type show the empirical properties in a phenomenological way [28]. E.g., a photo or drawing shows the visual appearance of an object [16],

The submicro or analog type is used to illustrate not directly visible structures [16]. Thus, it involves models depicting "the (assumed) arrangement of entities, such as atom or molecule models" ([28], p. 2). Analog images comprise structural (e.g., atom models) or functional analogies (e.g., electron drift as depiction of electric current in metal materials) [16]. In general, using analogies is fraught with pitfalls, since they may cause misinterpretations [16].

The last type of representations means that empirical properties are depicted by symbols, e.g. linguistic simplifications like 'H_2O' [28]. It also comprises diagrams, charts and graphics which aim to visualize data and functional relationships [16]. Since symbolic or logical representations are highly schematic and abstract, codes are used according to convention [16]. To avoid cognitive overload learners must know the system of symbols used, before they engage with such a representation [16].

In the following I will address visual and textual representations in more detail.

1. B. 1. 1. Visualizations

Visual representations are named visualizations. They are characterized in different ways. Firstly, one may define everything discerned through visual sense including algebraic notations, formulas, letters or even written text as visualizations [10]. Secondly, visual representations excluding linguistic information may be meant when talking about visualizations [10]. In this paper the latter definition is used.

A visualization provides all information it contains simultaneously [16]. In the context of teaching and learning, visualizations have various functions as described by Girwidz (2015a). In general, visualization means that information is coded in such a way that learners can picture it [16]. Using imagery is supposed to make empirical properties easier to memorize and to help learners to build mental models [16].

1. B. 1. 2. Texts

Texts are verbal representations of information. Like visualizations they are used to foster reflection and associations [16]. Indeed, some problems of image-processing can also be referred to texts [16]. In contrary to a visualization, a text provides all information it contains sequential [16]. However, there are several recommendations for writing a comprehensible text (e.g., simple sentences, structure and conciseness) [16].

1. B. 2. Multiple representations

In teaching physics, "more than only one representational format is often used to convey information and support knowledge construction" ([28], p.2). When two or more representations are used simultaneously, one can speak of a multiple external representation (MER) [28]. They are also referred to as "*multi-coded*" (cf. [18], p. 845f). Multiple representations are important and particularly foster learning, since information-processing depends on the implied codes, especially at the beginning [18].

1. B. 2. 1. Visualization-text-combinations

Usually visualizations and texts are combined. The former can be "static (e.g., illustrations, graphs, charts, photos, or maps) or dynamic (e.g., animation, video, or interactive illustrations)" ([24], p. 43). The latter can be written "(e.g., on-screen text) or spoken (e.g., narration)" ([24], p. 43). Learning from such combinations is also referred to as *Multimedia Learning* (see chapter 1. C. 2.) [24].

1. B. 2. 2. Other combinations

Ainsworth (2006) introduced the *DeFT (Design, Functions, Tasks) taxonomy* in which every kind of combination of representations is considered, e.g. combination of a mathematical equation and a table [28]. According to this concept, "multiple representations support comprehension, when they either contain qualitatively different aspects of the information to be learned, or when they convey the same information but in different ways" ([28], p. 9).

1. B. 3. Affordances of representations

The affordances of a representation acting as medium are its potentials for communication [11]. A single representation may have various affordances as different persons discern different aspects. As the concept of affordance focuses on the mutuality of object and subject, it is suitable for analyzing the use and effect of media [40]. Therefore, the focus must be on these affordances not only when developing but also when evaluating a certain representation.

1. B. 4. 1. Development of the term affordance

The term *affordance* was introduced by the psychologist **Gibson** (1977) and is etymologically related to the verb "*to afford*". Gibson defined it as follows:

> "The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. […] The noun affordance […] refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment." ([15], p.127)

Gibson argues that even though an affordance comprises physical properties taken in respect of a certain animal, it is independent of that animal [14]. This is since it is neither a value nor a meaning which depends on the observer but real and invariant [14]. Nonetheless, it is not an objective property of a thing as it must be measured relative to the animal [14]. Despite this relation to its observer, affordance is not subjective either

[14]. It rather is a combination of both as it overcomes the opposition of subject and object [14]. Therefore, the term *affordance* involves that subjects like animals or human beings perceive objects in their environment according to their physical background, i.e. their possibilities for action [40]. In addition, Gibson supports the principle of direct perception of affordances, i.e. there is no need to draw cognitive conclusions when perceiving affordances [40]. E.g. an apple affords eating, whether or not being hungry. Summing up, Gibson defines affordance as the possibilities of a certain subject for action afforded by an object. One problem associated with this definition is that quantifying affordances of a single object is impossible [4].

In contrast to Gibson, **Norman** (1988) was interested in the design aspect of things. Therefore, when talking about affordances, he focuses on the visible possibilities of using an object [40] and defined it as follows:

> "[T]he term affordance refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could possibly be used. [...] Affordances provide strong clues to the operations of things. […] When affordances are taken advantage of, the user knows what to do just by looking: no picture, label, or instruction needed." ([26], p. 9)

One problem associated with this definition is that affordance is dependent on the individual and the context and therefore not generalizable [4]. Norman slightly changed his definition of affordance in a revised edition of his book. In the new edition he distinguished between affordances, perceived affordances and signifiers. The first indicate *what actions* are possible, even though not all of them may be perceived [27]. The last signify *where* or *how* the action should take place, i.e. the appropriate behavior [27]. Perceived affordances may be signifiers themselves, but they are often ambiguous in contrast to signifiers which need to define actions clearly [27]. The step from the perception of an affordance to understanding the potential action may be influenced by cultural convention [27]. E.g. a doorknob affords opening or shutting a door but fixed on a wall it has different affordances like being a support [27].

1. B. 4. 2. Affordances in the context of education

In education context communication is mainly about sharing knowledge. However, it is important to distinguish between disciplinary and pedagogical affordance. The former refers to what a medium affords to members of the discipline and the latter to what it affords to learners.

The term ***disciplinary affordance*** was introduced by Fredlund *et al.* (2012) and defined

> "[…] as the inherent potential of that representation to provide access to disciplinary knowledge. Thus, it is these disciplinary affordances that enable certain representations to become legitimate within a discipline such as physics." (p. 658)

This definition of affordance strongly differs from the above-mentioned ones by Gibson and Norman, since it "focuses on the discipline's collective, agreed interpretation of the resource rather than the individual learner's experience" ([3], p.12). Fredlund *et al.* (2012) state that "Physics learning […] involves coming to appreciate the disciplinary affordances of representations" (p. 658). Indeed, learners may be overwhelmed by the high number of disciplinary affordances of a certain representation used within the discipline [3]. Therefore, they "cannot deal unaided with the dense disciplinary affordances of disciplinary-specific semiotic resources" ([3], p.25). Learners rather need representations that function as bridges to the discipline by supporting meaning-making processes [3].

Thus, Airey (2015) introduced the term ***pedagogical affordance*** and defined it as "*the aptness of a semiotic resource for teaching some particular educational content*" (p. 18).

According to Airey (2017) semiotic resources with pedagogical affordance have three main characteristics:

1) Firstly, they show less information to reduce the cognitive load [3].
2) Often, they are less abstract [3]. Accordingly, Rundgren and Tibell (2009) recommend "the use of less stylized, less schematic, and (hence) more realistic" (p. 225) resources.
3) Usually, their usability in the daily work of the discipline is limited [3].

These characteristics result in an indirect relation between disciplinary and pedagogical affordance of representations, i.e. the higher the disciplinary affordance, the lower is the pedagogical one as shown in FIGURE 4 [2].

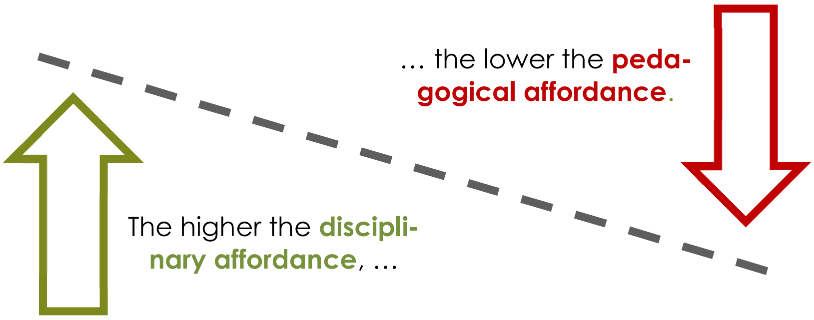

FIGURE 4: Relationship between **disciplinary** and **pedagogical** affordance

When evaluating the disciplinary affordance of a certain representation the focus is on how useful a representation is for disciplinary purposes, e.g. research, whereas it is on the usefulness for teaching purposes, when evaluating the pedagogical affordance [2]. However, disciplinary and pedagogical affordance are not inevitably each other's opposite. Moreover, according to Airey *et al.* (2014)

> "appropriate disciplinary learning <is> only possible when there is a match between: what a given semiotic resource affords to the student (cf. Gibson & Norman) and its disciplinary affordance (i.e. what it affords for the discipline)" (p. 27).

1. C. Relation between learners and representations

This chapter is about the relation between learners and representations. At first, I describe how learners perceive representations through senses, which is referred to as *(multi-)modality*. Then, the focus is on learning from multimodal representations, which is also called *multimedia learning*. Furthermore, I explain why the intended affordances of a representation and the participants' discernment are very likely to be different. Finally, recommendations to enhance learning possibilities from representations are given.

1. C. 1. Modality and multimodality

"*[M]edia of communication* are shaped and organized by a culture into a range of meaning-making systems, *modes*" ([22], p. 11). The traditional approach to communication and representation focused on the medium of language and can therefore be referred to as "*monomodal*" ([22], p. 2). "[T]he differentiation of speech and writing as distinct modes was not an insight of the monomodal approach" ([22], p. 2).
In context of psychology modality means perception through senses, i.e. sight, hearing, smell, touch and taste [4]. In addition, in linguistics even written language is defined as a mode and distinguished from extra-linguistic materials (e.g., pictures) [4].

In contrary to the above-mentioned monomodal approach, Kress *et al.* (2014) state that "communication is inevitably multimodal" (p. 3). Multimodal systems address more than one sense [17]. The theory of multimodality, which is concerned with communication and social semiotics, is "interested in the different communication potential of modes" ([4], p. 12). This means that the concept of affordance can be adapted to modes as done by Kress *et al.* (2014). In this regard the focus is shifted from a particular representation to a mode in general [4]. Nevertheless, this approach is fraught with pitfalls because "semiotic resources within the same mode can have different affordances" ([4], p. 23). Therefore, when talking about disciplinary and pedagogical affordances in this thesis, the affordances of a particular representation are meant [4].

1. C. 2. Multimedia learning

The above-mentioned modes also apply for educational contexts. Learning from multimodal systems means learning from more than one mode and is referred to as *multimedia learning* [18]. In this regard "each mode contributes to teaching and learning as *multimodal accomplishments* in specific ways" ([22], p. 10). In the most common case multiple external representations used for teaching purposes are multimodal systems because they can elucidate different aspects of a content and explain how these aspects are related to each other [18]. Since most of the multimodal systems are visualization-text-combinations, the focus of cognitive psychology is on how input from visual and auditory mode are processed in human mind [4]. Mayer and Moreno (2003) introduced three assumptions concerning the function principle of information-processing in human mind, which are as follows:

The first one is the *dual channel assumption* which says that information is processed in two separate channels, i.e. a visual or pictorial channel and a verbal or auditory channel [24]. When visualization and text are combined, information is processed in both channels [28]. This assumption is also referred to as *Dual Coding Theory* [24].

The *limited capacity assumption* states that "[s]imilar to the overall capacity of working memory, both channels are assumed to be limited regarding the amount of information they can process at a time and in parallel" ([28], p.5). Therefore, *Cognitive Load Theory* recommends using both channels simultaneously to avoid overloading only one of them [28].

Finally, the *active processing assumption* says that "meaningful learning requires a substantial amount of cognitive processing to take place in the verbal and visual channels" ([24], p. 44).

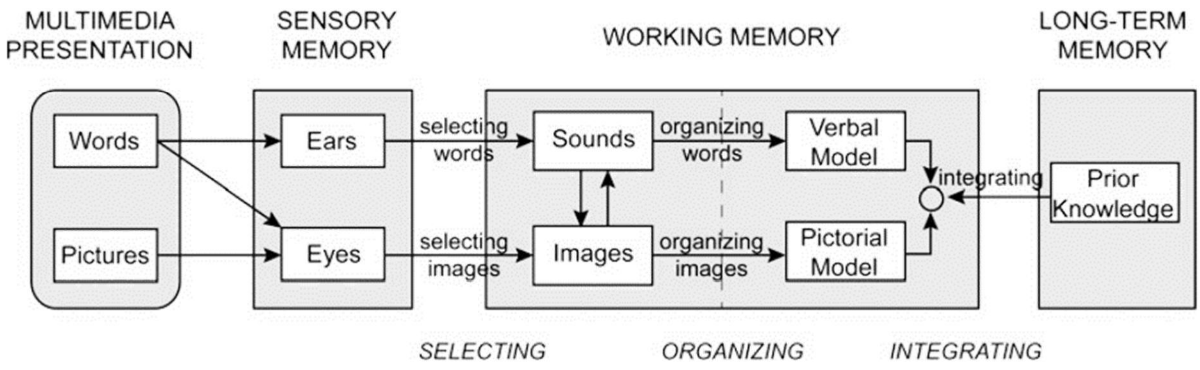

FIGURE 5: **Cognitive Theory of Multimedia Learning** according to Mayer and Moreno (2003) (reprinted from [18], p. 848)

How these assumptions are related to each other is shown in FIGURE 5.

According to the *dual channel assumption* the image consists of two rows representing the two channels [24]. Words can be perceived in two ways: Spoken words are perceived through the ears, whereas written ones are perceived through the eyes as shown in FIGURE 5 [24]. The sensory memory saves information only up to 2 seconds [16].

A selection of perceived words and images is further processed in working memory, where the actual learning happens [24]. To the working memory the *limited capacity assumption* applies [24]. There are three different types of cognitive load, i.e. extraneous, intrinsic and germane cognitive load [18]. The first one refers to the way information is represented [18]. If a learner is not familiar with the code, extraneous cognitive load is high, and thus no capacity for the actual learning process is left [18]. Intrinsic cognitive load is caused by the complexity of the information in relation to the prior knowledge of a learner [18]. Germane cognitive load means the cognitive activity, which is caused by the actual learning process [18]. According to *Cognitive Load Theory* learning is only possible, if, besides extraneous and intrinsic cognitive load, capacity of the working memory is left for the germane one [18].

In general, only a maximum of 7 information units, which can be present for about 20 seconds, are processed in the working memory [16]. These learning units, which are referred to as "*chunks*", are subjective and dependent on prior knowledge [16]. The prior knowledge is integrated from the long-term memory [24].

In FIGURE 5 the *active processing assumption* is represented by the arrows that say "organizing" or "selecting" and "integrating", since one must actively select and organize words and images as well as integrate prior knowledge in the working memory when learning [24].

According to the *Cognitive Theory of Multimedia Learning (CTML)* combining different types of representations randomly does not automatically lead to a successful learning process [28]. There are various, partly contradictory approaches. Mayer and Moreno (2003) introduced 12 recommendations for designing multimedia representations. Seven of them are particularly interesting for my research:

1. C. 2. 1. Multimedia principle

According to the *multimedia principle* visualization-text-combinations enhance learning possibilities [24].

1. C. 2. 2. Modality principle

The *modality principle* follows up on this and says that visualizations shall rather be combined with spoken than with written text to use the visual as well as the auditory channel [28].

1. C. 2. 3. Segmenting principle

However, the *segmenting principle* states that it may even be more effective to add written information, as long as there is enough time to observe the visualization and reread the text [28].

1. C. 2. 4. Spatial contiguity principle

It is less controversial that different representations should be presented closely together, i.e. "text parts might even be integrated into the respective parts of the picture" ([28], p. 6). This is also referred to as *spatial contiguity principle* [18]. In addition, Ainsworth (2006) introduced the *DeFT (Design, Functions, Tasks) taxonomy*, which also supports "integrated presentations of representations" ([1], p. 190).

1. C. 2. 5. Temporal contiguity principle

Similarly, according to *temporal contiguity principle*, when explaining a visualization, a teacher should show and talk about the respective one simultaneously [28]. That verbal and visual information should be given at the same time, is also stated by the *Integrated Model of Text and Picture Comprehension (ITPC)* [28].

1. C. 2. 6. Signaling principle

The *signaling principle* recommends to "[p]rovide cues for how to process the material to reduce processing of extraneous material" ([24], p. 46).

1. C. 2. 7. Coherence principle

To prevent cognitive overload the *coherence principle* recommends removing unnecessary information from the representation [24]. Only information necessary for a certain task should be included [18].

1. C. 3. Discernment versus affordances

FIGURE 6 shows the complex relation between learners and representations, i.e. *discernment* and *affordance* [7].

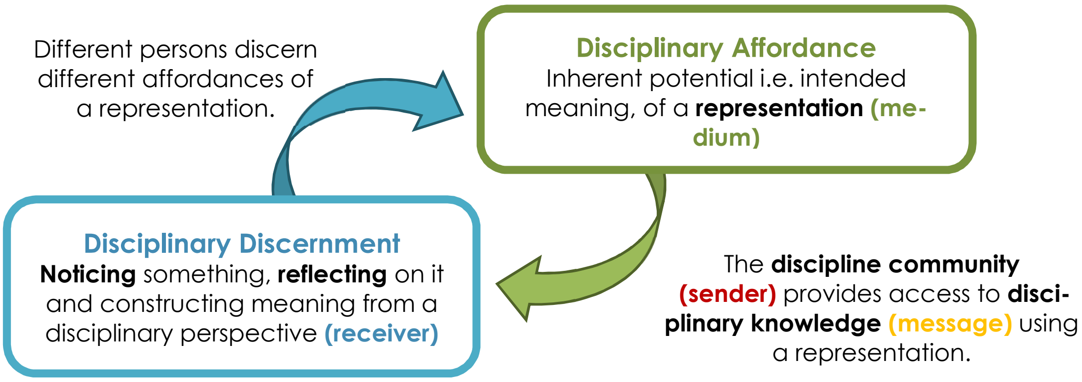

FIGURE 6: Relation between *disciplinary discernment* of the learners **(receiver)** and *disciplinary affordance* of the representation **(medium)**

As shown in FIGURE 6 the discipline community is the sender who wants to share specific disciplinary knowledge as a message. Therefore, members of the community (e.g., scientists or teachers), create a representation as medium whose intended meaning is to provide access to disciplinary knowledge [7]. Usually the medium has further affordances than the intended disciplinary one [7]. Thus, different persons, i.e. receivers, discern different aspects of the same representation which may be irrelevant from a disciplinary point of view [7]. Discernment is an individual process and consists of noticing something, reflecting on it and constructing meaning [7]. Due to the variety of affordances and the individuality of the discernment process the representation may be misinterpreted. Even though members of the discipline think the way physics is presented in a certain representation is straightforward, learners may struggle with interpreting the same representation [12].

1. C. 4. Recommendations for enhancing learning possibilities

In chapter 1. C. 3. I pointed out that the relation between learners and representations, i.e. discernment and affordance, is complex. Due to this complexity the inherent potential of a certain representation to provide access to disciplinary knowledge is limited. To enhance the possibilities for learning from representations Fredlund *et al.* (2015) proposed three factors one must bear in mind when developing or choosing representations to create or enhance learning possibilities:

1. C. 4. 1. Identify relevant aspects

At first, the developer must identify the disciplinary aspects and write instructions carefully. E.g., Fredlund *et al.* (2015) "define disciplinary-relevant aspects as those aspects of physics concepts that have particular relevance for carrying out a specific task" (p. 2). Identification of those aspects is very important because it enables the developer of a task to emphasize them and formulate instructions accordingly [12]. One of the main problems of learners is to focus on the relevant aspects for solving a certain task. [12]. When developing instructions for a task carefully, one can influence the learners in such a way that they shift their attention from aspects, which are neither disciplinary nor relevant, to disciplinary-relevant aspects [12]. This approach is similar to the above-mentioned *signaling principle* (see chapter 1. C. 2. 6.).

1. C. 4. 2. Select appropriate representations

Once the disciplinary-relevant aspects for solving the task at hand are identified, the developer must select appropriate representations. Fredlund *et al.* (2015) emphasize "from an educational perspective […] it is important that the selected representation includes as few aspects as possible over and above those needed for a given task." (p. 3). Additional irrelevant aspects may distract from the important ones [12]. Therefore, "unpacking a semiotic resource increases its pedagogical affordance but decreases its disciplinary affordance" ([2], p. 36). However, this approach is similar to the above-mentioned *coherence principle* (see chapter 1. C. 2. 7.).

In addition, one must bear in mind that the relevance of a certain aspect may vary when the representation is used in a different context [12]. Thus, identifying relevant aspects of a representation to solve a certain task is even more challenging for learners [12].

1. C. 4. 3. Create variation

The third factor according to Fredlund *et al.* is "creating variation around each disciplinary-relevant aspect" (p. 9). At first, disciplinary-relevant aspects are presented in a slightly different way, whereas the background remains unchanged [12]. This enables learners to distinguish between relevant and irrelevant aspects [12]. According to variation theory it is only possible to discern something from its background, if it is varied [31]. As a result, variation includes sameness and difference, since discerning something means not only discerning something as being itself, but also as not being anything else [31]. Besides, it is also part of the learning process to notice how the relevant aspects are related to each other [12]. Therefore, Fredlund *et al.* (2015) suggest the "co-variation of different disciplinary-relevant aspects" (p.8), i.e. one aspect is varied in a certain representation and the learners are encouraged to figure out how this variation affects another relevant aspect in the same representation [12].

1. D. Particle physics

In this chapter an overview of particle physics is given. In especial, the Standard Model of particle physics and the interaction between particles and matter are addressed.

1. D. 1. Standard Model

> "Indeed, the Standard Model of particle physics describes only about 5% of the universe. It does not explain dark matter, which accounts for approximately 25% of the universe—not to speak of dark energy, which supposedly adds the remaining 70% of the universe." ([39], p. 2)

Nevertheless, the Standard Model of particle physics is one of the fundamental basics of physics. Moreover, Wiener *et al.* (2017) claim that "every physics process can be traced back to fundamental interactions between elementary particles" ([36], p.1).

1. D. 1. 1. Fundamental particles

There are two types of fundamental particles, leptons and quarks, and six particles of each type [35]. They are supposed to neither have inner structure nor dimension [35]. All fundamental particles as well as their mass and charge are listed in TABLE 1.

TABLE 1: **Characteristics of the fundamental particles.** Note that the corresponding anti-particles are not mentioned. (cf. [35], p. 1363)

	Generation I	Generation II	Generation III	
QUARKS	**up (u)** +2/3 2,3	**charm (c)** +2/3 275	**top (t)** +2/3 173000	**Flavor** Charge [e] Mass [MeV/c²]
QUARKS	**down (d)** -1/3 4,8	**strange (s)** -1/3 95	**bottom (b)** -1/3 4500	
LEPTONS	**electron (e)** -1 0,511	**muon (μ)** -1 105,659	**tau (τ)** -1 1777	
LEPTONS	**electron neutrino (ν_e)** 0 <2 eV/c²	**muon neutrino (ν_μ)** 0 <0,19	**tau neutrino (ν_τ)** 0 <18,2	

Each type of fundamental particles is classified in three generations. As shown in TABLE 1 particles of higher generation have greater mass than the corresponding particle of the previous generation. Thus, the lightest particles, which are the most stable, constitute the first generation, "whereas the heavier and less-stable particles belong to the second and third generation"[1]. All stable matter in the universe is composed of first-generation particles because "any heavier particles quickly decay to more stable ones"[2].

[1] [CERN website], retrieved from https://home.cern/science/physics/standard-model (8.2.19)
[2] [CERN website], retrieved from https://home.cern/science/physics/standard-model (8.2.19)

Fundamental particles have half-integral spin $\left(s = \frac{1}{2}\right)$, which means that they are fermions and that the Pauli-principle applies to them [35]. In contrary, bosons are particles with integer spin to which the Pauli-principle does not apply [35].

Since fundamental particles are spin-$\frac{1}{2}$-particles, they are described by the Dirac-equation, which is a relativistic form of the Schrödinger-equation [35]. According to special relativity the energy of a particle is related to its mass and momentum via the equation $E = \pm\sqrt{p^2c^2 + m^2c^4}$ [35]. Wave functions, which pertain to the negative energies, are solutions of the Dirac-equation [35]. Therefore, Dirac claimed that there are antiparticles which are identical to the particles except for the charge [35]. As regards the electron, if the antiparticle is nearby both annihilate and are transferred into two photons, which have a minimum total energy of $2m_ec^2$, where m_e means the electron's mass [35]. The antiparticle of the electron is the positron and was the first to be discovered [35]. All fundamental particles have antiparticles, which can only be produced in particle-antiparticle-pairs [35]. Whereas spin and mass are the same for particles and antiparticles, they have opposite charges [35]. They have further opposite properties, e.g. the baryon number and the strangeness (see [35], p. 1363). However, the antiparticles are indicated by a horizontal bar above the letter that represents the particle (e.g., up u and antiup $\bar{u}$)[35].

1. D. 1. 2. Fundamental interactions

There are four fundamental interactions, namely strong, electromagnetic, weak and gravitational [35]. In general, particles interact with each other by the exchange of interaction particles, which are gauge (and vector) bosons [35]. By exchanging a gauge boson, particles transfer discrete amounts of energy[3]. The "property of an elementary particle that defines the fundamental interaction by which it is influenced" is its charge ([39], p.1). Hence, the "corresponding interaction particle 'couples' to a certain charge" ([39], p.1). Thus, there is an interaction particle associated with every interaction.

In the following the four fundamental interactions are described in more detail.

The strong interaction influences particles with a color charge (quantum chromodynamics, or QCD for short) [39]. Gluons (g) are the interaction particles of the strong interaction and accordingly couple to color-charged particles [39]. Since quarks, antiquarks, and gluons themselves carry color charge, they are influenced by the strong interaction [35]. The decay time of processes caused by strong interaction is typically 10^{-23} s [35]. Hadrons are influenced by the residual strong interaction, since they are

[3] cf. [CERN website], retrieved from https://home.cern/science/physics/standard-model (8.2.19)

composed of quarks [35]. The color charge of these quarks is not completely cancelled out when composing a hadron which results in a residual strong interaction between hadrons [35]. In general, hadrons comprise baryons and mesons [35]. The former are composed of three quarks and have half-integral spin (e.g., proton, neutron, …) [35]. The latter are composed of a quark and an antiquark and have integral spin (e.g., kaon, pion, …) [35].

All electrically charged particles are influenced by electromagnetic interaction (quantum electrodynamics, QED) [39]. Photons (γ) are the interaction particles of the electromagnetic interaction [39]. Thus, they couple to quarks and antiquarks, and electrically charged leptons and antileptons [39].

The weak interaction acts on particles with weak charge which is referred to as flavor (quantum flavor dynamics, QFD) [39]. The corresponding interaction particles are the weak bosons (W^+, W^- and Z^0) [39]. Since quarks and leptons, i.e. all fundamental particles, have flavor, weak interaction acts on them [35]. "Weak bosons can also interact with the photon (but this is a pure weak interaction, not an electromagnetic one)" ([39], p. 2). The decay time of processes caused by weak interaction is typically 10^{-10} s [35].

Whereas all fundamental interactions are described by the Standard Model of particle physics, the gravitational interaction is not [39]. However, mass constitutes the "charge" of the gravitational interaction. The graviton which hypothetically mediates the gravitational interaction has not been discovered yet [35].

In TABLE 2 the characteristics of the fundamental interactions are listed.

TABLE 2: **Characteristics of the fundamental interactions.** (after [35], p. 1363)

	Strong interaction		Electromagnetic interaction	Weak interaction	Gravitational interaction
	fundamental	residual			
acts on	color charge		electrical charge	weak charge (flavor)	mass
involved particles	quarks[1], gluons	hadrons (baryons[1], mesons)	quarks[1], electrically charged leptons[1]	quarks[1], leptons[1], photons	all[1]
interaction particles	gluons	mesons	photons	weak bosons	graviton[2]

[1] including the corresponding antiparticles
[2] not yet discovered

Besides the above-described fundamental forces, which are vector fields, there is the Brout-Englert-Higgs (BEH) field [39]. In contrary to the others it is a scalar field and thus, has a special effect, the Higgs mechanism [39]. "[I]t induces spontaneous symmetry-breaking, which in turn gives mass to all particles with which it interacts" ([39], p.1). This explains why bosons have mass, although they were considered to be massless [35]. The interaction particle of the BEH field is the Higgs (H). It couples to all massive particles and hence, also to itself but not to the massless gluon and photon [39].

1. D. 2. Interaction between particles and matter

To detect and identify particles in a detector, they must interact with its material [35]. Particles interact in various ways with matter (see [35]). This chapter focuses on the interaction of electrically charged particles from α- and $\beta^{\pm}$-transformations, and of photons from γ-transformations and X-ray radiation with silicon.

1. D. 2. 1. Charged particles

Charged particles loose energy when they traverse matter [35]. The energy is deposited and transferred to the electrons of atoms of the absorbing material [35].

The mean energy loss per path length is quantified by the *linear energy transfer* (*LET*) relation, which is also referred to as *stopping power S(E)* (see EQUATION 1) [21].

$$\boldsymbol{S(E) = -\frac{dE}{dx} = -LET}$$

EQUATION 1: **Stopping power**

According to the Bethe-Bloch-formula (see EQUATION 2) the mean energy loss per path length is dependent on the medium and the traversing particle [35].

$$\boldsymbol{-\frac{dE}{dx} = \frac{4\pi n Z^2}{m_e c^2 \beta^2}\left(\frac{e^2}{4\pi e_0}\right) * \left[\ln\left(\frac{2m_c c^2 \beta^2 \gamma^2 \Delta T_{max}}{I^2}\right) - \beta^2\right]}$$

EQUATION 2: **Bethe-Bloch-formula**

Relevant for the energy loss are the atomic number $\boldsymbol{Z}$ of the traversing particle, the electron density $\boldsymbol{n}$ of the material, and its mean excitation potential $\boldsymbol{I}$ which rises with the mass number of the material. Moreover, the relativistic speed $\boldsymbol{\beta = \frac{v}{c}}$ of the invading particle, the Lorentz-factor $\boldsymbol{\gamma = 1/\sqrt{1-\beta^2}}$ and the maximal energy transfer $\boldsymbol{\Delta T_{max}}$ caused by a central collision with a core electron, i.e. an electron that is bound to the core, determine the energy loss [35].

For low energies the term $\frac{1}{\beta^2}$ is dominant [35]. Thus, the higher the energy, the lower is the energy loss per path length. This seems plausible, since a particle has less time to influence the material's electrons, if it travels faster.

In contrary to that, for high energies the term $\ln \gamma^2$ becomes relevant due to relativistic effects [35].

If only the atomic number and the energy are taken into consideration, the stopping power caused by ionization is $-\frac{dE}{dx} \propto Z \ln E$, and hence proportional to the logarithm of the energy [35]. Relatively light particles, e.g. electrons, which traverse a material, predominantly lose energy in form of bremsstrahlung [35]. The energy loss caused by bremsstrahlung is $-\frac{dE}{dx} \propto Z^2\, E$, and hence linear proportional to the energy [35]. Thus, there is a distinction between collision and radiative stopping power. For low-energy particles the former is predominant, whereas for particles of higher energy the latter is predominant [35]. The crossing energy of both functions is referred to as critical energy [35]. It has the same value for all materials, namely $E_{crit} \approx \frac{6\ 10MeV}{Z}$ [35].

However, "[t]he stopping power can be approximated to an average value along the track within materials like silicon" ([21], p. 11).

The range, which a particle can traverse a material until it stops, can be calculated according the *continuous slowing down approximation range* $\boldsymbol{R_{CSDA}}$ (see EQUATION 3) [21]. It is calculated as the initial energy $\boldsymbol{E}$ of the particle, when it enters the material, divided by the stopping power [21]. Since the rest energy of the particle is neglected, the $\boldsymbol{R_{CSDA}}$ is an approximation [21]. According to EQUATION 3, the higher the stopping power is, the shorter the range that the particle can penetrate the material.

$$R_{CSDA} = \frac{E}{S(E)}$$

EQUATION 3: **Continuous slowing down approximation (CDSA) range**

FIGURE 7 shows the continuous slowing down approximation range in silicon for electrons and FIGURE 8 for helium ions, whereby the scales are logarithmic.

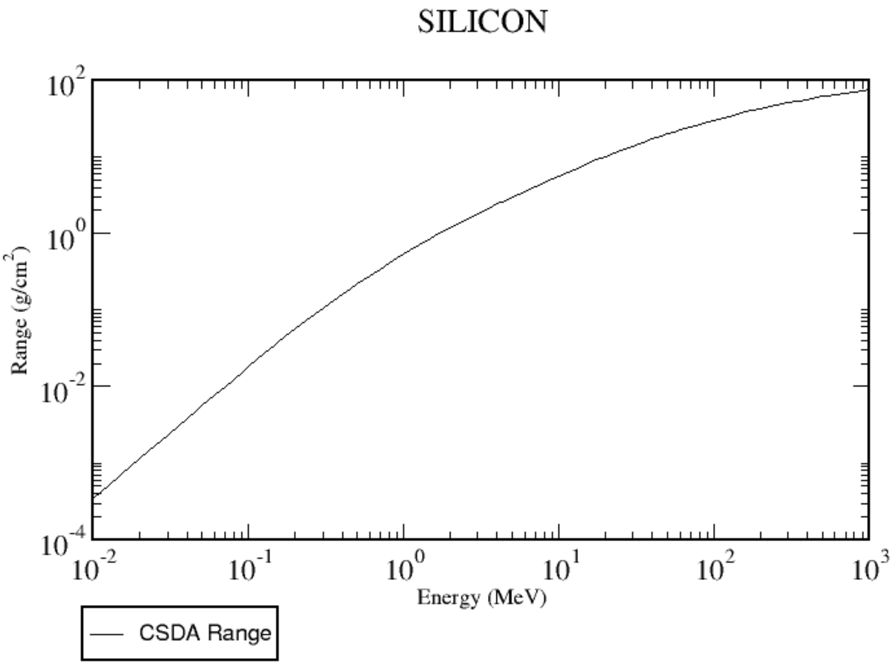

FIGURE 7: **CDSA Range as function of the energy for electrons in silicon** (reprinted from *NIST database*, retrieved from https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions (9.2.19))

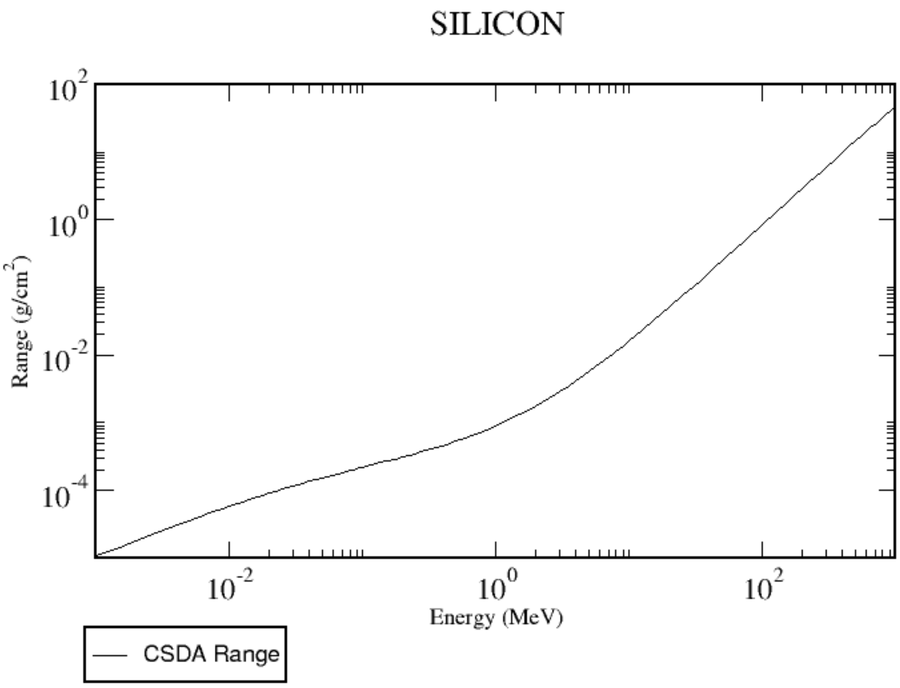

FIGURE 8: **CDSA Range as function of the energy for helium ions in silicon** (reprinted from *NIST database*, retrieved from https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions (9.2.19))

One can see that in general, the CDSA range of electrons is greater compared to helium ions. Furthermore, the graphs' shapes differ from each other due to the above-mentioned differences in stopping power. As shown in FIGURE 8 the CDSA range of a helium ion rises at higher energies, because the corresponding stopping power decreases. In contrary to that, the CDSA range of electrons decreases at higher energies, since the stopping power rises due to bremsstrahlung.

1. D. 2. 2. Photons

Whereas charged particles always interact with silicon, this does not apply to photons [21]. There are three main absorption processes: photoelectric absorption, Compton scattering and pair production (see [35]). The probability, that one of these reactions between the traversing photon and a particle of the material occurs, is described by the cross-section σ [35]. The corresponding absorption coefficient is the absorption probability per path length (see EQUATION 4:) [35].

$$\mu = \frac{\sigma}{A}\frac{dN}{dx}$$

EQUATION 4: **Absorption coefficient**, where $\boldsymbol{A}$ stands for the area and $\boldsymbol{N}$ for the number of particles

According to the ***photoelectric effect*** a photon frees a core electron [21]. Since the photon transfers all its energy to the electron, it is completely absorbed [21]. The cross-section for the photoelectric effect is $\sigma_{photo} \propto \frac{Z^n}{{E_\gamma}^3}$, whereby $n \approx 4 \dots 5$ [35].

The ***Compton scattering*** describes the elastic collision between a photon and a core electron [35]. "The result is a distribution of the original photon energy between a scattered, lower energetic photon and a freed Compton electron which both travel in different directions from the incident photon." ([21], p. 13f) The cross-section for the Compton-effect is $\sigma_{photo} \propto Z$ [35].

Finally, ***pair production*** means that the photon's energy is transferred to an electron-positron-pair [35]. The energy of the photon must have a minimum of $2m_ec^2$ [35]. The corresponding cross-section is $\sigma_{pair} \propto Z^2$ [35].

According to the different above-described cross-sections, photons with low energies mainly undergo the photoelectric effect, apart from the range of 1MeV, where the Compton scattering is predominant [35]. The main process for photons with energies above 100MeV is pair production [35].

FIGURE 9 shows the total absorption probability in silicon as a function of the photon energy with a range from 1keV to 100GeV using logarithmic scales. One can see that the total absorption probability for photons with an energy around 100keV in silicon is already reduced to 1%. "For comparison, the total absorption in cadmium-telluride is given representing a sensor material with a higher atomic number and a more than doubled material density." ([21], p. 14)

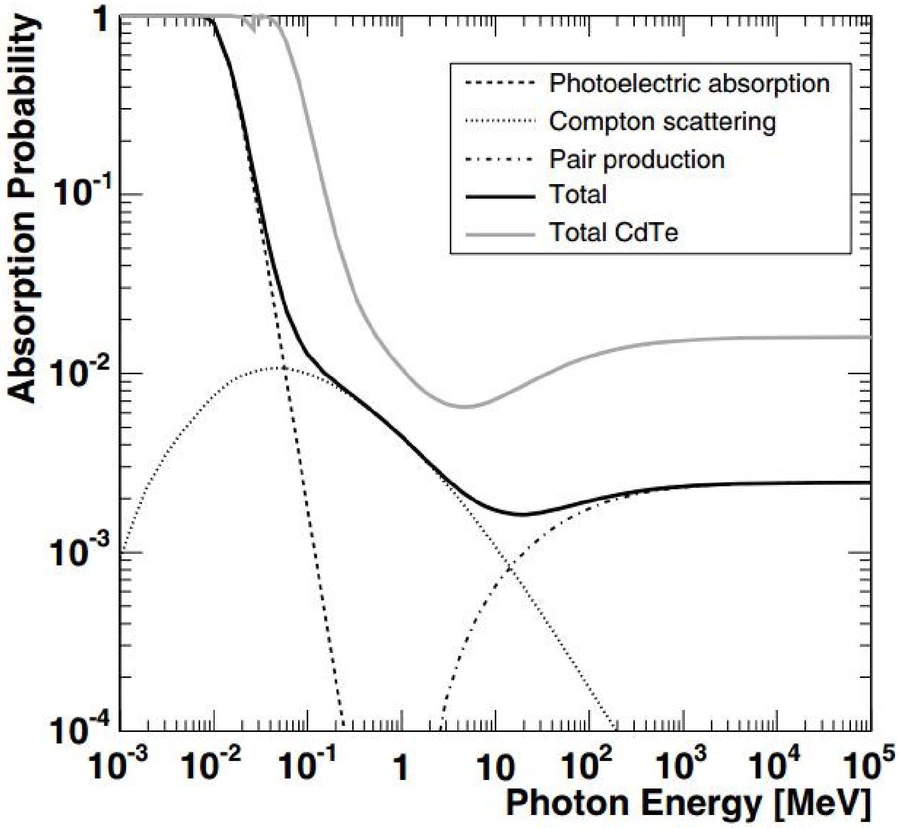

FIGURE 9: Total absorption probability of photons from γ-transformatios and X-ray radiation in a 300µm thick silicon (solid black) and CdTe (solid grey) for comparison (retrieved from [21] as reprinted from Rossi, L. *et al.* (2006). *Pixel Detectors*. Berlin: Springer)

1. E. Particle physics in school

Particle physics is not only fascinating but also fundamental, even though "in most countries the topic of modern physics is usually added at the end of physics education – if at all" ([36], p. 1). In the following I describe how particle physics can be tackled at earlier stages in school.

1. E. 1. Introducing the Standard Model of particle physics

Wiener *et al.* (2017) "developed a learning unit, which aims to introduce 12 year-olds to elementary particles and fundamental interactions" (p.1). The learning unit does neither depend on the curriculum nor on the learners' prior knowledge about particle physics and thus, can be used for all age-groups [36].

1. E. 1. 1. Key ideas about the subatomic structure of matter

The learning unit is based on "ten key ideas, which are fundamental to the introduction of the subatomic structure of matter" ([36], p. 3). They are described as follows by Wiener *et al.* (2017):

1. Matter is everything that can be touched, practically or theoretically.

2. Reality is described through models, e.g. the model of particle physics.
3. In the model of particle physics, there are atoms, which may combine to form compounds.
4. In this model, atoms are divided into two areas: the nucleus-space and the orbital-space.
5. In the nucleus-space, protons and neutrons are located.
6. Protons and neutrons are particle systems, which are made of quarks.
7. Quarks are indivisible. In this model, these are called elementary particles.
8. In the orbital-space, it is likely to find electrons.
9. Electrons are indivisible. In this model, these are called elementary particles.
10. In this model, apart from particles, there is only empty space. ([36], p. 3)

1. E. 1. 2. Representation of particles

It is a common teaching practice for visualizing abstract concepts to present everyday objects [9]. Thus, learners may believe that we can imagine any abstract concept as object, even submicroscopic particles [9]. Moreover, learners memorize such visual representations well, and thus they are not likely to question or give them up again [9]. Therefore, representing particles as spheres is fraught with pitfalls and causes misconceptions [36]. Instead Wiener *et al.* (2017) recommend "avoiding any pseudorealistic illustrations and focusing on abstract symbols" (p.3) and developed "typographic illustrations" for their learning unit about elementary particles (see [36]). When using these typographic illustrations, it is obvious that they function as models for something we cannot perceive visually [36]. Thus, the model aspect of science, and especially of particle physics, is emphasized [36].

1. E. 1. 3. Linguistic accuracy

Learners struggle with distinguishing between particles, which are made up of (elementary) particles, and elementary particles. Wiener *et al.* (2017) recommend using the term "*particle*" only for the latter [36]. The former shall be termed "*particle systems*" instead [36].

Furthermore, they divided the atom linguistically in two areas by introducing the terms "*nucleus-space*" and "*orbital-space*" [36]. These terms especially emphasize that both are areas where particles are located with a certain probability [36]. Teachers should also highlight that within their space particles do not have classical characteristics (e.g., location or path) [25]. In addition, talking about the nucleus- or orbital-space already implies that these are empty except for the particles [36].

1. E. 2. Semiconducting materials as particle detectors

When talking about semiconducting materials, especially about diodes, in school, it is also possible to include particle detectors. In this chapter I describe my personal teaching experience, key ideas, and recommendations for teaching practice.

1. E. 2. 1. Personal teaching experience

From my teaching experience I can tell that detectors are a catchy topic in the context of semiconductors and in especial diodes. Therefore, I usually talk about photodiodes and possible applications with my 8th grade students. Besides solar cells and TV receivers, we learn about the detector chip of a consumer camera and detectors at CERN. So far, I did this with four classes, i.e. with approximately a hundred students. I got the impression that they were really interested in this topic, but I may not be objective.

1. E. 2. 2. Key ideas about the function principle of particle detectors

The function principle of a particle detector used as a consumer camera and as specific detector at CERN is basically the same:

1. Particle detectors consist of photodiodes out of semiconducting material, usually silicon, which are operated in reverse direction.
2. When a charged particle or photon moves through the depletion zone of a diode, it deposits its energy to an electron. The electron is freed from its atom and hence, electron-hole-pairs are produced.
3. The electrons and holes function as free charge carriers.
4. The free charge carriers are collected by an externally applied electrical field and can be measured as voltage.
5. One can tell how much energy was deposited because the higher the energy deposit of the charged particle or photon, the more charge carriers are freed and the higher is the measured voltage.[4]
6. Since the detector is divided into several thousand pixels, one can further tell where the energy was deposied.

1. E. 2. 3. Representation of particle tracks

The detector data can be read out and displayed with a user interface. Since different particle types deposit characteristic amounts of energy and leave specific tracks in the detector, they can be identified [38]. The teacher must emphasize that "[t]he detected patterns do not picture the original dimensions and shape of the incident particle" ([21], p. 9). Only the location and the relative amount of free charge carriers, which are a result of the interaction between the particle and the sensor material, are imaged [21].

[4] Note that the energy is deposited in quants and via secondary processes.

1. E. 2. 4. Linguistic accuracy

It is necessary to make a clear distinction between ionizing radiation from radioactive transformations and the cover term "*ionizing radiation*", since other types of radiation are ionizing as well [20].

When talking about ionizing radiation from radioactive materials it is inevitable to distinguish between particles from α- and $\beta^{\pm}$-transformations, and photons from γ-transformations [20].

The former is referred to as particle radiation, which means that massive particles, namely helium cores and electrons, are propagating [20]. In addition, particle radiation also comprises cosmic radiation, e.g., propagation of muons and other elementary particles [20].

The latter pertain to electromagnetic radiation [20]. In contrary to particle radiation, energy transport does not include transport of matter in case of electromagnetic radiation [20]. The other types of ionizing electromagnetic radiation are X-rays and UV-light [20].

Finally, it is important to emphasize that the term "*radioactive radiation*" is a shortening of "*ionizing radiation from radioactive sources*" [20]. It is not the radiation that radiates radiation but a radioactive material [20]. In my opinion it may be helpful to explain that this shortening does not even make sense, since the term "*radioactive*" is derived from Latin and means "to emit radiation". If radiation is mixed up with the transport of radioactive material, which is a common preconception, this approach may not help though [20].

2. RESEARCH INTEREST

As little is known on what learners discern from visualizations in particle physics, the aim of this study is to obtain a better understanding of whether they are learning aids or obstacles. The research interest is similar to Eriksson *et al.* (2014) who carried out a study about an astronomical representation and introduced the A*natomy of disciplinary discernment.* In this study the ADD has been tested as a tool to evaluate the efficiency of using visualizations for teaching particle physics.

These are the main **research questions** [7]:

1. What is the **discernment** reported by **high school and university students and teachers** when they engage with the **same disciplinary** representations concerning particle physics?
2. How can this **discernment** be **characterized** from an **educational perspective** with respect to the *Anatomy of Disciplinary Discernment*?

3. ANALYZED REPRESENTATIONS

My research interest is to find out what learners discern, when they engage with visualizations in particle physics. Two representations concerning particle physics and related to CERN were analyzed, namely a video and a user interface.

3. A. Video

3. A. 1. Selection process

I aimed to analyze a video that was developed by CERN employees or is displayed in CERN's exhibition, as well as suitable for teaching particle physics in schools. Therefore, I searched for an appropriate video on the CERN CDS video website. In especial, I looked at two different videos. For comparison I listed their advantages and disadvantages in TABLE 3.

TABLE 3: PROs and CONs of different videos

VIDEO	PROs	CONs
"Voyage into the world of atoms" Link: https://videos.cern.ch/record/2307613 (17.12.18) ⇨ **STANDARD MODEL**	Suitable for teaching particle physics in schools (molecules – atoms – electron – nucleus – quarks)	Fibril structures are included
	Similar to the video "Flight over the Virgo Cluster" (zoom out of milky way until one can see other galaxies) analyzed by Eriksson *et al.* (2014)	Focus on proton, no details about the neutron included
		Continuum and discontinuum concepts are mixed up
	Can be divided into short clips	**Possible misunderstandings:** - Particle systems are bubbles filled with particles and air in between - Electrons look like drops
	Available either with or without labels	
"CERN OVERVIEW animation" https://videos.cern.ch/record/2020780 (17.12.18) suggested stop at 1:19 ⇨ **OVERVIEW**	Suitable for talking about CERN in schools, since it gives an overview (hydrogen source – accelorators – LHC – detectors)	What happens in the Duoplasmatron Proton Source/LINAC/…? ⇨ No further details included
	Protons move in opposite directions ⇨ Collisions in the 4 detectors Can be divided into short clips	**Possible misunderstandings:** Protons are red lines that move along the same path but in opposite directions ⇨ Proton collisions take place everywhere in the tunnels

Finally, I decided on the video called "Voyage into the world of atoms". This video was selected, since it involves several advantages and disadvantages that are interesting subjects to further investigation (see TABLE 3). E.g., the ways in which particles are visualized in this video are interesting for physics education research, since "[o]ne of the biggest challenges when it comes to teaching particle physics is its abstractness" ([36], p. 3).

3. A. 2. Video "Voyage into the world of atoms"

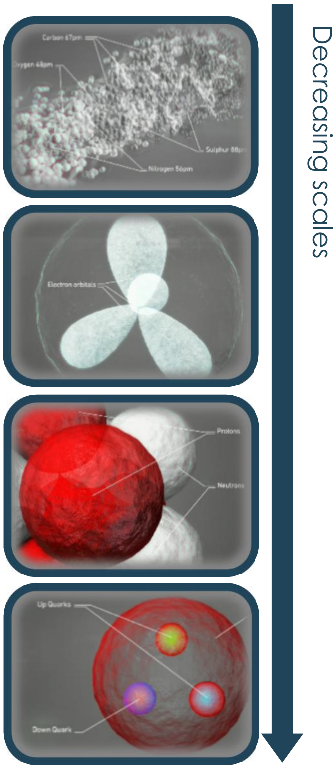

FIGURE 10: Endings of the four sections: representation of atoms, electron orbitals, protons, neutrons and quarks

The video "*Voyage into the world of atoms*" was developed by Daniel Dominguez, a CERN employee, and is displayed in CERN's Microcosm exhibition.
It shows the structure of matter at smaller and smaller scales. Zooming into a human hair, one passes through hair cells, fibril structures, keratin molecules, atoms, electron orbitals, nuclei, neutrons, protons, and finally quarks[5] (see FIGURE 10). The video was developed for educational rather than disciplinary-specific purposes. In general, it is meant to give an impression of what particle physics is about by using a daily-life example. Furthermore, the video deals with the ten key ideas of subatomic particles mentioned in chapter 1. E. 1. 1.

However, the video can be referred to as *multimodal representation*, since it consists of a dynamic visualization and a written explanation. In especial, a scale is included in the video which indicates the order of magnitude of the currently shown objects. Thus, the zooming is not only conveyed by itself but also by the scale.

Besides, the video is available with labels which provide further information of the objects in written form. They explain what is shown (e.g., they say "proton" and "neutron").

Since the video is a multimodal representation, it offers specific advantages and can be used for multimedia learning (see chapter 1. C. 2.).

For the main study the video was cut into four sections which lasted on average about 20 seconds. Their endings are shown in FIGURE 10. Cutting the video into shorter clips was necessary since it provides a huge amount of relevant information. Thus, displaying the whole video at once may overload cognition of the learner [24]. In "the concept of cognitive overload […] the learner's intended cognitive processing exceeds the learner's available cognitive capacity" ([24], p. 43). According to Mayer and Moreno (2003) segmenting is a solution for this problem. The *segmenting principle* states that "[s]tudents understand a multimedia explanation better when it is presented in learner-controlled segments rather than as a continuous

[5] Link to the video "Voyage into the world of atoms": https://videos.cern.ch/record/2307615 (30.11.18), Copyright: CERN 2018, Creator: Dominguez, Daniel

presentation" ([24], p. 47). Accordingly, "[p]resenting smaller segments at a time [...] enhances the possibility for a participant's focus to be sharpened and learning to take place" ([6], p. 143).

However, different groups of participants saw different versions of the video: Some of them saw the one with labels and the others the one without labels.
All participants were asked the same two open-ended questions for each clip in analogy to Eriksson's study concerning a video about the structure of the universe:

1. Please write what comes to mind when you watch this clip.
2. What, if any, "I wonder..." questions did this clip raise for you? ([7], p.171)

In addition, some follow-up questions were asked after the last clip (see chapter 10. A. 3.).

3. B. Representation of a measurement

The user interface "*Pixelman*" was developed by the Medipix2 collaboration at CERN and is used in *S'Cool LAB* for the *X-rays workshop.* Like the video the user interface "*Pixelman*" was developed for educational purposes.
Using the digital particle camera *MX-10* and the user interface one can study tracks of particles [38]. Different types of particles can be distinguished by their specific signature in the detector [38]. The sensitive area of the detector chip measures 1.4 x 1.4 cm^2 and is divided into 256 x 256 pixels. The deposited energy per pixel is measured.

The user-interface *Pixelman* is a *multimodal representation* as well, since a dynamic visualization and written text are combined.

A coordinate system is displayed on the screen, when using the interface *Pixelman*. The pixels are put on the X- and Y-axis of the coordinate system. Therefore, one can see where a particle hit the detector chip.

In addition, the energy deposit per pixel is represented by the color. This is indicated by a color map below the coordinate system where the deposited energy rises from left to right (see FIGURE 11) [38]. Accordingly, the higher the deposited energy, the brighter is the color of the pixel.

Neither the axes nor the color map is further explained than by numbers. Concerning the X- and Y-axis they indicate the number of the pixel. Concerning the color map, they tell how much energy was deposited. However, one would expect labels which say "*number of pixel*" and "*energy deposit per pixel*", as well as the corresponding units. "In such a representation, it becomes obvious that there are many different disciplinary affordances, which may be hidden to a novice or newcomer to the discipline" ([8], p. 2).

At the beginning of the part of the survey about the user-interface the participants got to read a short introduction about the function principles of a pixel detector. Afterwards they were asked what they discern from the representation of a measurement with the particle camera *MX-10* and the user interface “*Pixelman*” (see chapter 10. A. 3.). When developing the questions about the representation of a measurement, Urban Eriksson’s survey about Hertzsprung-Russel-Diagrams was used as a model (see [8]).

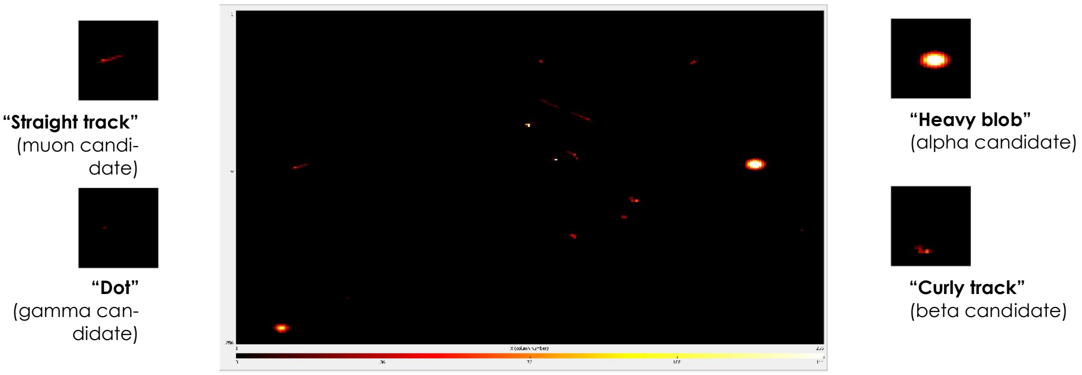

FIGURE 11: Representation of a measurement with a *MX-10* pixel detector and education user interface “*Pixelman*”: The participants only saw the screenshot in the middle. The zoomed details on each side provide additional explanations about the identification of particle tracks.

Although the chip is square shaped, the representation of the measurement adapts to the screen when displayed with *Pixelman*. Therefore, in the most common case when opening the user interface, the image is rectangular so that the particle tracks go out of shape. To make the survey as authentic as possible such a rectangular representation of the measurement was included as shown in FIGURE 11.

4. METHODOLOGY

The study approach was qualitative and interpretative-hermeneutic (see [6], p.137f). For the data collection an online survey with open-ended questions was created using "*Google Forms*". To analyze the data a category-based approach was chosen. Thus, it was possible to structure the participants' statements with reference to the five *Levels of Discernment* (see chapter 1. A. 2.).

4. A. Study approach

The qualitative approach was chosen because it has an "epistemological grounding that portrays knowledge as a human construction, and an aim that is to establish a new understanding of discernment" ([6], p. 137). Therefore, it is appropriate to figure out and describe what different persons discern and how they construct meaning from visualizations. My research rather answers qualitative questions, e.g. "what", "why" and "how", than quantitative ones, e.g. "how many" and "how much" [6]. Robson and McCartan (2016) defined typical features of qualitative social research (see [30], p.20) which I adapted for my study. The **characteristics of my qualitative research** are listed below:

- Results are presented verbally rather than numerical [30].
- The focus of the study is on the meanings associated with the evaluated representations [30].
- The research particularly pays attention to the discernment from the perspective of the learners who engage with the representations [30].
- "The design of the research emerges as the research is carried out and is flexible throughout the whole process." ([30], p. 20).
- It is considered that personal commitments of the researcher exist [30]. The researcher needs to be aware of and reflect on these commitments [30].
- The number of participants is small [30].

The approach was not only qualitative but rather hermeneutic-interpretive. Hermeneutics are appropriate since they aim to understand and determine meaning and to interpret [6]. Furthermore, they see "using a particular framework to construct a particular interpretation (understanding) of the experience of others constitutes a legitimate knowledge claim" ([6], p. 136).

4. B. Data collection

4. B. 1. Choice of method

For collecting data there are various methods with specific advantages and disadvantages described by Robson and McCartan (2016). In general, one can distinguish between three methods [30]:

1) The first one is *observation*, i.e. watching people and figuring out what is happening [30].
2) The second one is *interviewing*, i.e. asking people about what is happening [30]. For this purpose, questionnaires or tests are used either with or without direct, personal interaction between researcher and respondents [30].
3) The last data collection method is "*looking for evidence*" ([30], p.241) that people leave behind them [30].

Following Robson and McCartan (2016) the "selection of a method […] is based on what kind of information is sought, from whom and under what circumstances" (p. 241).

The information I sought was what learners discern when they engage with representations in particle physics. This means that my research aimed to find out what the participants "think, feel and/or believe" ([30], p. 242). For this purpose, Robson and McCartan (2016) recommend using interviews or questionnaires [30].

Besides, the circumstances need to be considered when choosing a data acquisition method since they have a large influence on practicality [30]. For carrying out my study I spent two months at CERN in summer 2018 which means that time was limited.

Considering the above-mentioned aspects, I preferred the use of questionnaires over interviews. According to Robson and McCartan (2016) questionnaire-based surveys have several advantages and disadvantages. The ones that apply for my research are listed below:

DISADVANTAGES

- of surveys in general

- "Data are affected by the characteristics of the respondents (e.g. their memory, knowledge, experience, motivation and personality)." ([30], p. 248)
- "Respondents won't necessarily report their beliefs, attitudes, etc. accurately (e.g. there is likely to be a social desirability response bias – people responding in a way that shows them in a good light)." ([30], p. 248)

- of self-administered surveys

- "Ambiguities in, and misunderstandings of, the survey questions may not be detected." ([30], p. 248)
- "Respondents may not treat the exercise seriously and you may not be able to detect this." ([30], p. 248)

- of Interview surveys

- "There may be interviewer bias, where the interviewer, probably unwittingly, influences the responses (e.g. through verbal or non-verbal cues indicating 'correct' answers)." ([30], p. 248)

ADVANTAGES

- of surveys in general

- "They provide a relatively simple and straightforward approach to the study of attitudes, values, beliefs and motives." ([30], p. 248)

- of self-administered surveys

- "They can be extremely efficient at providing large amounts of data, at relatively low cost, in a short period of time." ([30], p. 248)
- "They allow anonymity which can encourage frankness when sensitive areas are involved." ([30], p. 248)

- of Interview surveys

- "The interviewer can clarify questions." ([30], p. 249)
- "The presence of the interviewer encourages participation and involvement (and the interviewer can judge the extent to which the exercise is treated seriously)." ([30], p. 249)

4. B. 2. Development of the questionnaire

Data for my study was collected by computer-aided interviewing (CIA), since it provides several advantages (see [30], p. 254). An online questionnaire was created with "*Google forms*". This approach was chosen since it is free and easy to use even without having prior experience in developing questionnaires. According to Robson and McCartan (2016) "a good questionnaire not only:

- provides a valid measure of the research questions; but also
- gets the cooperation of respondents; and
- elicits accurate information." (p. 259)

To fulfill these criteria the questionnaire was developed step by step.

1. step: Initial draft of questionnaire

The first step was to precisely define the desired information. According to my research questions, desired information is what learners discern from visualizations in particle physics. Since my research interest is similar to Urban Eriksson's, I examined his surveys.

He created not only a questionnaire about an astronomical video but also about an astronomical diagram. The former is meant to be used for educational or entertaining purposes like the video about particle physics analyzed in my study. The latter is a specific representation used within the discipline which is a parallel to the representation of a measurement analyzed in my study. Besides Eriksson's questionnaires, I considered the recommendations given by Robson and McCartan (2016) (see [30], p. 254). In especial, I tried to "*[k]eep the language simple*" and the "*questions short*" as well as to "*[u]se personal wording*" ([30], p. 254). Since the focus was on individual discernment, I decided on using open-ended questions which particularly disclose the respondents' way of thinking [19]. Furthermore, it is possible to distinguish between different levels of discernment when using open-ended questions [19]. I created an initial draft of the questionnaire for my survey in German (see chapter 10. A. 1.). It was structured as follows:

At beginning of the questionnaire, the respondents had to agree to the ethical arrangements. Besides there were two questions concerning the personal background of the participants.

One part of the questionnaire was about the video. For the test version of the questionnaire the video was cut into six sections and the version with labels was used. Two questions about the discernment of the participants were posed for each videoclip. "In accordance with the 'segmenting principle' […] the individual clips could be re-played as many times as wanted by the participants while they answered the clip questions." ([6], p. 144). FIGURE 12 shows a screenshot of the questions about the first videoclip and the accompanying introduction.

FIGURE 12: Screenshot of the questions about the first videoclip displayed

The other part of the questionnaire was about the representation of a measurement with Pixel detector *MX-10* and user-interface *Pixelman*. At first the respondents read an introduction about the function principle of pixel detectors. A question about this introduction was posed to make sure that the participants have at least the minimum knowledge needed to fill in the survey. Afterwards a screenshot of a measurement was presented accompanied by an introduction as shown in FIGURE 13. The set of questions about the visualization was divided and displayed in subsets, each of it accompanied by the screenshot and the introduction.

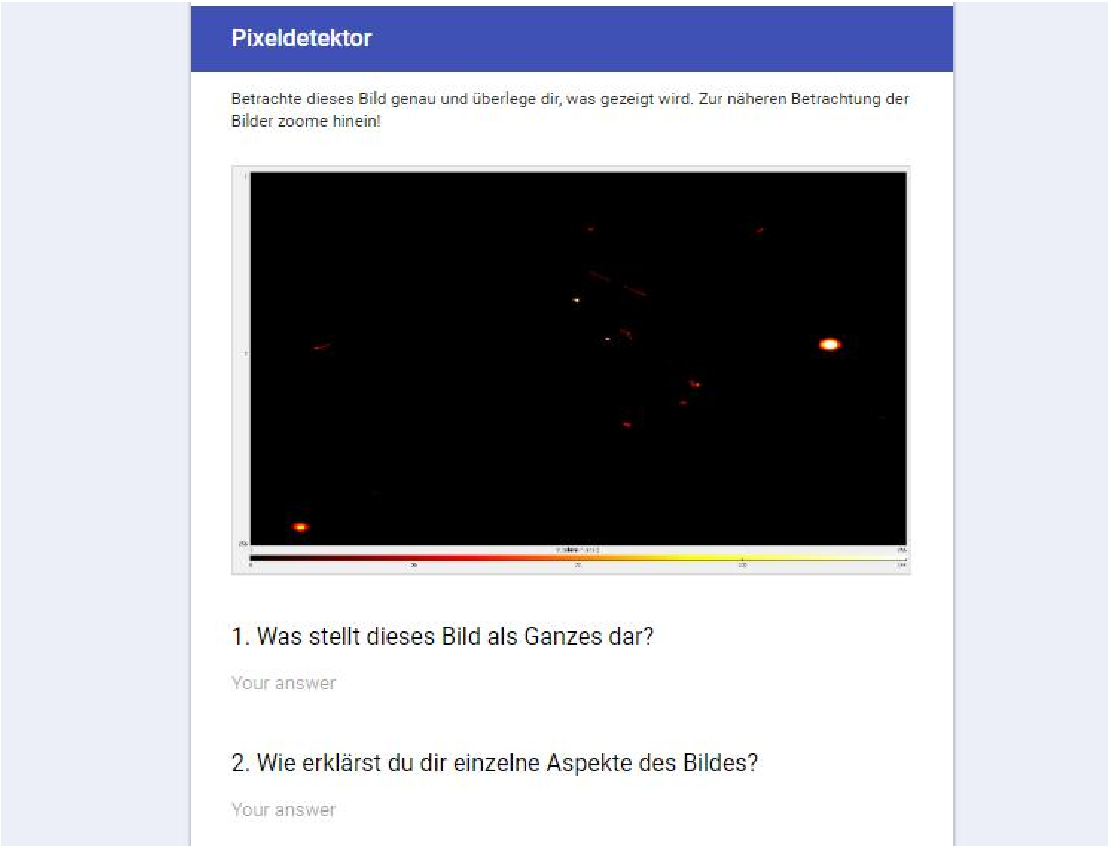

FIGURE 13: Screenshot of the first subset of questions about the representation of a measurement with Pixel detector *MX-10* and user-interface *Pixelman*

2. step: Prestudy

Secondly, I carried out a prestudy. I tested the questionnaire on a group of high school students (see chapter 5.). For the prestudy I created two online forms with different order of parts, i.e. one questionnaire started with questions about the user interface and the other way around. This was done to find out, if the order of the posed questions effects the answers given by the respondents. A positive side effect was that by using two questionnaires I could make sure that seatmates filled in different versions, and thus could not copy from each other.

3. step: Revision of the questionnaire

After analysis of the results the questionnaire was revised. This was necessary because my survey contained questions that ask two questions at once, i.e. "*double-barrelled questions*" ([30], p. 254). Furthermore, some follow-up questions concerning the video were added. Besides, minor changes of the video itself were made. In detail the modifications of the questionnaire were as follows:

As in the initial version of the questionnaire the respondents had to agree to ethical arrangements and answer two questions concerning their personal background.

In the revised version of the questionnaire the video was cut into four sections instead of six. The first section contained the first three videoclips used in the initial draft since they were of low interest for my research. As the first clip should still not be longer than the others, the speed was increased. Furthermore, the two different versions of the video, with and without labels, were analyzed. Note that each group of participants only saw one version. This enabled me to compare the answers given by groups who saw the labeled version with those given by groups who saw the unlabeled version. Besides, the links to the videos were renamed. This was necessary because in the prestudy some respondents wrote what they discerned from the name of the link and not from the visualization itself. The two questions about each videoclip were retained but follow-up questions about the whole video were added. These "questions were used to further address aspects that the participants may have discerned in the […] clips and which they were subsequently thinking about in retrospect" ([6], p. 144).

Furthermore, minor changes of the questions concerning the Pixel detector were made. The introduction to pixel detectors and the corresponding question were retained. After this question the same screenshot and explanation as before were presented for each subset of questions. One question was added to the last subset to find out, if learners recognize particle tracks correctly.

4. step: Evaluation

The fourth step was to test the modifications on a group of German teachers (see chapter 5.). After analysis of the results my colleagues at CERN and I discussed them. We thought that the revised version of the questionnaire served its purpose. My colleagues and I agreed on including the results of this trial group in the main study.

5. step: Final version of the questionnaire

In total there were eight different final versions of the questionnaire. There was a version of the questionnaire including the labeled videoclips and another including the unlabeled videoclips. Furthermore, each version was available not only with different orders of questions, but also in German and English (see Appendix).

After development of the questionnaire the actual data collection process for the main study could start. Filling in each part of the questionnaire took about 25 minutes. Thus, filling in both parts took twice as long.

4. B. 3. Data collection process

Robson and McCartan (2016) introduced a model of the survey data collection process which I adapted for my research (see FIGURE 14).

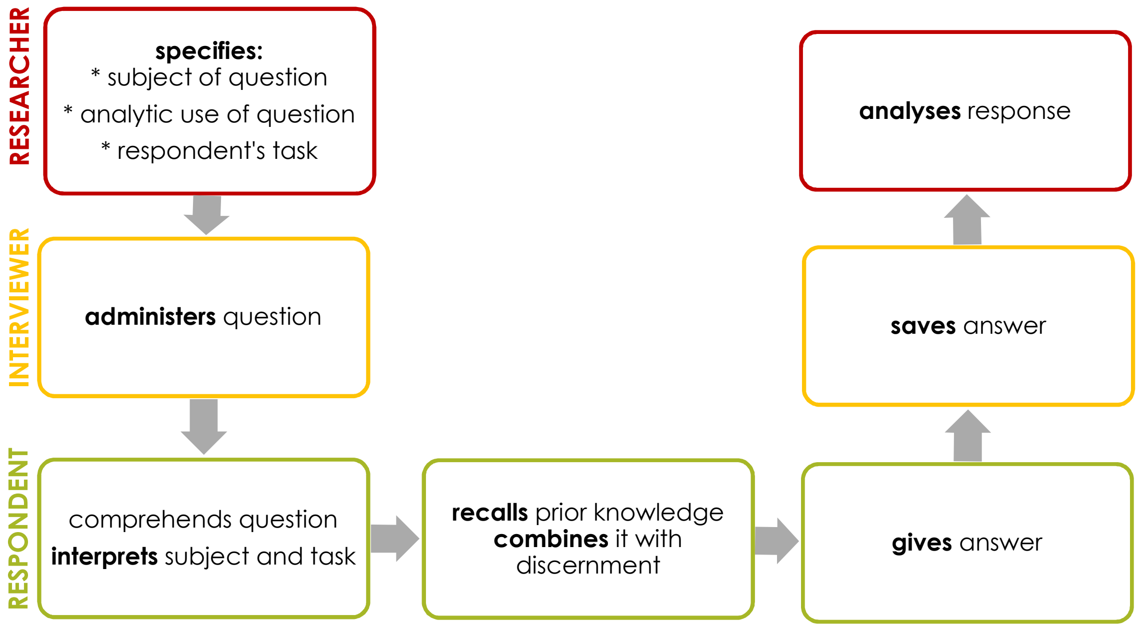

FIGURE 14: Adapted model of the survey data collection process after Robson and McCartan (2016) ([30], p. 259)

The researcher and the interviewer may be the same person as was the case in my study.

As a researcher I specified the subject of question, the corresponding analytic use, i.e. the research interest (see chapter 2.), and the respondents' tasks, i.e. the questionnaire (see chapter 4. B. 2.).

As an interviewer I administered the questions to the respondents using computer-aided interviewing. This approach involved not only advantages but also disadvantages (cf. [30], p. 254). To the former count that no paper needed to be printed [30]. To the latter count that problems associated with IT were encountered [30]. E.g. the battery of some laptops failed so that they needed to be plugged in all the time [30]. Furthermore, the program crashed from time to time and thus, some participants had to start again from the beginning or their answers were lost. However, for administering the online survey I created links using the "CERN URL shortening service". This contributed not only to convenience but also to professional appearance.

The online questionnaire was administered using two different approaches:

The first one was "on a group basis" ([30], p. 250), i.e. I gathered a group of participants in one room where they filled in the survey at the same time. This approach involved not only characteristics of a self-administered but also some of an Interview survey as listed above (see chapter 4. B. 1.). As mentioned above, presence of the interviewer is advantageous. Thus, I was present to clarify questions and make sure that participants treat the survey seriously. However, problems were encountered, too. E.g., a room needed to be available with enough space for up to 45 people. Since I was at CERN to conduct this research, I had access to S'Cool LAB as well as CERN's main auditorium for data collection. Besides, a large number of laptops needed to be provided. Again, I could use S'Cool LAB property. My colleagues helped me to book and to prepare the rooms for data collection. Preparation included bringing the laptops in the room and putting them on the tables. In addition, they were turned on to check if they are working and needed to be charged, and the online survey was started on each of them. It took two persons about 45 minutes to prepare the room.

The second approach of data collection was purely self-administered. This means that I sent out the questionnaire to some participants per mail. As listed above, the self-administered approach involves specific advantages and disadvantages (see chapter 4. B. 1.). However, one big advantage of this approach is that it is less time consuming for the interviewer in comparison to the above described approach.

All respondents had to answer the questions by themselves in written form. This so-called "*[s]elf-completion*" ([30], p. 250) approach was an appropriate way of data acquisition for my research, since it enabled me to ask many persons in a limited amount of time.

Thanks to computer-aided interviewing it was easy for me as an interviewer to record, download and save the answers given by the participants since it was not necessary to type them in [30]. Therefore, as a researcher I could conduct data analysis very soon after collection [30].

4. C. Data analysis

There are various methodologies for analyzing the collected data within hermeneutics but all of them have one thing in common: The researcher must constantly compare subsets of the data with the set as a whole [6]. However, as mentioned above to analyze the data for my research a category-based approach was chosen.

4. C. 1. Category-based approach

Category-based analysis is defined as assigning single statements to certain categories [23]. When developing categories for analyzing statements, they should be theoretically grounded and empirically useful [19]. The number of evolving categories is important, since the general principle is that they must be logically independent from each other [19]. Accordingly, two categories which are related to each other must be unified [19]. When the aim of the analysis is to show different levels of discernment of complex structures, a relatively large number of categories is useful [19]. To simplify an intricate category system, several categories may be merged subsequently under a cover term [19]. The goal is to obtain "the minimum number of independent categories to represent the data" ([29], p. 34f).

Concerning the content categories, the approach was inductive, i.e. the categories were derived from the statements. In contrast, concerning the analysis categories, the approach was deductive, i.e. the categories were derived from theoretical considerations [23]. According to Hammann and Jördens (2014) this is particularly useful, if the study aims to measure comprehension in scientific context [19]. Since my analysis, especially research question 2, focuses on characterizing the statements according to the *Levels of Discernment,* these were taken as reference from Eriksson *et al.* (2014).

As the term *"code"* is often used as a synonym for *"category"*, the process of assigning statements to categories is also called *"coding"* [23].

4. C. 2. Rules for coding

When doing category-based analysis Kuckartz *et al.* (2009) established rules for coding statements (cf. [23], p. 78f). I adapted these rules for my study:

4. C. 2. 1. Coding single statements

A statement is defined as a participant's answer to one certain question of the survey and must be coded as one [23]. If it is about more than one aspect, only the part relevant for the chosen category is coded [23].

4. C. 2. 2. No double coding

A certain aspect must only be coded once per person [23]. If somebody e.g. criticizes in two statements that the representation of protons as bubbles is misleading, it is only coded once.

4. C. 2. 3. Spread coding

All answers of a person shall be considered [23]. If a person e.g. gives recommendations for the representation of a proton, when asked what new connections the movie made for the participant, the statement shall be assigned to the respective category unless it would be a double coding [23].

4. C. 2. 4. Coding of missing values

Empty answers or answers which shall be counted as empty (e.g., dash "-") shall be assigned to the category "Missing" [23]. The answer "none" or "nothing" shall function as own category [23], e.g. when asked what new connections the clip made for the participant.

4. C. 3. Coding process

For the coding process I used the program *Microsoft Excel*, in which I assigned the statements manually to the analysis categories. Each category was indicated by a capital letter in the *Category* column as shown in FIGURE 15. The categories and the corresponding letters are explained in detail in chapter 7. A. 3. for the video and 7. B. 2. for the user interface.

1. Please write what comes to mind when you watch this clip.	Category	2. What, if any, "I wonder ..." questions did this clip raise for you?	Category
It gets even smaller	A	None	N
I realized how small an atom is and how much space the electron orbitals take up in the nucleus.	C	I wonder why the electrons are in this pattern.	B
it is a useful video as it shows the different scales using human hair as an example	X	I have not noticed anything new.	N
I didn't realise yet that hair is made out of carbon	B		M

FIGURE 15: Screenshot of the data coding process

4. C. 4. Statistical analysis

After coding all the statements, I compiled a statistic. To answer my research questions, the focus of the statistical analysis was on the relative frequency of answers in a certain category per group of participants. The quantitative analysis was done separately for each part of the survey, i.e. the part about the video and the part about the user interface.

The program *Mircrosoft Excel* was used. At first, the total of answers concerning the video or the user interface was calculated for each group of participants. Then I compared the total of answers assigned to a certain analysis category with the overall sum. Thus, I could calculate the relative frequency of answers of each group of participants in a certain category.

5. Participants

For my research it was more important to have a wide variety of described discernment than many participants. In total 174 persons, 83 females and 90 males, with various backgrounds in terms of education and nationality participated in the main study. In the *Ethical arrangements* I guaranteed that the data is treated confidentially. The only aspects that are linked with the answers given by the participants are the gender and the educational background. Therefore, I cannot provide further details about the groups of participants. However, all group of participants and their characteristics are listed in Table 4. Furthermore, one can see which groups filled in which parts of the survey as well as whether the questionnaire involved videos with labels or without.

Table 4: **Participants** of the prestudy and the main study

		CERN visitors		Others
		short-term	**long-term**	
PRE-STUDY	**High school students**	19 German (6♀, 13♂): • Video (labels) • User interface		
MAIN STUDY	**High school students**	25 German (11♀, 14♂): • Video (no labels) • User interface	32 international – *S'Cool LAB Summer Camp* (18♀, 14♂): • Video (labels) • User interface	13 Austrian (8♀, 5♂): • Video (labels)
	University students		39 international – *Summer Student Programme* (17♀, 22♂): • Video (labels) • User interface	
	Teachers	21 German (10♀, 10♂, 1 n. a.): • Video (no labels) • User interface	44 international – *International Teachers Weeks* (19♀, 25♂): • Video (labels) • User interface	

The respondents were mostly visitors at CERN's site.

When analyzing the collected data, one must distinguish between short- and long-term visitors. The former are likely to have had less disciplinary prior knowledge than the latter who attended lectures about particle physics held by scientists at CERN. This bias must be considered.

Most of the CERN visitors had to fill in the survey on a group base because their program, e.g. lectures, visits or workshops, was on a group base anyway. To motivate them to participate in my survey, my colleagues and me offered them additional program in return. E.g., the German high school students could participate in a *Cloud Chamber Workshop* and both group of teachers could attend a workshop about 3D printed school experiments.

However, for the international summer students the self-administered approach was chosen. Therefore, I sent out an e-mail to my fellow summer students and kindly asked them to participate in my survey. As a thank you I gave to the respondents P*article identity badges.*

Besides, a group of Austrian high school students was asked to fill out the survey on a group base at school in Vienna. There was no need to particularly motivate them to participate in my survey because it was a welcome change during their regular physics class.

6. QUALITY ISSUES

6. A. Introduction to quality issues

When doing any research, quality issues need to be considered. For different research approaches the focus is on specific aspects [6]. Thus, there is a myriad of key terms concerning quality issues. I engaged with several researchers who published papers on this matter, e.g. Schmiemann and Lücken (2014) and Stiles (1993). The former focused on the validity of tests about content knowledge and therefore, I cannot apply all key terms they define to my research. For my study I developed questionnaires that are rather about individual discernment than well-defined content knowledge. Thus, I followed the latter whose focus is on "[q]ualitative investigations of human experience" ([34], p. 593). In terms of quality issues this is applicable to my research. Furthermore, Eriksson (2014) whose study is similar to mine followed Stiles (1993) as well.

According to Stiles (1993) "qualitative research shifts the goal of quality control from the objective truth of statements to understanding by people" (p. 593). Thus, "characteristically qualitative trustworthiness issues arise because words do not mean the same thing to everybody and because events look different from different perspectives" ([34], p. 602).
However, for quality issues in context of qualitative research the main key term is trustworthiness which includes two aspects: Reliability and validity [34]. The former concerns the data and the latter the interpretations [34]. Another key term is objectivity [33].

6. A. 1. Reliability

Reliability is about the process of data collection [34]. The main question is "whether the observations are repeatable (after allowing for contextual differences)" or not ([34], p. 602). This comprises questions like "Do different participants say similar things?" or "Does one participant give consistent answers to questions worded different ways?" ([34], p. 602).

To fulfill the criteria included in reliability Stiles (1993) gives several recommendations for good practice (see [34], p. 602 ff). I adapted them for my research:

6. A. 1. 1. Disclosure of Orientation

The investigator discloses "expectations for the study, preconceptions, values, and orientation, including any theoretical commitments" ([34], p. 602). Thus, it is easier for the reader to conclude what the data means to the investigator [34]. Furthermore, disclosure of orientation makes it possible to retrace the study's impact on the theory [34].

6. A. 1. 2. *Description of internal processes of investigation*

The researcher describes his or her internal processes while collecting and interpreting the data [34]. To do so questions like "How did the investigation affect you?", "Were you surprised?" or "Did the data make you change your mind?" ([34], p. 603) are answered. However, this is only possible to a certain extent because one may not be aware of all internal processes [34].

6. A. 1. 3. *Engagement with the material*

In qualitative research engagement with the material may be the most time-consuming part [34]. It involves reading the whole dataset several times and searching for similarities between subsets of it [34]. For "developing empirically grounded theoretical categories" ([34], p. 605) it is necessary to alternate between data and theory, i.e. to compare developed categories repeatedly with the dataset. In addition, the evolved interpretations are discussed with other researchers and adapted if necessary [34].

6. A. 1. 4. *Grounding of interpretations*

"Interpretations […] require grounding, and qualitative researchers have worked out a variety of procedures for linking their more abstract interpretations with their more concrete observations" ([34], p. 605). Stiles (1993) describes e.g. the "content analysis" approach (cf. [34], p. 605): After reading the data reoccurring topics and patterns are subsumed under several generic terms and thus, content categories evolve [34]. These are presented with illustrative examples [34]. Then, the researcher searches for similarities between different content categories [34]. In addition, already existing theories are taken into consideration when organizing the content categories into analysis categories [34].

6. A. 1. 5. *Ask "What?", not "Why?"*

"Good practice enjoins qualitative researchers to ask participants questions that they can answer" ([34], p. 606). E.g., "although people may not know why, they do know what" ([34], p. 697). Even if the respondents may not be able to express their reasoning, when they are asked "what", their answers may divulge the reasoning [34]. Thus, the researcher can interpret them and derive a theory from them [34].

6. A. 2. Validity

There are various definitions of validity.

Schmiemann and Lücken (2014) define it as the efficiency of the data collection method. Thus, the main question is, if it measures the aspect that it was intended to measure. e.g. a test for content knowledge is not valid, if it rather measures reading comprehension than content knowledge [33]. Furthermore, they claim that before development of the data collection device the researcher must define clearly what shall be measured and why [33].

However, according to Stiles (1993) validity in qualitative research refers to the interpretation and concerns if it "is internally consistent, useful, robust, generalizable, or fruitful" (p. 607). Since my study approach is interpretive-hermeneutic, validity is extremely important for my research. Stiles (1993) describes various types of validity. The ones that apply for my research are listed below.

6. A. 2. 1. Triangulation

Triangulation encompasses several aspects:

Data triangulation refers to the data and "means seeking information from multiple data sources" ([34], p. 608), i.e. using multiple methods of data collection.

Methodological triangulation means combining methodological approaches within one study, e.g. a qualitative and a quantitative approach [30].

Following *theory triangulation* "multiple prior theories or interpretations" are considered ([34], p. 608).

Investigator triangulation means that more than one researcher is involved when developing an interpretation of the data and convergence is assessed [34]. This type of triangulation is similar to *replication* and *consensus among researches* (see [34], p. 612).

6. A. 2. 2. Coherence

Coherence "refers to the apparent quality of the interpretation itself" ([34], p. 608). It must hang together and thereby be internally consistent and comprehensive [34]. Furthermore, in an ideal interpretation the arguments of an opponent are explained and disproved [34]. Accordingly, it must go beyond simply matching data with theories [34].

6. A. 2. 3. Uncovering and self-evidence

When evaluating an interpretation, the main question is if the research questions have been answered [34].

6. A. 2. 4. Reflexive validity

Reflexive validity is concerned with how the data effects the researcher's way of thinking as well as the theory [34]. As mentioned above (see chapter 6. A. 1. 3.) engagement with the data and interpretation take turns in qualitative research. Thus, the effect is intended and especially obvious [6]. However, *Reflexive validity* is related to *Disclosure of orientation* and *Description of internal processes* in terms of the reliability of a study.

6. A. 3. Objectivity versus bias

Objectivity is essential for the quality of any research and the corresponding antonym is bias. Biases are threats to objectivity and "can be described as impermeability to new experience" ([34], p. 613). There are three types of biases that must be considered when addressing quality issues: investigator's, participant's, and reader's bias [34]. All of them have one thing in common, namely that they are due to prior expectations and values of the involved persons [34]. However, all three groups of persons can be surprised, change their way of thinking and come to a new understanding [34]. Therefore, the "initial biases are not immutable" ([34], p. 613).

I want to describe the first type of bias, i.e. investigator's bias, and how to deal with it in more detail in this chapter.

Investigator's bias means that the investigator may perceive and report selectively [34]. Thus, it is essential to reveal his or her "personal involvement and commitments and the process of investigation" ([34], p. 614), i.e. *Disclosure of orientation*, *Description of internal processes of investigation* and *Reflexive validity.* These approaches allow "readers to incorporate the investigator's part in the story into their understanding and to adjust their understanding to compensate for the investigator's biases" ([34], p. 614). Thus, "[t]he strategy of revealing rather than avoiding involvement is consistent with the broader shift in goals from the truth of the statements to the understanding by participants and readers" ([34], p. 614). Another strategy for compensation of investigator's bias is *Investigator triangulation* (see chapter 6. A. 2. 1.). However, seeking consensus with other researchers may be accompanied by intentional pressure as well as unintentional influence of established investigators on others [34].

6. B. Quality control in this study

In my research quality control refers to several aspects that I want to discuss in terms of reliability, validity and bias.

6. B. 1. Reliability

To enhance reliability of my research I will now disclose the prior orientation and how the data effected my way of thinking.

My expectations for the study were that the *Levels of discernment* introduced by Eriksson *et al.* (2014) are also valid for visualizations in particle physics. Furthermore, like Eriksson (2014) I was surprised "how little disciplinary knowledge some participants used in their discernment descriptions" ([6], p. 157). However, this finding did not influence me in a negative way. It rather had a positive effect on my analysis, since it forced me to have an analytic mindset, especially when defining the content and the analysis categories. Thus, I tried to make a clear distinction between non-disciplinary and disciplinary discernment.

Furthermore, I expected that several problems arise when learners engage with these visualizations since they look at them from a different point of view than teachers do. In especial, I expected the representations of particles and particle systems to be problematic, since models need to be used for illustrating abstract concepts. Therefore, I was surprised by the data in a positive way because more respondents than expected criticized the visualization of particles and particle systems. At first, this positive feeling crept into the analysis process. When I started to assign the statements to categories, I associated too many with the *disciplinary evaluation* level. When repeating the coding process, I recognized that not every statement mentioning the representation of particles and particle systems is evaluative and that I overestimated some of them. Therefore, I argue that the more I engaged with the date, the more I could shift my mindset from evaluation towards analysis.

Then, I want to address reliability in terms of engagement with the data and grounding of interpretations. These were the main parts of data analysis in my research. I used the earlier described "content analysis" approach. At first, I developed content categories by studying the representations. Then I considered the data I gained to define the content categories in greater detail. Since I engaged intensively with the data, read and reread it and compared subsets with the whole set, the definition of these categories was revised multiple times as well. Besides, the *Levels of discernment* were taken into consideration to divide the content categories into groups of analysis categories. Therefore, I argue that interpretations of data are grounded properly.

Finally, I tried to enhance reliability by asking the right type of questions. When developing my questionnaire, I followed theoretical guidelines and studied the questionnaires developed by Eriksson (see [6] and [8]). Thus, I "asked specifically for 'what' the participants discerned and not 'why' they did so" ([6], p. 157),

6. B. 2. Validity

In this chapter I want to address quality control of my research in terms of *internal* and *external validity* regarding the above described aspects (see chapter 6. A. 2.).

6. B. 2. 1. Internal validity

The focus of the internal validity is on data collection and analysis with respect to a specific research question. A research is internally valid, if "valid information about the respondents and what they are thinking, feeling or whatever" ([30], p. 247) is obtained. To ensure internal validity several aspects were taken into consideration which are as follows:

At first, I want to address the data collection method. For this study data was collected using an online survey. The questionnaire was developed carefully to make it as understandable as possible for the participants by considering recommendations and theory (see chapter 4. B. 2.). Following Schmiemann and Lücken (2014) whose focus is on the efficiency of the data collection method I will discuss internal validity in terms of data collection method separately for both parts of my questionnarie.

The video is about zooming into a human hair. It starts with the representation of a daily life object which the participants are familiar with and not with the representation of a physics model. Thus, I argue that most of the participants know at least what the video is about in general. This claim is confirmed by the data. Furthermore, the questions about the video are straightforward and focus on individual, visual perception. Since the intention of my questionnaire is to find out what learners discern from visualizations in particle physics, I am convinced that the part about the video is valid in terms of the definition by Schmiemann and Lücken (2014).

When developing the questions about the representation of a measurement one problem arose. Without additional information or prior knowledge, it is barely possible to recognize the screenshot as representation of a measurement. In addition, it only shows visualizations of abstract concepts, namely the energy deposit per pixel in false colors, but not the particles themselves. Thus, I decided on including a short introduction to pixel detectors at the beginning of this part of the survey. The arising problem may be that the test partly measures reading comprehension of the participants as well. Since the introduction gives essential information for understanding the image, I claim that the probability of high-level discernment is higher for participants who understood the text better. To moderate this effect. I posed a single-choice question concerning the introduction which is "In how many pixels is the detector chip divided?". My motivation was to enhance the probability that the participants know that at least and re-recognize the pixel numbers in the image. Indeed, some of the respondents even guessed my intention. When asked what the image represents, some answered e.g. "Probably hits in the silicon detector from the last slide", "The above-mentioned silicon chip" and "As the revious [sic!] question was about particle detectors then I am biased to answer that it represents energy deposited, most probably by a particle". Although I asked about the number of pixels, the importance of reading comprehension may still be an issue for the validity of this part of the questionnaire. In addition, one must bear in mind that the text was in English for the international groups of participants and reading comprehension may be restricted by language skills as well. However, I took a close look at the data and neither for the high school nor for the university students I could find any traces of this being an issue, but there were a few exceptions among the teachers. I found that some of them have bad English skills because they could not express themselves properly in English. Thus, I argue that their reading comprehension is limited. The difference in reading comprehension causes a spread in prior knowledge of the participants. Since the data I want to gain is various descriptions of discernment, I argue that the overall negative effect on my results is close to zero. Anyway, when the focus is on the efficiency of the test, validity may be limited but I could not think of any other option than a written introduction. Similar problems would have arisen when giving an oral introduction since it is likely that not all participants pay attention.

All in all, the answers given by the participants indicate that they understood the questions and took the survey conscientiously, apart from some exceptions that are described below. In addition, as in the study by Eriksson (2014) "the length of the survey and the time it took on average to complete could have been an issue" ([6], p. 155). Again, apart from some exceptions, I could not find any indices of these issues. Some university students even gave positive feedback as further comments, e.g. "I liked the survey" and "It was nice and interesting".

Then, I want to address the administration approach of my study. In general, it may be a threat to internal validity of the study that participants' answers given in a survey may differ from those given in a natural environment and a conversational context [6]. My survey was handed out using two different approaches (see chapter 4. B. 3.).

The first approach of data collection was on a group base. Thus, the data collection took place in S'Cool LAB or the main auditorium and teachers were present who gave instructions. Accordingly, the context was similar to regular school lessons. Most of the participants of my study were high school students and teachers who are particularly familiar with that kind of situation. Therefore, threats resulting from unfamiliarity were limited [6]. One must notice though that the teachers are rather indirectly than directly used to such a situation. However, comparing the answers given by the high school students and the teachers there are neither obvious differences concerning the length nor the effort that was put in. In general, both group of participants answered the questions in great detail.

In contrary to that there were differences in comparison with the university students' answers. For the university students the self-administered approach was chosen. Therefore, they were less familiar with the setting for filling in the survey. In addition, when engaging with the data it is obvious that some university students did not take the survey seriously, and hence put less effort in answering the questions. I got the impression that some of them did not see the relevance of the survey and were bored. E.g., one participant gave the statement "I wonder how long this damn survey is going to go on for?". This attitude may be due to the absence of an instructor who could have explained the relevance in detail and contributed to the personal commitment of the participants. According to Robson and McCartan (2016) "[t]he problem of securing a high degree of involvement by respondents to a survey is more intractable […] when it is carried out by post or the Internet" (p. 247). To compensate the negative effect of the self-administered approach, I removed ten university students from my data who answered just one or two questions in one of the survey's parts.

Furthermore, I want to address the internal validity of my study as discussed by Stiles (1993). He introduced methods to enhance validity.

Triangulation is one of them and encompasses several aspects. According to *data triangulation*, I used a self- and a group-administered approach of data collection in my study. Besides, *methodological triangulation* was done because I combined qualitative and quantitative methodologies to answer my research questions. According to *theory triangulation* I engaged with several theories concerning learners, representations and the relation between both before I started my research. Besides, *investigator triangulation* played an important part in my research. To validate the content categories, the analysis categories and the coding I asked an independent researcher to be my interrater and to engage with subsets of the data. Afterwards, several aspects were discussed until consensus was reached (see chapter 6. B. 3.).

Besides, similar to Eriksson (2014) *coherence* "was addressed by continuously checking the interpretations made with the original data" ([6], p. 158). Thus, the evolving categories "were found not to be contradictory but to present unified interpretations of the expressed meanings in the data" ([6], p. 158).

Finally, in terms of *reflexive validity* I described in detail which prior expectations I had before the analysis as well as how they were changed by the data (see chapter 6. B. 1.).

6. B. 2. 2. External validity

Finally, I want to address the *external validity* or *generalizability* of my research.

Faultiness of the sampling is one type of external validity problem [30]. Since my study involved a small-scale survey, a non-probability sample was employed (see [30], p. 279). This approach is "acceptable when there is no intention or need to make a statistical generalization to any population beyond the sample surveyed" ([30], p. 279). I aimed at interviewing specific groups, i.e. high school and university students and teachers. Thus, my sampling may also be referred to as "*purposive*" ([30], p. 279). The data I gained from all groups of participants was useful, apart from the above discussed and compensated restrictions. Furthermore, I could not find remarkable differences in the data within a type of participants in terms of educational background, e.g. all high school students answered in a versatile but overall similar way. In addition, the spread concerning the educational background of my participants turned out to be good, and thus the sampling of my study was appropriate.

"Another type of external validity problem occurs if we seek to generalize from what people say in a survey to what they actually do" ([30], p. 247). Since, as mentioned above, within a type of participants the answers are versatile but overall similar, I cannot find any traces of this being an issue.

6. B. 3. Objectivity versus bias

I have already discussed issues related to *investigator's bias* in detail, when talking about *Disclosure of orientation*, *Description of internal processes* and *Reflexive validity*. Therefore, I argue that I have intensively engaged with being biased as an investigator and put a lot of effort in avoiding negative effects on my results. This chapter focuses on the interrater reliability, i.e. how the interrater affected the analysis and contributed to the objectivity of my results. Furthermore, I want to address *participants bias*.

6. B. 3. 1. Interrater reliability

In general, interrater reliability means that two or more independent coders agree to a certain extent when assigning statements to categories [19]. For my study I did not aim to achieve high interrater reliability, but I rather aimed to have a second opinion. Thus, I asked a colleague from the Physics Education Research group at CERN to assign 10% of the data, i.e. the statements given by 18 participants, to the analysis categories as well. The data table including the interrater's and my coding is attached (see chapter 10. B.).

Concerning the statements about the video, the relative compliance is 0,67 which is an acceptable value. When considering the questions individually, two show perspicuous differences between the interrater and me (see chapter 10. B. 1.) which lowered the overall relative compliance.

Concerning the user interface, the relative compliance is 0,57 which is an usatisfying value. However, when considering the questions individually, it is again perspicuousous that the overall relative compliance is lowered by the low compliance values relating to three questions (see chapter 10. B. 2.).

The differences in coding between the interrater and me were caused by various aspects.

The fist one is the imprecision of the corresponding category definitions. Thus, I revised them. E.g., concerning the user interface I clearified that it is "Disciplinary Explanation" to relate the bright dots to the energy deposit of particles.

Moreover, the interrater coded some statements as "None" which must not be assigned to this category or did not code some statements as "Double coding", although they were given more than once by the same participant. Besides, as I did when starting to code the data, the interrater chose high-level discernment (e.g., "Disciplinary Evaluation") too often. Thus, I highlighted in the definition of categories that the lower *Levels of Discernment* are necessary for high-level ones.

Furthermore, some statements mention various aspects and thus, can not be coded unambigiously.

Finally, some differences are because I was mistaken when choosing a category which is unavoidable regardlessly how often I code the data.

6. B. 3. 2. Participants bias

As mentioned earlier the participants of my study differ in terms of their educational background which is essential to answer my research questions. In addition, to these desired educational differences there are ones related to their visit at CERN as described in chapter 5. The international participants of my study have more prior knowledge about particle physics than regular high school and university students and teachers. This results in limitations for the generalizability of my results. I will address this issue separately for all three types of participants in the following.

At first, the teachers are discussed. When comparing the statements given by the internationals and the Germans, there are some differences. The international long-term visitors at CERN attended lectures and workshops about challenges when and recommendations for teaching particle physics. Thus, they are used to analyze materials in terms of their usability for teaching purposes. Their main guide during their stay at CERN was my colleague Jeff Wiener. A few participants mentioned him in their statements and thought about his opinion on the visualizations, e.g.:

- "As Jeff mentioned on Friday, students might think that the orbitals are #inside# the atoms, that the atoms are containers made of something different."
- "I wonder what Jeff thinks of the colour scheme of the atoms and their representation as spheres or with electron orbitals."
- "Jeff won't like this - it looks like the spheres are something"

Considering these quotes, the bias, i.e. the additional prior knowledge due to the lectures, is obvious. However, I could not find any traces of this being an issue in the data because the results of the German and the international teachers are similar. In my opinion the positive effect on the prior knowledge of the internationals and the negative effect of the lacking language skills balance out overall. Thus, I argue that the participant's bias is not an issue concerning the teachers.

Then, I want to focus on the university students. Similar to the international teachers the university students have to attend lectures about particle physics. Thus, it is likely that their prior knowledge is higher than regular students' one, but it is not possible to generalize this. Firstly, the internationals are not obliged to attend these lectures and secondly, not all of them are physics students. Besides physicists there are engineers and computer scientists among the summer students, undergrads and graduates. Thus, I argue that the positive effect of the additional lectures and the negative effect of not being physicists even out overall. This claim is confirmed by the data since I could not find any traces of participant's bias being an issue concerning the international students.

Finally, the high school students are addressed. There are no differences when comparing the Germans and the Austrians. Both groups of participants answer the questions similarly in terms of length and apparent effort and the average age is the same. However, there are differences in comparison to the international high school students. They are not only older on average but also biased towards physics. The selection process for the *Summer Camp* is though and thus, only extraordinarily interested and motivated students apply. Regular high school students visit CERN with their teachers as a school trip, whereas the *Summer Camp* participants apply of their own accord and with a lot of effort. In addition to this bias, the internationals must attend lectures and workshops and intensively engage with particle physics. Thus, I claim that they can even be counted among the university students in terms of prior knowledge. However, I claim that as long as this bias is considered when interpreting the data, it has no negative influence on the results of my study. Since the focus is on what persons with various prior knowledge discern from visualizations, it does not matter whether the university students or a particular group of high school students knows more beforehand.

7. Analysis

An interpretative-hermeneutic approach was used to analyze the answers of the participants as described in the chapter 4. C. To answer the research questions the statements of the participants were read several times to get a good overview. Then content categories for both visualizations were constructed, which were further divided into groups of analysis categories. Afterwards the statements of the participants were assigned to the analysis categories.

7. A. Video "*Voyage into the world of atoms*"

When analyzing the video there were two approaches for the assignment process: The initial was categorization per individual person, the final was categorization per single statement.

7. A. 1. Initial approach

The initial approach was to categorize the answers per individual participant. All statements of one participant were read to get a common impression which allowed to choose one *Level of Discernment* per person as described in chapter 1. A. 2. The choice was made according to the highest level the person showed throughout the survey. E.g., if the respondent evaluated the affordances of the video in one statement, the level *Disciplinary Evaluation* was chosen. For categorization per person only the participants who answered all the question were taken into consideration.

Firstly, the participants' levels of all groups who saw the **unlabeled videoclips** were compared with each other, i.e. German high school students and teachers. Both groups were short-term visitors at CERN.

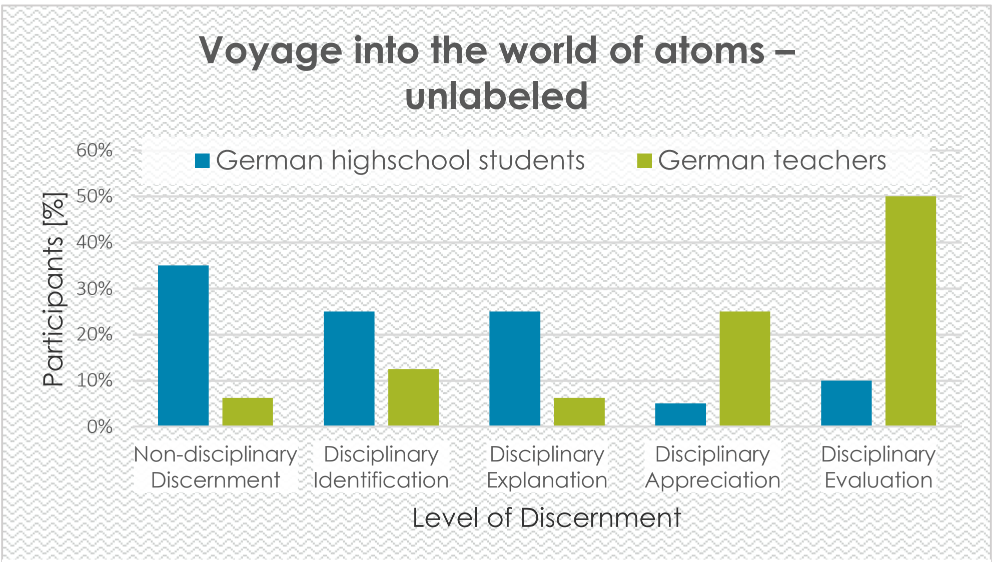

CHART 1: **Categorization per person:** Participants [%] per Level of Discernment – Unlabeled videoclips

CHART 1 shows the percentage of participants per *Level of Discernment* for the German high school students and teachers who saw the unlabeled clips, whereby the *Levels of Discernment* are plotted on the x-axis and the relative number of participants on the y-axis. The **teachers** are represented by the **green** bars and the **students** by the **blue** ones. Due to educational background and disciplinary knowledge teachers are more likely to discern disciplinary affordances of a representation. Moreover, they are mainly found on the level of *Disciplinary Evaluation*, whereas students tend to focus on non-disciplinary affordances.

Secondly, the participants' levels of groups who saw the **labeled videoclips** were compared with each other, namely of the international high school students, university students and teachers.[6] For categorizing the data concerning the labeled clips the definition of each category was slightly changed, since more disciplinary information is explicitly given than in the unlabeled clips. Therefore, it is not possible to compare the values for both versions of the video with each other when using this approach.
CHART 2 shows the percentage of participants per *Level of Discernment* for the groups who saw the labeled clips. Again, the *Levels of Discernment* are plotted on the X-axis and the relative number of participants on the Y-axis.

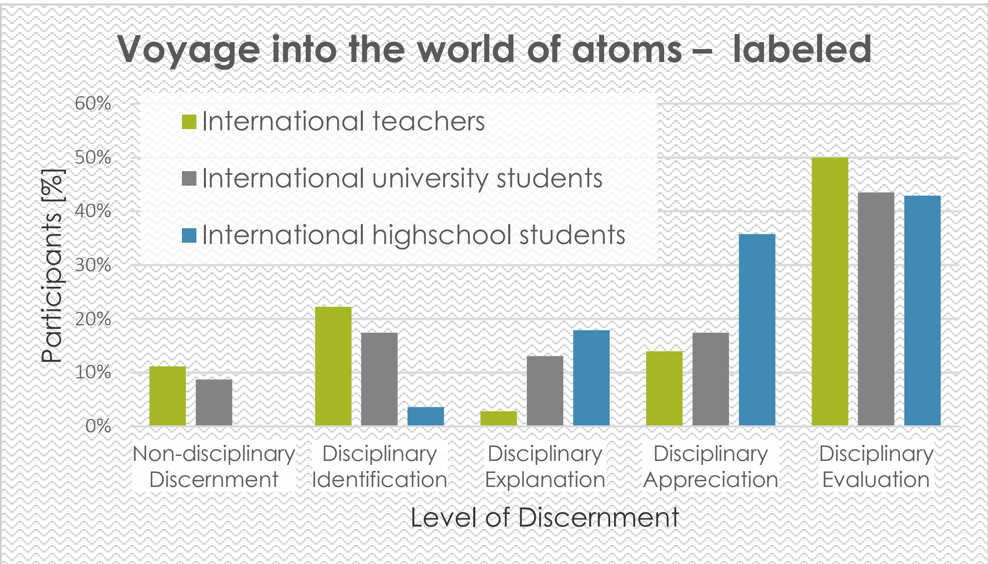

CHART 2: **Categorization per person:** Participants [%] per Level of Discernment – Unlabeled videoclips

The international **teachers** are represented by the **green** bars and are the most likely to be on *Disciplinary Evaluation* level compared to the other groups. However, more than 20% of the international teachers are found on *Disciplinary Identification* level. This may be a consequence of the poor English skills of several international teachers which became obvious when reading all the statements of individual participants as mentioned in chapter 6. B. 2. 1.

[6] The answers of the Austrian high school students were not analyzed with this initial approach, since they participated in my survey at a later time.

As shown in CHART 2 the international **university students** represented by the **grey** bars are distributed in a similar way, i.e. one peak on *Disciplinary Evaluation* level and another one on *Disciplinary Identification* level. It is clear that the former is due to the high disciplinary knowledge of most of the summer students. Concerning the latter one must consider that the summer students have various educational backgrounds, e.g. physics, computer science and engineering. Thus, their disciplinary knowledge differs and as a consequence more than 15% of them are assigned to the *Disciplinary Identification* Level. This assumption becomes even more likely when distinguishing between summer students with physics background and those without (see TABLE 5). As listed in TABLE 5 30% of the summer students without physics background are found on *Disciplinary Identification Level.*

TABLE 5: Percentage of physics and other **summer students** per *Level of Discernment*

	Physics Summer Students	Other Summer Students
Disciplinary Evaluation	38%	20%
Disciplinary Appreciation	23%	20%
Disciplinary Explanation	23%	10%
Disciplinary Identification	8%	30%
Non-Disciplinary Discernment	8%	20%

The **international high school students** are represented by the **green** bars in CHART 2. Their distribution is linear, i.e. the percentage of participants per level increases with increasing *Level of Discernment.*

In general, the outcomes of categorization per person underpin that the *Anatomy of Disciplinary Discernment* is a suitable and valid model for analyzing representations in particle physics. Therefore, the data was further analyzed with reference to the ADD, although the categorization approach was changed as described in the following.

7. A. 2. Construction of content categories

Similar to the study by Eriksson *et al.* (2014) the aim of my study was to analyze the participants' discernment with respect to two aspects: Firstly, the focus was on what was noticed, and secondly, on how it was interpreted.

The initial analysis approach rather focused on the latter aspect. Thus, the approach for categorization was changed after a video call with Urban Eriksson who explained that Eriksson *et al.* (2014) assigned every single statement to a category when analyzing data for their study. Furthermore, we agreed that categorization per statement is not only better but rather crucial because some aspects of the data may be counted as less important than others or be even overlooked when categorizing per participant.

The aim of the final approach for data analysis in my study was to consider both aspects, noticing and interpretation, equally and hence, all statements were assigned to categories.

At first, the focus was on what was noticed to answer the first research question (see chapter 2.). Seven content categories of statements showing different noticing and interpretation with respect to particle physics emerged, when engaging repeatedly with the data. These are

Zoom identification, *Emergence of particle model awareness*, *Relative size*, *Growth of particle model awareness*, *Identification of representation as model*, *Critique of model-like representation* and *Advanced particle model awareness*. In TABLE 6 the content categories are characterized, and details of their construction are provided.

TABLE 6: Definition of **content categories** (cf. [7], p. 425)

Content category	**Discernment Detail**		**Central manifestation characteristic**	**Contemplation**
	What is noticed?	What meaning is assigned?		Questions that the participants ask
Zoom identification	Zoom, enlargement	Zooming into a human hair to discover the structure of matter: e.g. atoms, protons, quarks	**Detecting zoom**	And if I go outside the hair, in space? I wonder if there is an end, does it stop at a moment or can we zoom in forever?
Emergence of particle model awareness	The internal structure of a hair: fibril structures, particle systems (e.g., protons), particles (e.g., quarks)	Matter has internal structures and properties Particle systems (e.g., protons) are made of particles (e.g., quarks)	**Seeing smaller parts within bigger parts**	I wonder how far you would have to zoom in to see the nucleus/individual quarks. What can be inside the quark?
Relative size	Particle systems and particles (e.g. atoms, nucleus, quarks) differ in size AND/OR magnitude scale is noticed	Different objects are compared in terms of their relative size	**Comparing objects in terms of size**	I wonder how small the quarks are. How small is the nucleus compared to orbitals? What means “pm”?
Growth of particle model awareness	The empty space between the components of matter (e.g. particle systems, particles)	Between the particles is empty space	**Contemplation of the empty space**	I wonder what this space is filled with. How much empty space is there really between each "component"? I wonder how much of matter is just vacuum.
Identification of representation as model	Particle systems and particles are represented as balls	To represent particles models must be used	**Contemplation of the ‘spherical’ particles**	How can we know there are balls? Are any of these particles actually spherical?

cont.

Critique of model-like representation	The spherical surface representing an atom or a nucleon remains, even though already being at a smaller scale	The representation of atoms or nucleons as balls containing other balls is misleading	**Reflection on representation of atoms or nucleons as spheres**	I wonder if the students think that the proton is a container for quarks. Do atoms have an outside spherical surface like this?
Advanced particle model awareness	Particle systems or particles stick together without fundamental interactions	Fundamental interactions are not visualized	**Contemplation of fundamental interactions**	Where are the gluons? Is it possible to visualize the force that binds the particles?

These categories were constructed for categorizing the statements of the participants according to disciplinary content. All of them are rooted in the discipline, as they include discernment descriptions grounded in particle physics concepts, except for the first category *Zoom identification*. Therefore, there are six categories of discernment related to the discipline of particle physics. The level of discernment increases, i.e. participants in the category of *Advanced particle model awareness* seem to have more disciplinary knowledge than the ones in the category of *Critique of model-like representation* and so on.

7. A. 3. Definition of analysis categories

After construction of the content categories the analysis focused on correspondence to the *Levels of Discernment* to answer the second research question (see chapter 2.). Thus, analysis categories were defined as shown in TABLE 7. In addition to the *Levels of Discernment* three further categories were defined, namely *None, Missing value* and *Double coding*. This was done to fulfil the rules for coding introduced in chapter 4. C. 2.

TABLE 7: Definition of **analysis categories** according to Eriksson *et al.* (2014) (cf. [7], p. 172ff)

Letter	Analysis category	Description	Corresponding content categories
A	**Non-disciplinary Discernment**	Participants • do not know what they are seeing [7]. • notice different structures and begin to reflect on what these may be [7]. • focus on the experience offered by the zoom. ⇨ "What is …?"	**Zoom identification**

cont.

B	**Disciplinary Identification**	Participants • focus on certain parts of the video and distinguish what these afford from a disciplinary point of view [7]. • identify representations of particle-systems and particles at different scales. ⇨ "This is …!"	**Emergence of particle model awareness**
C	**Disciplinary Explanation**	Participants • explain and assign disciplinary meaning to the discerned objects [7]. • start to use their disciplinary knowledge to interpret what they see in terms of particle physics [7]. • compare particle-systems and particles in terms of their relative size and use the concept of empty space. ⇨ Shift from the *what*- towards a *why*-perspective	**Relative size, Growth of particle model awareness**
D	**Disciplinary Apprecia-tion**	Participants • analyze and acknowledge "the value of the disciplinary affordances of the representation" ([7], p. 174). • "combine disciplinary knowledge […] to build a holistic understanding of what the representations are intended to afford" ([7], p. 174). • realize that models are used to visualize particle-systems and particles. ⇨ Previous disciplinary explanation is necessary for appreciation	**Identification of representation as model**
E	**Disciplinary Evaluation**	Participants • analyze and criticize the model-like representation used for visualizing particle-systems and particles. • evaluate the representation in terms of its usability for teaching practice [7]. ⇨ Shift from appreciation towards positive as well as negative critique	**Critique of model-like representation, Advanced particle model awareness**
N	**None**	Answers like "none" or "nothing"	
M	**Missing value**	Empty answers or answers that shall be counted as empty (e.g., "-")	
X	**Double coding**	Answers given more than once by a respondent (except for "Missing value" and "None")	

Single statements given by the respondents were assigned to the analysis categories using a letter for identification (see chapter 4. C. 3.).

7. A. 4. Categorization of statements

All statements were assigned to the analysis categories defined in chapter 7. A. 3. Some exemplary statements for each analysis category are listed below. They comprise of the corresponding content categories and other aspects, which are characteristic for each *Level of Discernment* as described in TABLE 7. The statements are direct quotes from the data, whereby German ones were translated into English. Since it does not matter for defining the categories, whether the statements have been given by students or teachers, this information is not provided.

7. A. 4. 1. Non-disciplinary Discernment

- **Zoom identification:** "I enjoy the zoom aspect of things like these", "It's getting smaller and smaller", "Zooming in", "Zoomed in well"
- **Fascination:** "It's cool to see it visualized like it is done in the video.", "I really have to appreciate the visuals, they're beautiful, but I think they need to be a little brighter", "The fascinating world of the smallest particles"
- **Lack of disciplinary knowledge:** "What exactly is that?", "The atoms have a solid nucleus", "I realized that the quarks spin within the proton"

7. A. 4. 2. Disciplinary Identification

- **Emergence of particle model awareness:** "I did know about keratin in our hair but didn't know it has oxygen and nitrogen in it", "Atomic model", "Components of protons", "This is the nucleus", "Structure of the nucleus", "Quarks"

7. A. 4. 3. Disciplinary Explanation

- **Relative size:** "The different layers of a single hair and their relative sizes", "How tiny the nucleus is, in comparison to the whole atom", "Wow, the nucleus is MUCH smaller than the span of the electron orbitals!", "How small protons and neutrons are"
- **Growth of particle model awareness:** "The size of the quarks relative to the proton shows that the nucleus is mostly empty space", "I notice how much empty space there is in the microscope world"
- **Further disciplinary knowledge:** "I wonder how protons and neutrons stay together inside the nucleus (they say It's the strong force)", "The mass of the constituent quarks inside the proton is not equal to the mass of the proton"

7. A. 4. 4. Disciplinary Appreciation

- **Identification of representation as model:** "It's just a model and I lost track at which point we switched from 'This is how a hair looked like in close up' to 'That's a model of an atom'", "Anything at a very small scale is just a model because those things are impossible to see visually", "I know that the representation of particles is just a model and we don't know what it really looks like but it seems like this is a good representation"

- **Appreciation as learning aid:** "The scale is very helpful to visualize the dimensions of the particles and the whole video really helps you understand what each component is made of to the smallest elementary particles", "The video gives a good sense of starting from the macroscopic world and zooming into the subatomic", "It is good, that the size of nucleus is so obviously smaller than size of atom in this video", "It gives an ok visualization of the emptiness that is within an atom"

7. A. 4. 5. Disciplinary Evaluation

- **Critique of model-like representation:** "I'm irritated by the structure of the surface of the proton. It is just a model and there is no need for the proton to have this 'wobbly' surface.", "It should be emphasized that this is just a model"
- **Advanced particle model awareness:** "Gluons are missing", "What about gluons?", "No gluons! : - ("
- **Further critique:** "This did a good job of emphasizing how small the nucleus is compared to the atom, although they seemed to have dropped the actual size labels next to the name labels which is disappointing", "Making the nucleus 'glint' as the camera approached was a bit silly", "It might have been worth showing that the nucleus is not a static lump of protons and neutrons in fixed positions"

7. A. 5. Results

At first, I compared the relative amount of statements per group of participants in the categories "Missing value" and "None" with the relative amount of statements assigned to one of the *Levels of Discernment* (see TABLE 8).[7]

TABLE 8: The relative amount of **statements** [%] in the categories **„Missing value"** and **„None"** (1st and 2nd row) and the sum of both (3rd row), as well as the relative amount of **statements** [%] assigned to one of the ***Levels of Discernment*** (4th row) and the category **"Double coding"** (5th row) are listed.

	High school students			University students	Teachers	
	German	International	Austrian		German	International
None	16%	15%	18%	17%	21%	7%
Missing value	13%	11%	12%	20%	5%	15%
None + Missing value	**29%**	**26%**	**30%**	**37%**	**26%**	**22%**
Levels of Discernment	**64%**	**66%**	**67%**	**57%**	**63%**	**72%**
Double Coding	7%	8%	3%	6%	11%	6%

[7] In this regard it is important to mention that the answer "None" was mainly given, when asked, what - if any - "I wonder"-questions the clip raised for the participants.

In average 28,5% of all statements given by a group of participants were assigned to the category "None" or "Missing value" (3rd row). The values for each group are overall similar and close to average, with two exceptions. Firstly, the international teachers gave the least amount of such statements (22%), which indicates that they took the survey especially consciously. In contrary to that, a total of 38% of statements given by the university students were assigned to the categories "None" or "Missing value". This comparatively high amount may be due to the self-administering approach as discussed in detail in chapter 6. B. 2. 1.

In average 65% of the statements were assigned to one of the *Levels of Discernment* (4th row). When comparing the different groups of participants, the above-made assertion is underpinned, since the international teachers have the largest relative amount of statements assigned to one of the *Levels of Discernment* (72%), whereas the international university students have the least (57%).

Then, I analyzed how the statements are distributed among the individual *Levels of Discernment.* When doing so, only the statements assigned to the *Levels of Discernment* were taken into consideration. The relative number of statements assigned to the category "Double coding" (5th row) was not included in the analysis, because each statement must only be counted once, although the statements would have been rated among the *Levels of Discernment*.

The distribution of statements within the *Levels of Discernment* is shown in TABLE 9. The columns are sorted by the different groups of participants, whereby they are clustered according to educational background. The rows are sorted by the *Anatomy of Disciplinary Discernment*, whereby the *Levels of Discernment* rise from bottom to top.

In TABLE 9 the relative number of participants in each category differs for the different groups. The differences are even remarkable, when only comparing within a certain cluster of participants. However, there are two main causes for these differences. Firstly, discernment depends on the representation and its affordances and secondly, on the participants and their prior knowledge.

Concerning the representation and its affordances, when interpreting the data, one must consider that the groups of participants saw different versions of the video, i.e. with and without labels. By comparing groups, which have the same educational background but have not seen the same version, it is possible to draw conclusion, whether labels are learning aids or obstacles.

Concerning the participants and their prior knowledge, the participants have various educational backgrounds as well as different programme at CERN. By comparing groups, which have seen the same version of the video, the effect of prior knowledge can be analyzed.

These aspects are discussed separately for the three clusters of participants, and afterwards parallels and differences between the results are pointed out.

TABLE 9: Distribution of **statements** [%] **within the *Levels of Discernment***

	High school students			University students	Teachers	
	German	International	Austrian		German	International
Disciplinary Evaluation	2%	6%	0%	9%	14%	15%
Disciplinary Appreciation	5%	11%	2%	6%	7%	8%
Disciplinary Explanation	14%	23%	10%	17%	8%	13%
Disciplinary Identification	23%	22%	49%	28%	37%	28%
Non-disciplinary Discernment	56%	38%	39%	40%	34%	36%

At first, the focus is on the high school students, and in especial on the German and the Austrian group. Both were short-term visitors at CERN and thus, their educational background was similar. However, there is a major difference between these groups. While the former saw the not labeled version of the video, the latter saw the labeled version.

As listed in TABLE 9 56% of statements given by the German high school students were assigned to the category "Non-disciplinary Discernment", whereas it is only 39% of answers given by the Austrians. This means that the group who had additional, descriptive labels was way less likely to discern non-disciplinary affordances.

Concerning the German high school students, the higher the *Level of Discernment* is, the lower is the relative amount of statements as listed in TABLE 9. The outcome is overall similar concerning the Austrians, with another considerable difference. The highest relative amount of statements, namely 49%, was assigned to the category "Disciplinary Identification". Thus, I argue that the descriptive labels enabled this group to at least identify and name what they have seen.

One may raise the objection that less statements were assigned to "Disciplinary Identification" because slightly more statements were assigned to the highest three *Levels of Discernment*. In total, only 44% of statements given by the German high school students were assigned to one of the *Levels of Disciplinary Discernment,* i.e. not to the category "Non-disciplinary Discernment", whereas it is 61% of the Austrians' statements. Since the slightly higher number of statements in the highest three *Levels of Discernment* does not even out the low number on the level of "Disciplinary Identification", when all *Levels of Disciplinary Discernment are considered*, the objection is disproven.

Furthermore, I want to emphasize that the German high school students were at CERN, in contrary to the Austrians. Thus, it is likely that their prior knowledge is higher than the Austrians' who have not heard anything about particle physics before participating in my survey. Nevertheless, the latter showed more disciplinary discernment than the former.

Then, I want to compare the results of the Austrian high school students with the third group in this cluster. The international high school students were long-term visitors at CERN who participated in the S'Cool LAB *Summer Camp.* As described in detail in chapter 6. B. 3., it is likely that their prior knowledge is higher than of average high school students.

Concerning the representation and its affordances, the Austrian and the international high school students saw the labeled videoclips. The relative amount of "Non-disciplinary Discernment" statements is similar for both groups, namely 39% of the statement given by the Austrians and 38% of the statements given by the internationals as listed in TABLE 9. Accordingly, 62% of statements given by the internationals and 61% of those given by the Austrians were assigned to one of the *Levels of Disciplinary Discernment,* i.e. not to the "Disciplinary Identification" category. This parallel supports the above-made assertion that descriptive labels enable the learners to focus on the disciplinary affordances of a representation and to identify at least what they see.

Nevertheless, there is a crucial difference between the results of both groups which concerns the amount of statements in the highest three *Levels of Discernment.* Whereas only 12% of statements given by the Austrian high school students were assigned to these categories, it is 40% of the ones given by the internationals. The high amount of high-level disciplinary statements underpins the claim that their prior knowledge is better than average. Moreover, they achieved the highest values of "Disciplinary Explanation" (23%) and "Disciplinary Appreciation" (11%) in comparison with all groups of participants. This supports the finding by Eriksson *et al.* (2014) that the higher the prior knowledge of learners is, the more likely they are to discern disciplinary aspects of a representation.

Furthermore, the focus is on the international university students who were long-term visitors at CERN and saw the labeled version of the videoclips. As explained in chapter 7. A. 1., the educational background varies within this group because there are physicists, engineers and computer scientist, graduates and undergrads subsumed under the cover term "Summer Student". However, since they are long-term visitors at CERN, they must attend lectures, and thus their prior knowledge about particle physics is likely to be higher than average. Their statements are distributed among the *Levels of Discernment* in such a way that the higher the level is, the lower is the relative amount of statements as listed in TABLE 9. However, there is a considerable exception, namely that more statements were assigned to the category "Disciplinary Evaluation" than to "Disciplinary Appreciation".

Finally, the focus is on the teachers. The international teachers were long-term visitors at CERN who had to attend lectures about particle physics and thus, they are likely to have higher prior knowledge about particle physics than average teachers do. They saw the labeled version of the videoclips. In contrary to that the German teachers were short-term visitors and saw the unlabeled videoclips. When comparing the two teacher groups, one must consider these two major differences.

Both groups attained similar amounts of statements in the category "Non-disciplinary Discernment". As listed in TABLE 9 it is 36% for the international teachers and 36% for the German. This means that the relative number of statements assigned to one of the *Levels of Disciplinary Discernment*, i.e. not to the category "Non-disciplinary Discernment", are similar as well. In addition, as regards the levels "Disciplinary Appreciation" and "Disciplinary Evaluation", there is no considerable difference between both groups either. To the former 8% of statements given by the internationals and 7% of those given by the Germans were assigned, and to the latter 15% or 14% of statements.

However, there are considerable differences apparent, when comparing the amount of statements in the categories "Disciplinary Identification" and "Disciplinary Explanation". Whereas on the lower level the relative amount of statements given by the Germans is higher (37% to 28%), it is the other way around on the higher level (8% to 13%). In my opinion there are two crucial factors which led to these results. Firstly, due to the descriptive labels the international group did not have to find out *what* they were seeing. Thus, they could focus on *why* the discerned objects were represented in a certain way. Secondly, their prior knowledge is likely to be higher which may cause a shift from mere identification to explanation.

Then, the results of the three clusters of participants are compared with each other. For further analysis I visualized the data listed in TABLE 9. The relative amount of statements per *Level of Discernment* for all groups is shown in CHART 3. The *Levels of Discernment* are plotted on the x-axis, whereby the *Level of Discernment* rises from left to right. The relative number of participants is plotted on the y-axis. The colors of the bars represent different groups of participants who saw different versions of the video as explained in the legend.

At first, the focus is on the comparison of high school and university students. In CHART 3 the **German high school students** are represented by the **dark blue** bars, the **international** by the **light blue** and the **Austrian** by the **green** bars, whereas the **international university students** are represented by the **orange** bars.

The amount of high-level discernment of the university students is higher compared to the German and Austrian high school students. This is another indication for the correlation between prior knowledge and disciplinary discernment.

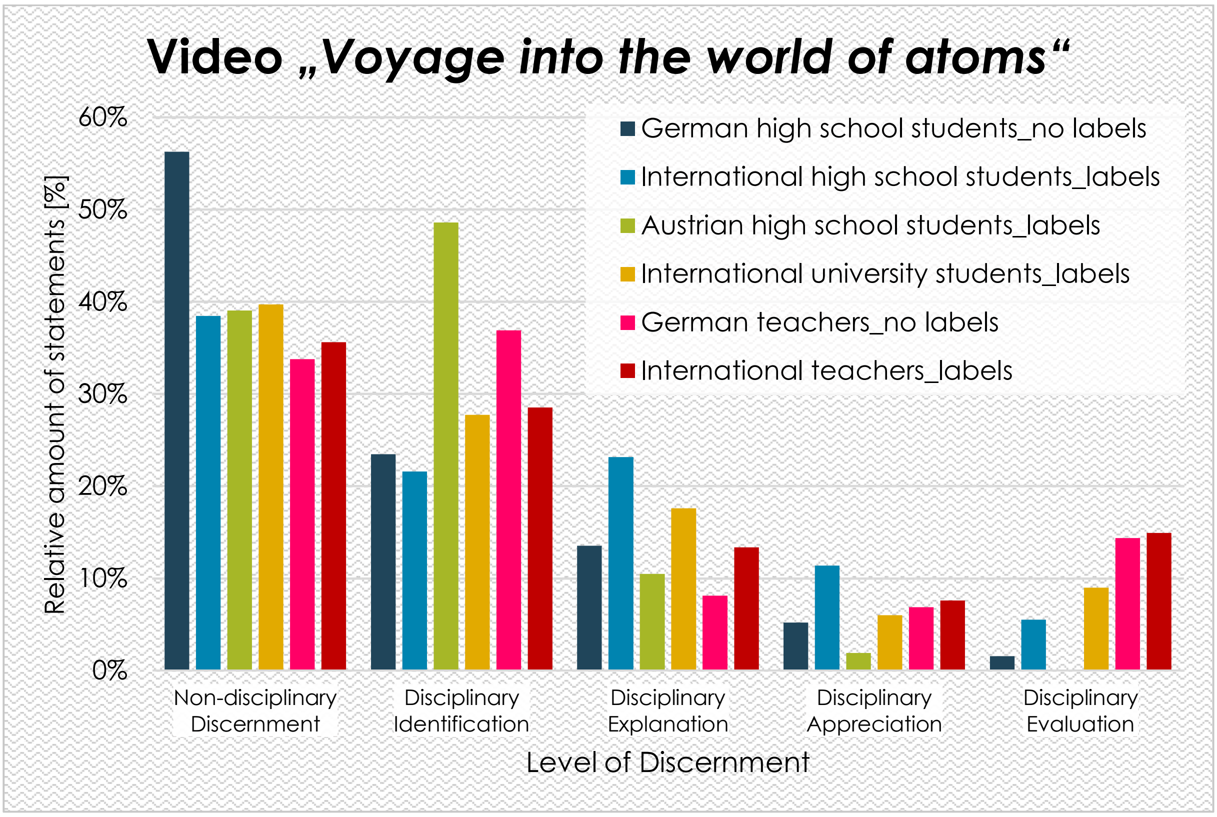

CHART 3: Relative amount of statements per *Level of Discernment*

When comparing the international high school and university students, there is an interesting finding. More statements assigned to the highest three *Levels of Discernment* were given by the former (40%) than by the latter (32%). In my opinion this is due to the differing administering approach as described in chapter 6. B. 2. 1. I was present, when the high school students filled in my survey and they were extraordinarily interested and motivated, and thus they put a lot of effort in answering the questions. In contrary, the university students received the survey per e-mail and could fill it out whenever and wherever they wanted without supervision. When reading and comparing the statements of all participants, it is apparent that the university students' ones tend to be shorter and less precise than the others.

Then, the results are further compared with the teachers. The **German teachers** represented by the **pink** bars saw the unlabeled videoclips, whereas the **internationals** represented by the **red** bars saw the version with labels. There are two considerable differences in comparison to the other groups.

Firstly, the teachers gave the least amount of non-disciplinary statements which may be due to higher prior knowledge as argued above.

Secondly, the largest amount of statements assigned to the category "Disciplinary Evaluation" was given by the teachers. When analyzing this finding, one must not only consider the higher prior knowledge of the teachers, but also their professional way of thinking. The attitude of different clusters of participants vary. Concerning the teachers, evaluate representations in terms of usability for teaching practice is part of their professional attitude. Apart from the prior knowledge, this may also cause the high percentage of statements on "Disciplinary Evaluation" level.

Finally, the effect of descriptive labels concerning the different clusters of participants is discussed. As mentioned above, the positive effect is especially apparent within the cluster of high school students, since it leads to a large shift from "Non-disciplinary Discernment" to "Disciplinary Identification" statements. Concerning the teachers, they also cause a shift from "Disciplinary Identification" to "Disciplinary Explanation", although the effect is less pronounced.

7. A. 6. Recommendations for improvement

While evaluating the answers of the participants, various aspects of the video were directly criticized by the participants or caused difficulties indirectly. These are listed below together with recommendations for improvement.

- The **representation of particles and particle systems as spheres with wobbly surface** reinforce inaccurate preconceptions about particles as described in chapter 1. A. 1. 1. In this regard it is especially problematic that at some zoom levels these spheres do not even disappear, but remain as outside shields, when zooming further in. E.g., the electron orbitals are surrounded by a sphere representing the atom and the quarks are inside a proton-sphere.

  The video could easily be improved by using a smooth model-like surface, instead of the pseudo-relistic wobbly one, as well as by letting the outside shields disappear, when zooming in.

  Moreover, the typographic illustrations developed by Wiener *et al.* (2017) could be used instead of the spheres, which underline the model-aspect of the representation.
- The **continuous cloud-like representation of electron orbitals** is also misleading and reinforcing the above-mentioned preconceptions. Thus, it should be explained that this represents the space where an electron can be located with a certain probability.

  As a minimum, the video could be improved by representing the electron density distribution as dot-cloud which depict the results of many location measurements. As described by Müller and Schecker (2018), such an illustration would be the most appropriate in terms of the quantum physical model of the atom.

  Again, a further improvement could be the typographic approach developed by Wiener *et al.* (2017).
- Many participants thought about the **movement of the quarks** that make up the proton, since it caused confusion. They may be moving, in contrary to the static representation of the particle-systems, to underline that they are the elementary particles. Furthermore, the **colors of the quarks** have been subject to assumptions, since they do not

appropriately represent the color charge. Thus, a revision of the representation of the quarks is recommended.

- The **interactions**, e.g. gluons, are **not represented**. When using a typographic approach, they could easily be included.
- Since. in accordance with the *multimedia principle*, the **combination of visualization and descriptive labels** resulted in more high-level discernment, the use of the labeled video is recommended for teaching practice. The text could further be improved by linguistic accuracy as introduced by Wiener *et al.* (2017).
- To further foster learning from the video, the **descriptions** could be **spoken** rather than written as recommended by the *multimodality principle*.

7. B. User interface "*Pixelman*"

7. B. 1. Construction of content categories

The user interface was analyzed in a similar way as the video "Voyage into to world of atoms". At first, content categories concerning the representation of a measurement with the pixel detector *MX-10* and the user interface "Pixelman" were defined to answer the first research question (see chapter 2.). There was a total of eight content categories, namely *Color differences, Coordinate system, Relative energy deposit, Representation of pixel detector data, False colors, Particle tracks, Absence of labels*, and *Shape of the representation*. These are listed and characterized in TABLE 10.

TABLE 10: **Content categories** of the representation of a measurement with a pixel detector and user interface *Pixelman* [7]

Content category	**Discernment Detail**		**Central manifestation characteristic**
	What is noticed?	What meaning is assigned?	
Color differences	Dots of lighter color on a dark background	Lighter colors indicate radiation	**Contemplation of color differences**
Coordinate system	The numbers that frame the image belong to the horizontal and vertical axis of a coordinate system	The coordinate system uses numbers to determine the position of energy detection	**Identification as coordinate system**

cont.

Relative energy deposit	Dots differ in color according to their energy, The color map on the bottom of the image refers to the detected energy	Different dots are compared in terms of energy based on their color, The color map connects the colors and the corresponding amount of detected energy ⇨ The brighter the color, the higher is the energy deposited by the radiation	**Relating colors and deposited energy, Explaining the color map**
Representation of pixel detector data	The bright dots pertain to particles that hit the detector chip, The image represents a measurement with a particle detector and a user interface	The dots represent deposited energy detected by the chip of a pixel detector, The measurement is displayed with a user interface that uses a color map to indicate the amount of deposited energy per pixel as well as a coordinate system to determine the position of the pixel	**Identification as representation of a measurement**
False colors	The color map uses false colors	The amount of detected energy per pixel is indicated by false colors since the detected radiation itself is not visible	**Contemplation of the colors used in the color map**
Particle tracks	A single particle influences more than one adjoining pixel of the particle detector	Different particles can be distinguished by the specific track they leave in the detector chip	**Comparing detected particles**
Absence of labels	Absence of description of the axes and the color map	The axes and the color map are not labeled properly, since they are not explained by titles or units	**Reflection on the intuitive user guidance of the interface**
Shape of the representation	The representation of the measurement is rectangular	Although the detector chip is square shaped, the measurement's representation is rectangular	**Contemplation of the shape of the representation**

In Table 10 the content categories are arranged according to increasing level of discernment. The first content category, *Color differences*, is not related to the discipline of particle physics unlike the other categories. Thus, there are seven content categories of disciplinary discernment.

7. B. 2. Definition of analysis categories

The content categories were divided into groups to construct analysis categories to answer the second research question (see chapter 2.). Like the analysis categories concerning the video, each category was indicated by a letter, which were used to assign single statements to a certain category when analyzing the data. The analysis categories are listed and characterized in TABLE 11.

TABLE 11: Definition of **analysis categories** according to Eriksson *et al.* (2014) ([7], p. 172ff)

Letter	Analysis category	Description	Corresponding content categories
A	**Non-disciplinary Discernment**	Participants • do not know what they are seeing [7]. • express their noticing of different colors and begin to reflect on what these might be. • focus on the color differences.	**Color differences**
B	**Disciplinary Identification**	Participants • focus on certain parts of the user interface and distinguish what these afford from a disciplinary perspective [7]. • recognize the coordinate system and relate colors to energy levels.	**Coordinate system**
C	**Disciplinary Explanation**	Participants • explain and assign disciplinary meaning to the discerned aspects [7]. • start using their disciplinary knowledge to interpret what they see [7]. • identify the image as representation of a measurement. • relate the brighter dots to the energy deposit of particles that hit the detector chip.	**Relative energy deposit,** **Representation of pixel detector data**

cont.

D	**Disciplinary Appreciation**	Participants • analyze and acknowledge "the value of the disciplinary affordances of the representation" ([7], p. 174). • "combine disciplinary knowledge […] to build a holistic understanding of what the representations are intended to afford" ([7], p. 174). • identify different types of particles due to their specific track. ⇨ Previous disciplinary explanation is necessary for appreciation	**False colors, Particle tracks**
E	**Disciplinary Evaluation**	Participants • analyze and criticize the representation used for an intended affordance [7]. • evaluate the representation in terms of its usability for teaching practice [7]. ⇨ Shift from appreciation towards positive as well as negative critique	**Absence of labels, Shape of the representation**
N	**None**	Answers like "none" or "nothing"	
M	**Missing value**	Empty answers or answers that shall be counted as empty (e.g. "-")	
X	**Double coding**	Answers given more than once by a respondent (except for "Missing value" and "None")	

7. B. 3. Recognition as representation of a measurement

When evaluating the representation of a measurement with user interface "*Pixelman*", the first question of the survey, i.e. "What do you think the image represents as a whole?", may be the most interesting. By analyzing the corresponding answers five main categories were elaborated, namely *Pixel detector, Particles, Astronomical image, Collision*, and *Others*. CHART 4 shows the percentage of participants per answer category for the first question of the survey.

The answer category "Pixel detector" is the correct one and corresponds to the analysis category "Disciplinary Explanation". Statements like "particle traces" were assigned to the category "Pixel detector" as well. In addition, it is debatable whether the answer category "Particles" is correct or not. In my opinion it is inaccurate, since it is not the particles that are represented, but the traces that they leave in the detector. Thus, for analyzing the data the answer category "Particles" corresponds to the analysis category "Disciplinary Identification".

That a considerable number of participants considered the image as an astronomical one, may be due to the used false colors. The yellowish dots on a black background remind of stars in the night sky or images of galaxies.

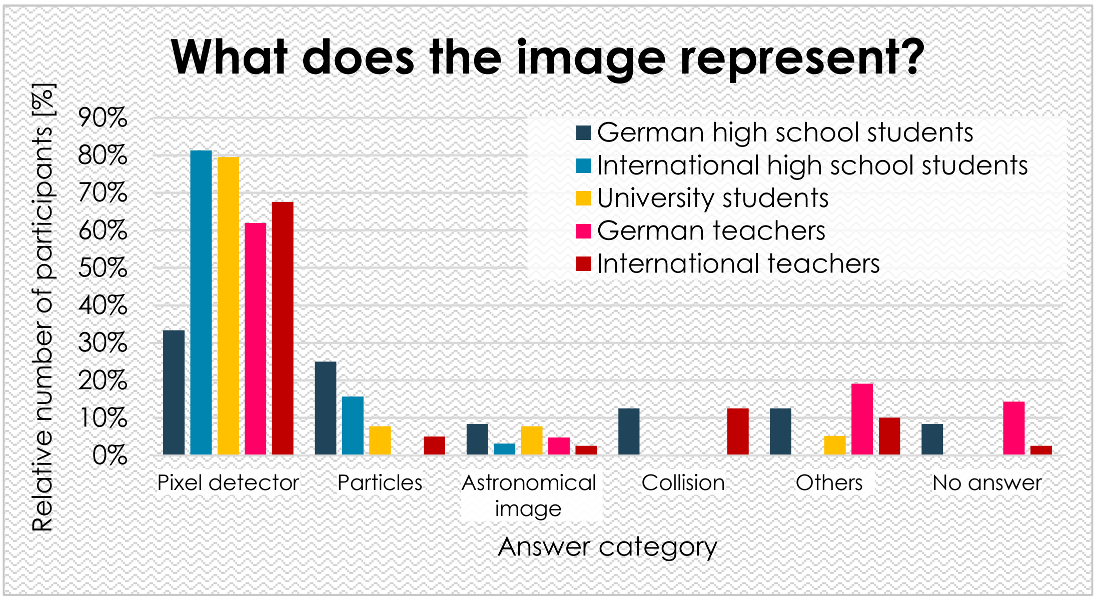

CHART 4: Relative number of participants per answer category

I argue that some participants considered the image to represent a collision because they were visiting CERN's site where the particle collider. The **international high school students** represented by the **light blue** bars and some of the **university students** (**yellow** bars) have used the pixel detector in a workshop at CERN before participating in the survey. Concerning the latter, one must consider that some of them were also working directly or indirectly with detectors. Approximately 80% of the above-mentioned groups identified the image correctly as the representation of a measurement with a pixel detector as shown in CHART 4. Furthermore, when regarding the category "Particles" as correct, nearly all participants of these group were right, the high school students were slightly better though. However, the good result of both groups is rooted in their prior experience with pixel detectors. This is another indication that prior knowledge is a crucial factor for disciplinary discernment.

In general, long-term visitors at CERN who must attend lectures are more likely to give the correct answer than others. Therefore, in addition to the international high school and university students, the **international teachers** (**red** bars) are mainly located in the first answer category. Short-term visitors are more likely to have less prior knowledge. Thus, the number of **German teachers** (**pink** bars) in the first answer category is slightly less in comparison to the internationals. However, there is a striking difference as regards the **German high school students** represented by the **dark blue** bars. They are way less likely to be found in the first answer category in comparison to all the other groups. In contrary, they are the most strongly represented group in the category "Particles". This may be caused by a lack of disciplinary knowledge and the participants might have thought that "Particles" is a good answer when being at CERN. Besides, they might have had difficulties in understanding that the image represents the energy deposited by particles and not of the particles themselves.

7. B. 4. Categorization of statements

For analyzing all questions concerning the user interface "*Pixelman"* according to the *Anatomy of Disciplinary Discernment* the approach was categorization per statement. Thus, each statement was assigned to one of the analysis categories. Some exemplary statements for each category are listed below.

7. B. 4. 1. Non-disciplinary Discernment

- **Color differences:** "Galaxies", "Universe", "Cosmos", "Lifetime of a star", "Collision events", "Particles after collision", "Heatmap of some sort"

7. B. 4. 2. Disciplinary Identification

- **Coordinate system:** "Horizontal pixels – vertical pixels", "Column number – row number"

7. B. 4. 3. Disciplinary Explanation

- **Relative energy deposit:** "It is probably the quantity of deposited energy. More energy ⇨ brighter color of the pixel.", "Its energy by the color of the pixel on the plot."
- **Representation of pixel detector data:** "The black areas are ones in which particles were not found to hit the chips, while the parts that are colored are locations on the detector at which there were detections", "Visualization of pixel detector data"

7. B. 4. 4. Disciplinary Appreciation

- **False colors:** "Intensity of ionization in false color"
- **Particle tracks:** "The colored lines and dots represent the tracks of the particles on the surface of the detector." "They have different energies and tracks, therefore you can differentiate them."

7. B. 4. 5. Disciplinary Evaluation

- **Absence of labels:** "It is unlabeled", "Graph has poor x and y labels", "I am not sure. If the bright spots are particles, it could be their energy. I thought the color was related to how many particles are there. There is no unit or label in the color scale."
- **Shape of the representation:** "The x and y axes run from 1 to 256, although the graph is rectangular instead of the square plot one might expect. This means the elliptical blobs are probably circular in reality."

7. B. 5. Results

At first, the focus was on the amount of statements assigned to the categories "None" and "Missing value" in comparison to those assigned to one of the *Levels of Discernment*. The relative amount of statements assigned to these categories is listed in TABLE 12.

When comparing the distribution of the statements among the categories, there are no striking differences between the group of participants. The only conspicuous aspect is the high amount of missing values concerning the German high school students and the international teachers.

TABLE 12: The relative amount of **statements** [%] in the categories **„Missing value"** and **„None"** (1st and 2nd row) and the sum of both (3rd row), as well as the relative amount of **statements** [%] assigned to one of the ***Levels of Discernment*** (4th row) and the category **"Double coding"** (5th row) are listed.

	High school students		University students	Teachers	
	German	International		German	International
None	2%	0%	1%	1%	1%
Missing value	8%	2%	4%	4%	11%
None + Missing value	**10%**	**2%**	**5%**	**5%**	**12%**
Levels of Discernment	**88%**	**93%**	**91%**	**94%**	**86%**
Double Coding	2%	5%	4%	1%	3%

However, for further analysis only the statements assigned to one of the *Levels of Discernment* are considered. TABLE 13 shows the distribution of statements within the *Levels of Discernment* for all groups of participants.

Above all, the focus is on comparing the results within the three clusters of participants and then, on seeking for parallels and differences between them.

In TABLE 13 it is apparent that the results of the two high school student groups are different. The internationals gave way less non-disciplinary statements than the Germans (10% to 38%). Furthermore, the former attained higher amounts of "Disciplinary Appreciation" and "Disciplinary Evaluation" statements. As mentioned above the internationals have already used pixel detectors in a workshop at CERN in contrary to the Germans, and thus these differences are not surprising.

TABLE 13: Distribution of **statements** [%] **within the *Levels of Discernment***

	High school students		University students	Teachers	
	German	International		German	International
Disciplinary Evaluation	0%	1%	3%	1%	1%
Disciplinary Appreciation	1%	18%	8%	4%	4%
Disciplinary Explanation	33%	43%	42%	42%	30%
Disciplinary Identification	28%	28%	35%	26%	32%
Non-disciplinary Discernment	38%	10%	13%	27%	33%

Comparing the two teacher groups with each other, it is apparent that the German attained slightly better results as regards "Disciplinary Identification" and "Disciplinary Explanation" and hence, their amount of non-disciplinary statements is less.

For comparing the clusters with each other I visualized the data in CHART 5.

The relative amount of statements assigned to the categories "Disciplinary Identification" and "Disciplinary Explanation" is similar for all groups apart from the above-discussed issues. This finding is caused by the specific questions that were asked in this part of the survey (see chapter 10. A. 3.). E.g., when asked "What is plotted on the x-axis?", the participant had to focus on this aspect, otherwise he or she would not have been able to answer. This also results in the relatively high amount of "Disciplinary Identification" and "Disciplinary Explanation" statements. However, there are no striking differences concerning the category "Disciplinary Evaluation" either. In fact, the amount of statements assigned to this category is close to zero, which is another cause for the relatively high amount of "Disciplinary Explanation" statements.
Thus, for comparing the different groups of participants with each other, the analysis focuses on the categories "Non-disciplinary Discernment" and "Disciplinary Appreciation".

Concerning the category "Non-disciplinary Discernment", it is apparent that the international high school and university students attained a low amount in accordance with their prior experience with pixel detectors (see chapter 7. B. 3.). The university students are slightly stronger represented, which may be since not all of them have worked with pixel detectors before. However, the German high school students and both teacher groups gave way more non-disciplinary statements, whereby the high school students are the most strongly represented in this category.

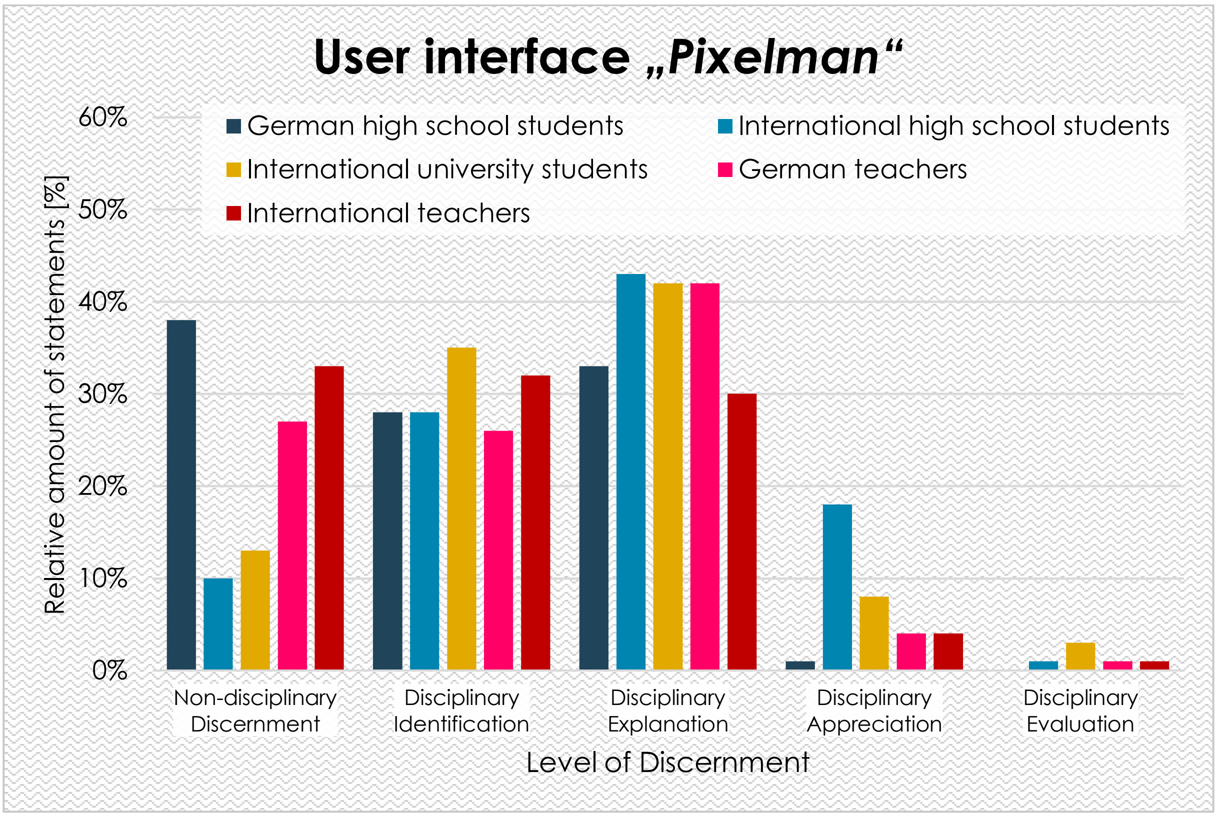

CHART 5: Relative amount of statements per *Level of Discernment*

Concerning the category "Disciplinary Appreciation", the international high school students gave the largest amount such statements (18%) followed by the university students (8%). Overall, the amount of appreciative statements regarding the user interface "*Pixelman*" is low. That the representation is not appreciated by the participants may be an indication that its user guidance is neither intuitive nor simple.

7. B. 6. Recommendations for improvement

In accordance with the participants's statements, the following recommendations for improving the user interface "*Pixelman*" can be given:

- The **axes and the color scale** should be **labeled with titles and units**.
- The coordinate system representing the detector chip should have a **fixed square shape**.
- The **detection mode** should be indicated.

8. CONCLUSIONS

Two crucial factors were identified that have an impact on the **discernment from visualizations** in particle physics.

The first factor concerns the participants in terms of their prior experiences and knowledge. The results of this study indicate a correlation between prior knowledge and disciplinary discernment and support the assertions by Eriksson *et al.* (2014). Thus, further evidence has been provided that the *Anatomy of Disciplinary Discernment* is a useful tool to analyze representations.

The second factor concerns the representation in terms of its composition and corresponding affordances. The results of this study suggest that descriptive labels foster disciplinary discernment. This agrees with the *multimedia principle* as described in chapter 1. C. 2. 1., which states that learning is more effective, if visualizations are combined with text.

Concerning the relation between both factors, the results of this study indicate that the positive effect of descriptive labels on the disciplinary discernment is less pronounced, if the prior knowledge is high anyway.

Besides, the initially mentioned **preconceptions** have been confirmed by the data collected in the frame of this study.

However, the most important **limitations** of the study also lie in the preconceptions and the prior knowledge of the participants. For analyzing the data the definition of the prior knowledge of the participants was based on the educational background and on further assumptions in terms of their stay at CERN, but the individual's way of thinking was not investigated.

Thus, for further analysis of visualizations in particle physics the development of a test item to evaluate the preconceptions of the participants, before they engage with the representation and answer questions about their discernment, would be valuable.

Taken together, when asked, whether **visualization in particle physics** are **learning aids or obstacles**, one has to differentiate. Visualizations in particle physics can be learning aids, if the model aspect of the representation is clear and unambiguous. Thus, when choosing a model, one must always keep the learners' preconceptions, prior experiences, and knowledge in mind, since the appriopriatness of a specific model varies with the recipients.

In this regard, I hope that the results of this research as well as the recommendations for improvement will lead to a rethinking and revision of the analyzed representations.

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10. APPENDIX

10. A. Questionnaire

10. A. 1. Initial draft of the questionnaire (German)

"Liebe Kollegin, lieber Kollege/liebe Schülerin, lieber Schüler",

Du befindest dich gerade im S'Cool LAB des CERN, in dem Teilchenphysik-Experimente durchgeführt werden. Wir arbeiten kontinuierlich daran, unsere Veranstaltungen weiterzuentwickeln. Dazu benötigen wir deine Hilfe: Bitte lies dir die folgenden Aufgabenstellungen gut durch und beantworte die Fragen so ausführlich wie möglich. Dieser Fragebogen ist KEIN Test und deine Antworten bleiben anonym! Vielen Dank für deine Mithilfe! P.S.: In der Teilchenphysik-Community ist es üblich, dass sich alle (Studierende, Professorinnen, Nobelpreisträger, …) untereinander duzen. Wir hoffen, dass es für dich in Ordnung ist, wenn wir uns im S'Cool LAB Kontext ebenfalls duzen!

- ☐ Ich nehme zur Kenntnis, dass meine Daten anonym behandelt und zu Forschungszwecken weiterverarbeitet werden.

- Ich bin …
  - ☐ weiblich.
  - ☐ männlich.

- Seit wie vielen Jahren "*unterrichtest/lernst*" du Physik?

Questions about the video

In den folgenden Abschnitten siehst du nacheinander Teile eines Videos. Öffne den Link, schau dir das Video an und beantworte die Fragen!

1) https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/1_Haarzelle.mp4 (12.12.18)
2) https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/2_Makro_Mikro_Protofibrille.mp4 (12.12.18)
3) Beachte: Carbon=Kohlenstoff, Sulphur=Schwefel, Nitrogen=Stickstoff, Oxygen=Sauerstoff
   https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/3_Keratin_Atome.mp4 (12.12.18)
4) Beachte: Carbon=Kohlenstoff
   https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/4_Kohlenstoffatom_Elektronenorbitale.mp4 (12.12.18)

5) https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/5_Kern_Protonen_Neutronen.mp4 (12.12.18)
6) https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/6_Proton_Quarks.mp4 (12.12.18)

Note: *Question a) and b) were asked for each of the six videoclips.*

a) Beschreibe, was dir in den Sinn kommt, wenn du diesen Videoclip siehst!
b) Was erscheint dir bekannt, neu, überraschend oder verwirrend?

Questions about the user interface

Um Teilchen sichtbar zu machen, werden Pixeldetektoren wie z.B. der MX-10 genutzt. Sein Detektorchip besteht aus dem Halbleiter Silizium. Wenn Teilchen mit hoher Energie durch den Halbleiter fliegen, werden Elektronen (negative Ladungsträger) von den Atomen gelöst. Je höher die Energie der Teilchen, desto mehr Elektronen werden gelöst. Die frei beweglichen Elektronen wandern zur positiv geladenen Elektrode. Dieses Stromsignal wird ausgewertet. Indem man die gesamte Detektoroberfläche in kleine Bereiche (Pixel) unterteilt, kann man einem Signal einen Ort zuzuordnen. Der Silizium-Detektorchip des MX-10 ist 1,4x1,4cm^2 groß und in 256x256 Pixel unterteilt.

- Aus wie vielen Pixeln besteht der Detektorchip des MX-10?
  - ☐ 256x256
  - ☐ 10
  - ☐ 1,4x1,4

Betrachte dieses Bild genau und überlege dir, was gezeigt wird. Zur näheren Betrachtung der Bilder zoome am Bildschirm mit zwei Fingern hinein!

Note: *The set of questions about the visualization was divided and displayed in subsets as listed below:*

- Was stellt dieses Bild als Ganzes dar?
  Wie erklärst du dir einzelne Aspekte des Bildes?
- Was ist auf der x-Achse aufgetragen?
  Was ist auf der y-Achse aufgetragen?
  Wofür steht die Farbskala am unteren Rand des Bildes?
- Dieses Bild zeigt die Signalauswertung des Detektorchips. Es werden einige Eigenschaften von Teilchen dargestellt. Welche Aussagen kannst du über ein beliebiges Teilchen treffen?
- Unterscheiden sich die Teilchen, die auf den Detektorchip treffen? Wenn ja, wodurch?

10. A. 2. Final version of the questionnaire (German)

"Liebe Kollegin, lieber Kollege/liebe Schülerin, lieber Schüler/…",

Du befindest dich gerade im S'Cool LAB des CERN, in dem Teilchenphysik-Experimente durchgeführt werden. Wir arbeiten kontinuierlich daran, unsere Veranstaltungen weiterzuentwickeln. Dazu benötigen wir deine Hilfe: Bitte lies dir die folgenden Aufgabenstellungen gut durch und beantworte die Fragen so ausführlich wie möglich. Dieser Fragebogen ist KEIN Test und deine Antworten bleiben anonym! Vielen Dank für deine Mithilfe! P.S.: In der Teilchenphysik-Community ist es üblich, dass sich alle (Studierende, Professorinnen, Nobelpreisträger, …) untereinander duzen. Wir hoffen, dass es für dich in Ordnung ist, wenn wir uns im S'Cool LAB Kontext ebenfalls duzen!

☐ Ich nehme zur Kenntnis, dass meine Daten anonym behandelt und zu Forschungszwecken weiterverarbeitet werden.

- Ich bin …
  - ☐ weiblich.
  - ☐ männlich.
- Seit wie vielen Jahren "*unterrichtest/lernst*" du Physik?

Questions about the video

Note: *Since the two different versions of the video, with and without labels, were analyzed, links to both versions of the clips 1) to 4) and the accompanying explanation are listed below. Each group of participants only got the links to one version of the clips.*

In den folgenden Abschnitten siehst du nacheinander Teile eines Videos. Öffne den Link, schau dir den Videoclip an und beantworte die Fragen!

1) ***Unlabeled clip:*** https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/Abschnitt_1_nolabel.mp4 (12.12.18)
   Labeled clip: https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/Abschnitt_1_labeled.mp4 (12.12.18)
2) ***Unlabeled clip:*** https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/Abschnitt_2_nolabel.mp4 (12.12.18)
   Labeled clip: https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/Abschnitt_2_labeled.mp4 (12.12.18)
3) ***Unlabeled clip:*** https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/Abschnitt_3_nolabel.mp4 (12.12.18)
   Labeled clip: https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/Abschnitt_3_labeled.mp4 (12.12.18)

4) ***Unlabeled clip:*** https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/Abschnitt_4_nolabel.mp4 (12.12.18)
Labeled clip: https://scool.web.cern.ch/sites/scool.web.cern.ch/files/vidsstudie/Abschnitt_4_labeled.mp4 (12.12.18)

Note: *Question a) and b) were asked for each videoclip.*

a) Beschreibe, was dir in den Sinn kommt, wenn du diesen Videoclip siehst!
z.B. Dinge, die dir auffallen, neue Erkenntnisse oder Verknüpfungen, Überraschendes oder Verwirrendes
b) Welche Fragen hat dieser Clip für dich aufgeworfen?
Wenn du nichts Neues bemerkt hast, teile uns dies bitte hier mit!

Note: *These are the follow-up questions.*

Du hast nun alle Clips gesehen. Bitte beantworte die Fragen zum GESAMTEN Video!

- Wo hat die Reise begonnen und wo geendet?
  Bitte erkläre dies so ausführlich wie möglich!
- Zähle auf und begründe, was deine Aufmerksamkeit besonders erregt hat!
  z.B.: Dinge, die dir neu sind, die du nun anders wahrnimmst oder die du bemerkenswert findest
- Konntest du aufgrund des Videos neue Verknüpfungen zwischen Phänomenen oder Strukturen knüpfen? Wenn ja, welche?
  Bitte erkläre dies so ausführlich wie möglich!
- Hat dich etwas im gesamten Video überrascht? Wenn ja, was?

Questions about the user interface

Um Teilchen sichtbar zu machen, werden Pixeldetektoren wie z.B. der MX-10 genutzt. Sein Detektorchip besteht aus dem Halbleiter Silizium. Wenn Teilchen mit hoher Energie durch den Halbleiter fliegen, werden Elektronen (negative Ladungsträger) von den Atomen gelöst. Je höher die Energie der Teilchen, desto mehr Elektronen werden gelöst. Die frei beweglichen Elektronen wandern zur positiv geladenen Elektrode. Dieses Stromsignal wird ausgewertet. Indem man die gesamte Detektoroberfläche in kleine Bereiche (Pixel) unterteilt, kann man einem Signal einen Ort zuzuordnen. Der Silizium-Detektorchip des MX-10 ist 1,4x1,4cm^2 groß und in 256x256 Pixel unterteilt.

- Aus wie vielen Pixeln besteht der Detektorchip des MX-10?
  - ☐ 256x256
  - ☐ 10
  - ☐ 1,4x1,4

Note: *After this question the screenshot of a measurement and an explanation were presented together with each subset of questions.*

Betrachte dieses Bild genau und überlege dir, was gezeigt wird. Zur näheren Betrachtung der Bilder zoome am Bildschirm mit zwei Fingern hinein!

- Was stellt dieses Bild als Ganzes dar?
  Wie erklärst du dir einzelne Aspekte des Bildes?
- Was ist auf der x-Achse aufgetragen?
  Was ist auf der y-Achse aufgetragen?
  Wofür steht die Farbskala am unteren Rand des Bildes?
- Dieses Bild zeigt die Signalauswertung des Detektorchips. Es werden einige Eigenschaften von Teilchen dargestellt. Welche Aussagen kannst du über ein beliebiges Teilchen treffen?
- Unterscheiden sich die Teilchen, die auf den Detektorchip treffen? Wenn ja, wodurch?
  Wie viele Teilchen sind auf den Detektorchip getroffen?

10. A. 3. Final version of the questionnaire (English)

Dear "*student/teacher/…*",
I kindly ask you to participate in this survey and answer some questions related to particle physics. By participating in this survey, you also agree to the ethical arrangements* below.
Thank you very much!
Physics Education Research Group, CERN

*Ethical arrangements
By proceeding to take this survey you are giving your explicit consent for us to use the answers that you provide in the survey for research purposes at the PER group, CERN, Switzerland. We guarantee total confidentiality. The analytic use of the data will be to answer specific research questions dealing with aspects of discernment that may be made possible by the representation used in the survey. The only linked personal information that may be used in the analysis and its reporting are the answers you give to the questions about gender and academic background. We guarantee that no other personal links will be made to this information. With this guarantee you are also consenting to: (1) having the data shared digitally amongst our research group and stored on our computers and (2) to have the data used in the verbal and written reporting of our analysis. This includes digital and paper publication of my results. The reporting of these results may also include some exact quotations from your written answers that you provided.

- To which gender identity do you most identify?
  - ☐ male
  - ☐ female

- How long have you been “teaching/studying” Physics?

Questions about the video

Note: *As in the German version of the questionnaire the labeled and the unlabeled version of the video were used. Each group of participants either had to fill in a survey with links to the labeled or to the unlabeled videoclips. However, the links were accompanied by the following instruction:*

Watch this clip and answer the questions!

Note: *The same two questions about each of the four clips were asked.*

a) Please write what comes to mind when you watch this clip.
   e.g. things you noticed, sudden new realizations or connections, surprising or confusing things
b) What, if any, "I wonder ..." questions did this clip raise for you?
   If you have not noticed something new, feel free to say so.

Note: *These are the follow-up questions.*

- Now that you have seen the whole video, did you get a good sense of where the journey started and where it ended?
  Please explain as fully as possible.
- With respect to the video, mention those things that particularly caught your attention and explain why.
  e.g. new things that you noticed, things you noticed differently now when you have seen the whole video, or things that you found amazing to notice
- What, if any, new connections between phenomena or structures did the video as a whole make for you?
  Please explain as fully as possible.
- What, if anything, surprised you in the video as a whole?

Questions about the user interface

To make high-energy particles visible you can make use of pixel detectors out of semiconductor materials. These detectors are based on the following principle:
High-energy particles fly through the semiconductor material and free electron-hole pairs. Electrons or holes are collected through an externally applied field, converted into voltage pulses

and digitized. By dividing the whole detector surface into small parts (pixels), you can measure the location of a detected particle.
The detector chip of the detector “MX-10” measures 1.4×1.4 cm^2 and is divided into 256 x 256 Pixels.

- In how many pixels is the detector “MX-10” divided?
  - ☐ 256x256
  - ☐ 10
  - ☐ 1,4x1,4

Note: *After this question the screenshot of a measurement and an explanation were presented together with each subset of questions.*

Examine this image carefully and think about what it shows!

- What do you think the image represents as a whole?
  Please describe your understanding of as many parts of the image as you can.
- What is plotted on the X-axis?
  What is plotted on the Y-axis?
  What does the colour scale at the bottom of the image represent?
- This image shows the screenshot of a measurement with an MX-10 pixel detector and Pixelman software. It represents particles and some of their properties. What can you tell about a particular particle?
- How do the particles which hit the detector chip differ from each other?
  How many particles hit the detector chip?

10. B. Interrater data table

10. B. 1. Video “Voyage into the world of atoms”

Participant	1. Please write what comes to mind when you watch this clip.	Category	Category_interrater	Compliance	2. What, if any, "I wonder ..." questions did this clip raise for you?	Category	Category_interrater	Compliance
1	GOING TO THE SMALLEST	A	A	Y	NEW WORDS	A	A	Y
2	order of magnitude	A	C	N	and if I go outside the hair, in space?	A	A	Y
3	inside of matter	A	A	Y	-	M	M	Y
4	we can probe closer and closer and we can still find matter that made up the whole thing	B	A	N	I wonder how close can we probe? What is the smallest thing that human can observe?	B	A	N
5	I love the animation of this clip, going step by step to microscopic level.	A	D	N		M	M	Y
6	fishermen thread	A	A	Y	is that really the human hair?	A	A	Y
7	coool. nicely done. it would be nice to see this somewhen during elementary school	C	E	N	I wonder how it would look like if it continued "zooming".	A	A	Y
8	Bad memories to my biology classes...Would have been nice if it continued to particle physics instead of stopping at atoms...	B	B	Y	none	N	N	Y
9	I dont have H.264 encoder in my firefox :(	A	N	N		M	N	N
10	none	N	N	Y	none	N	N	Y
11	nothing really	N	N	Y	none	N	N	Y
12	It's a beautiful and somewhat intuitive visualisation of many orders of magnitude because it starts on a well known scale and dives into the micro world in steps that are nice to follow.	D	D	Y		M	M	Y
13	It gives the sense of the diference between the macroscopic and microscopic world, even though they work in a union constantly. Yet, I always have trouble actually getting a sense of the absolute minuscule scale that our world functions at.	C	C	Y		M	M	Y
14	I didn't know that there were cells also in hair.	A	B	N	I had already seen this video and I didn't know about the fibrils.	B	B	Y
15	Gives an idea of constitution of a trivial object as human hair as well as a comparison scale for particles at different levels of this hierarchy of constitution (strand of hair to keratin to molecules making the whole structure)	C	C	Y	If size of molecules is of order 10^-8 times thickness of hair, the thickness of hair would be tremendously larger than the dimensions of elementary particles. It's not a question, it's just an astonishment as to how small the world of elementary particles is	C	C	Y
16	I didn't know that keratin was located within the hair, rather I had the impression that it served as an outer coating/layer of the hair. Also, I wasn't aware of how many different elements are present in human hair.	A	B	N	I wonder how fine-tuned and complex nature can get all around us.	A	A	Y
17	The visualisation that normal thing from ours day life can be related to those incredible scales is really impressive and impacting.	A	C	N	It made me wonder how deep things we see can go and we may not even notice that most of the time	A	A	Y
18	the clip is using a really nice way of zooming in effects which gips the viewer into exploring more of what the clip will provide, the way it ended wasn't as satisfying as it was anticipated to be. the details of for example a hair on the 100 micrometre scale was aesthetically pleasing. the video shows an articulate way to make the viewer wonder how beautiful it is that complex creatures like us are made of simpler and simpler things.	D	E	N	why was everything in the shape as it is now.	A	D	N
		Total number of statements		18		**Total number of statements**		18
		Compliant coding		9		**Compliant coding**		15
		Relative compliance		0,50		**Relative compliance**		0,83

1. Please write what comes to mind when you watch this clip.	Category	Category_interrater	Compliance	2. What, if any, "I wonder ..." questions did this clip raise for you?	Category	Category_interrater	Compliance	1. Please write what comes to mind when you watch this clip.	Category	Category_interrater	Compliance
AN ATOM	B	B	Y	NO	N	N	Y	NUCLEUS	B	B	Y
.	M	M	Y	and if I go further?	A	A	Y	why am I always seen "balls"?....	X	E	N
Chemistry	A	B	N	-	M	M	Y	atom	B	B	Y
chemistry? about atoms, orbitals	B	B	N	How sure are the scientists about the orientation of the particles inside the atom?	A	D	N	colors of neutron and proton? how close can humans probe the inside of an object?	B	D	N
Interesting, but do look the orbitals like so?	B	E	N		M	N	N	Are protons red and neutrons white? Do they stick together without any motion? Why do they stick together without any motion?	E	E	Y
Aquatic weeds	A	A	Y	Are they molecules	A	A	Y	structure of the atom	B	B	Y
I remembered my high school chemistry classes, where we learned about orbitals, elements etc.	B	B	Y	I wonder how it looked like on a particle level.	B	B	Y		M	N	N
No I guess there is a third clip coming...	A	N	N	I wonder if I am right, that there is a third clip...	X	A	N	There will be at least one more clip	A	A	Y
I just noticed that they used electron clouds for electron position	B	D	N		M	N	N	I realized how small is the nucleus in respect to the whole atom	C	C	Y
	M	M	Y		M	N	N	cool pictures and visualization	A	A	Y
again. nothing really	N	N	Y	none	N	N	Y	nothing really	N	N	Y
Same as before...it's a nice step-by-step introduction into the world of the smallest existing particles.	X	X	Y		M	M	Y	same as before	X	X	Y
I do not like it when the subatomic world is represented in such a way with simple spheres and physical conections between them, as this is not how the world actually operates on this level. Yet the video does not fail in its original goal, that is to display and give a visual representation of the scaling of the universe	E	E	Y	One unsatisfying element with almost all of these videos, is that they give the sense and illusion of being forever continuing and zooming. When the video eventually has to stop, as our models cannot explain further, it leads to a sense of unacomplishemnt and disappointment, in my eyes. I brought this up earlier, and this is why I see a fault in desrcribing the microscopic universe in terms of everyday manners such as 'zooming'.	E	E	Y	It gives an ok visualization of the emptiness that is within an atom.	D	E	N
sp3 hybridization	B	B	Y	Nothing new	N	N	Y	Yes, the nucleus is tiny.	C	C	Y
Electrons are arranged in discrete cloud-like orbitals	C	C	Y	Nothing	N	N	Y	Typical subatomic structure of nucleus	B	B	Y
We are taught to visualise atoms in a very different way at school, especially when it comes to electrons that are thought to move around the nucleus in circular shells.	A	E	N	I wonder how the atom really works	A	D	N	The nucleus has quite a familiar shape but this is not the way I visualised the whole atom up to now.	A	D	N
how many different materials are originated from carbon	A	B	N	It made me think in the reason why carbon is the main constitute of the things we see on earth	B	B	Y	I notice how much empty space there was in the microscope world	C	C	Y
this clip also resembles the one that was played earlier, it shows fascinating visualizations of what everything is made of.	X	X	Y	I wonder why when you zoomed in on the atom and showed the orbitals was there a shield covering the atom?	C	B	N	same as the earlier answer	X	X	Y
	Total number of statements		18		Total number of statements		18		Total number of statements		18
	Compliant coding		11		Compliant coding		11		Compliant coding		13
	Relative compliance		0,61		Relative compliance		0,61		Relative compliance		0,72

2. What, if any, "I wonder ..." questions did this clip raise for you?	Category	Category_interrater	Compliance	1. Please write what comes to mind when you watch this clip.	Category	Category_interrater		2. What, if any, "I wonder ..." questions did this clip raise for you?	Category	Category_interrater	Compliance
NO	N	N	Y	COMPONENTS OF PROTONS	B	B	Y	NO	N	N	Y
no news	N	N	Y	misleading representation of nucleons ad balls containing other balls....	E	E	Y	am I going to see other "balls"going further?.....	X	E	N
-	M	M	Y	elementary particles	B	B	Y		M	M	Y
I wonder how protons and neutrons stay together inside the nucleus (they say its the strong force).	C	C	Y	the mass of the constituents quarks inside the proton is not equal to the mass of the proton	C	C	Y	I wondedr if we could observe an individual quark in the future (overcoming the strong force).	B	C	N
I wonder, if it was possible to animate moving particles in the nucleus.	X	D	N	Why don't this particles leave the nucleus? Where are the gluons? Where are the seaquarks?	E	E	Y	I wonder if it was better to add gluons and perhaps seaquarks in this animation to understand the interaction properly.	X	E	N
nucleus found in the core	B	B	Y	colours of sub atomic particles	B	A	N	colour band	A	A	Y
I want to see more!	A	A	Y	Despite knowing that our hair is made of particles, I still find it mindblowing seeing this visualisation.	B	D	N		M	N	N
none	N	N	Y	No I think we are done here	A	N	N	None	N	N	N
	M	M	Y		M	M	Y		M	M	Y
I wonder how close to reality is this animation	B	D	N	nice	A	A	Y	none	N	N	Y
none	N	N	Y	nothing really	N	N	Y	none	N	N	Y
	M	M	Y	Even though it's clear that at some point the concept of colours (red up-quarks etc.) doesn't exist anymore it's a nice visualisation.	E	E	Y		M	M	Y
	M	M	Y	Again, as a visual representation of the aspects of size, it does a great job, but gives a bad representation to the machenism of the universe, like saying a propon is just made of three simple quarks.	E	E	Y	I said this earlier, but I am left with a sense of "ok, now what?"	A	E	N
Nothing new	N	N	Y	Colour charge!	B	C	N	nothing new	N	N	Y
Nothing	N	N	Y	Composition of a proton and its radius	B	B	Y	Nothing	N	N	Y
it did not raise any	N	N	Y	There is also empty space within the protons and neutrons	C	C	Y	none	N	N	Y
It made me wonder how empty matter is	X	C	N	It made me remember of Russians dolls	A	A	Y	I wonder if there is something beyond quarks	B	B	Y
same as the earlier answer	X	X	Y	all the information provided in this clip were previously understood	A	N	N	what are quarks made of in turn	B	B	Y
	Total number of statements		18		Total number of statements		18		Total number of statements		18
	Compliant coding		15		Compliant coding		13		Compliant coding		12
	Relative compliance		0,83		Relative compliance		0,72		Relative compliance		0,67

Now that you have seen the whole video, did you get a good sense of where the journey started and where it ended?	Category	Category_interrater	Compliance	With respect to the video, mention those things that particularly caught your attention and explain why.	Category	Category_interrater	Compliance
FROM THE HAIR OF THE WOMAN TO THE SMALLEST INNER PART OF THE ATOM	B	A	N	I SAW THIS VIDEO BEFORE	A	A	Y
yes	A	N	N	none	N	N	Y
	M	M	Y	existence of quarks	B	B	Y
Somehow. From the macroscopic world until the smallest possible particle that man has observed so far.	C	A	N	I find the zooming part cool. It shows that the human body is composed of a lot of quarks!	B	B	Y
Yes, this "high-zoom" is a very nice animation and will be a good way to explain students the dimension of subatomar particles. However, I miss somme things in the animation.	D	E	N	I think it is a nice animation and the way it was animated caught my attention.	A	D	N
no	A	N	N	the magnification of the structure of the human hair... so surprising	A	A	Y
Yes!	A	N	N	The scale.	B	C	N
Nothing new here	A	N	N	I think it was well made.... Painting elementary particles might not be the most realistic thing to do, but the video gives a good impression overall. If quarks are elementary they probably shoudn't have any structure at all, but that is much harder to visualize	D	E	N
Since I didn't watch the whole video, I guess the journey from macro-scale world to the smallest of dimensions.	B	C	N		M	M	Y
yes	A	N	N		M	M	Y
yes, I believe it would be interesting for someone with little knowledge on how small the building blocks of nature are or the size of things explored at the LHC	D	E	N	none	N	N	Y
Yes, it's a consistent journey.	A	A	Y	I like that it started at something we know from everyday life: a person, hair, ...	A	A	Y
Yes, I do fully understand where the video begins and ends, as it is properly and nicely noted both the names of the objects and their size.	D	A	N	Before entering the atomic world, everything was colourless, but upon entering the microscopic scene, objects that cannot give sense to have a color (disregarding quark colors of course) were given bright colors. I would have preffered the overworld to be colorfull and the atomic world being a dark and muystic place	A	E	N
I could see how small particles are.	C	C	Y	I didn't know about the structure of hair.	A	B	N
The strand of hair of a hundred microns consists of DNA molecules with size of order of nanometres which are further constituted by various atoms of size of picometres inside of which there is a whole universe of electrons and nuclei with nucleons further consisting of smaller particles	C	C	Y	Nothing	N	N	Y
Yes because everything got progressively smaller and an indication of the scale was very useful because at some point things stop being measureable as you probe deeper and deeper.	D	C	N	It started out as a particular blonde woman with certain specific features and characteristics that we find unique in every person but as the video progressed and things went down to the atomic level, we can see that we are all actually the same thing.	A	B	N
I could get the sense of the journey beginning in a human to an quark really well. Was able to see how hair was made of a material that was constituted of something else and going like this as far as the quark.	B	B	Y	I was wondering about how matter interacts with matter while we have plenty of empty space and how it is fulfilled with forces. Other really amazing point is the electrons and how we identify them in the particles, not with a position but with probability.	C	C	Y
yes, but videos like this makes me question if we can understand everything from the beginning of the formation of the first atom to organic material to living beings right now	A	B	N	I have focused a lot of my self-studying to physics and particle physics, and this video showed me things that make up biological structures which also makes me curious about what makes up everything	A	B	N
	Total number of statements		18		Total number of statements		18
	Compliant coding		5		Compliant coding		11
	Relative compliance		0,28		Relative compliance		0,61

What, if any, new connections between phenomena or structures did the video as a whole make for you?	Category	Category_interrater	Compliance	What, if anything, surprised you in the video as a whole?	Category	Category_interrater	Compliance
	M	M	Y		M	M	Y
none	N	N	Y	none	N	N	Y
	M	M	Y		M	M	Y
Quarks is just a small part of a human body, just like us being a small part of the universe.	C	C	Y	None	N	N	Y
	M	M	Y		M	M	Y
making science and its new discoveries real and factual	A	A	Y	well	A	N	N
It just reminded me of what I already know but never seem to think about (the particles we - our bodies are made of).	B	B	Y	How well it was visualised.	D	D	Y
	M	M	Y		M	M	Y
	M	M	Y		M	M	Y
interesting to visualize the scale of things, helps in better understanding	D	E	N		M	M	Y
none	N	N	Y	no	N	N	Y
none	N	N	Y	none	N	N	Y
none	N	N	Y	nothing	N	N	Y
I didn't know about the structure of hair. Particles are so small!	X	X	Y	That scales are correct, especially about the dimention of the nucleus	D	D	Y
There is a hierarchical structure even inside the smallest thing we can visualise in daily life	A	C	N		M	M	Y
none	N	N	Y	the electron orbitals were very different to what we were taught up to now	X	E	N
electrons and how we identify them in the particles, not with a position but with probability	X	C	N	empty space and the electric probabilistic field	X	C	N
the connection between biology, physics and chemistry: it reminded me of how the colours of quarks make white at the end and unify to what we know of to be life.	A	A	Y	non since its all previous video	N	N	Y
	Total number of statements		18		Total number of statements		18
	Compliant coding		15		Compliant coding		15
	Relative compliance		0,83		Relative compliance		0,83
				Total relative compliance			0,67

10. B. 2. User interface "Pixelman"

Participant	1. What do you think the image represents as a whole?	Category	Category_interrater	Compliance	2. Please describe your understanding of as many parts of the image as you can.	Category	Category_interrater	Compliance
1	The image represents the measurements of all the pixels of the detector (coordinate scales to left of and below the image).	C	C(B)	Y	The color scale at the bottom assigns colors to probably either intensity or number of particle having passed through a certain pixel. Lines or dots in the image represent the traces of various particles that have passed through the detector.	D	C	N
2	The screen or measuring area of the pixel detector and the particles it picked up.	C	C	Y	The image shows what particles the pixel detector picked up. The dark spot means that no particles where in this area, while the other colours show particles and their path. Each line is a separate particle and its projection on the screen shows a part of its trajectory. The colour of the particle corresponds to the energy, which is shown on the scale below. Higher energy particles are represented by lighter colours. The detector only measures charged particles.	D	D	Y
3	different particles measured using a pixel software	C	C	Y	this image represents different particles (eg alpha, beta, gamma) and are represented by different energy levels (which are represented by different colors)	D	D(C?)	Y
4	The particles passing through the pixel detector.	C	C	Y	The colored lines and dots represent the tracks of the particles on the surface of the detector. The colors of the tracks represent the amout of energy of the particles	D	D	Y
5	I think the image represents the picture taken mentioned in the previous question, and we can see active pixels that light has interacted with as highlighted spots. White correlates to a higher number that I assume is energy	C	C	Y	The 256x256 is the dimensions of the detector in pixels, and th ebar on the bottom gives a visual comparimsent to measurements and values via colors.	D	C	N
6	Reepresents particles coming from a source of radiation.	B	C	N	The more particles arrive the brighter the dots are. The position of the dots is where particles arrive on the detector.	C	C	Y
7	Gamma particles detected by a pixel detector.	B	C	N	Bright light could refer to emitted gamma particles.	B	C	N
8	Read out of a pixel detector	C	C	Y	Some brighter area represent the passage of a particle with higher energy loss (more ionizing) which could indicate by what means it is reacting. It might also indicate its size	C	D	N
9	image taken from a detector.	C	C	Y	One can see that this image describe a charge particles moving throw a detector. The charge particles with hight energy are those with hight lumenosity (Orange cercle) and those with low energies leave a small pick of energy.	D	D	Y
10	Particle tracks.	B	D	N	Perhaps the straight lines are tracks and the spots are incoming particles (head-on)	C	C	Y
11	galaxies	A	A	Y	some kind of imaging that is filtering out red - yellow light emitted from objects in the universe	A	A	Y
12	Number of particles going through each area of the detector	C	C	Y	The X and Y axis goes from 0 to 256, which would be the size of the pixeldetector. Then the bar at the bottom shows probably the number of detections at each spot.	C	B	N
13	I think this is the image produced by a pixel detector which shows the glows left by high energy particles as they take off electron-hole pairs from a semiconductor crystal.	C	D	N	The image shows a number of bright spots on a dark background. I believe this image is produced as a result of high energy particles breaking off electron-hole pairs from the pixel semiconductor crystal. some of the spots are brighter than others. The brighter spots may indicate the particles with higher amount of energy compared to those that produce the less bright spots. Some of the spots are of a larger diameter than others, these spots were actually hit by a large cluster of particles rather than a single particle. The unilluminated background actually indicates points that have not been hit by particles.	D	D	Y
14	the area of particle's detector	C	A (could also be C)	Y	we can see the beams of some kind of particle	A	C	N
15	the meteorite	A	A	Y	night, gear moving down and emitting a sateen	A	A	Y
16	particles	B	C	N	y axis: 256-1, x axis: column number and a colour parameter	A	B	N
17	256x256 pixels of the detector	C	C	Y	There appear to be 12 different signals which appear on the detector. These may be showing the paths of different particles, probably with different orientations and energies. The large circular signals may be from particles following paths roughly perpendicular to the image (into or out of the page), and the ones that appear as lines may show paths with a component in the plane of the screen.	C	D	N
18	Tracks of different types of particles.	D	D	Y	The long and narrow ones are electrons, muons, the short and wide ones are protons.	D	C	N
		Total number of statements		18		Total number of statements		18
		Compliant coding		13		Compliant coding		9
		Relative compliance		0,72		Relative compliance		0,50

1. What is plotted on the X-axis?	Category	Category_interrater	Compliance	2. What is plotted on the Y-axis?	Category	Category_interrater	Compliance
The column number of the pixel in the detector	B	B	Y	The row number of the pixel in the detector	B	B	Y
The horizontal location of the particle.	B	B	Y	The vertical location of the particle.	B	B	Y
a spectrum representing different energy levels	A	A	Y	position (where the particle was spotted)	B	B	Y
The column number (the horizontal coordinate of the detected particle)	B	B	Y	The row number (the vertical coordinates of the detected particle)	B	B	Y
the x coordinate of the particle	B	B	Y	the y coordinate of the particle	B	B	Y
x coordinate	B	A	N	y coordinate	B	A	N
Dimension like lenght	A	A	Y	Dimension like hight	A	A	Y
pixel	B	A	N	pixel	B	X	N
	M	M	Y		M	M	Y
Position in detector.	B	B	Y	Position in detector.	B	X	N
	M	M	Y		M	M	Y
X axis of the pixels	B	B	Y	Y axis of the pixels	B	B	Y
Displacement on the horizontal direction	B	B	Y	Displacement in the orthogonal direction to the x	B	B	Y
the luminosity of the particle	A	A	Y	the area of radiation	A	B	N
column number	B	A	N	antitude	A	A	Y
column number	B	A	N	the location of the particles	A	B	N
column number	B	A	N	It is not labelled. Perhaps it is row number?	E	E	Y
The ratio of the place in X.	B	A	N	The ratio of the place in Y.	B	A	N
	Total number of statements		18		**Total number of statements**		18
	Compliant coding		12		**Compliant coding**		12
	Relative compliance		0,67		**Relative compliance**		0,67

3. What does the colour scale at the bottom of the image represent?	Category	Category_interrater	Compliance	This image shows the screenshot of a measurement with an MX-10 pixel detector and Pixelman software. It represents particles and some of their properties. What can you tell about a particular particle?	Category	Category_interrater	Compliance
Energy of the particle the detector detected	C	C	Y	You can tell which direction it moved and how much energy it had	C	C	Y
The particle's energy.	C	C	Y	There is one particle in the top right that is particularly large and bright. This means it was a high energy particle. There are some lower energy particles with small trajectories in the middle. However, we can't really tell much about the trajectories because the detector only measures in two dimensions and particles move in three. We can tell the particles location and energy at a certain location and map a part of its trajectory.	C	D	N
different energy levels as well as the amount of particles (the more the particles, the lighter the color)	C	C	Y	from this image, I can guess that the lighter colored dots represent the alpha particle. however, different particles can also be present (eg beta, gamma, electrons, etc)	D	C	N
The amount of energy of the detected particles	C	C	Y	The track on the surface of the particle and the energy. If you only see a dot then the particle passed perpendicular to the surface.	D	D	Y
Their energy	C	C	Y	the one to the right at the centre has a higher energy than the others, while we can also see several more straight tracks that may be formed from charged particles coming in on askew	C	C	Y
The energy of particles which arrive.	C	C	Y	One particle was coming from aside	B	C	N
Scale showing the intensity of the particles.	B	C	N	One can see the intensity of the particle.	X	C	N
the number of particle	A	A	Y	its trajectory (into or along the detector)	B	C	N
	M	M	Y	Momentum, charge, energy	C	C	Y
Intensity.	B	C	N	Its energy	C	C	Y
	M	M	Y		M	M	Y
Density of particles	A	A	Y	The brighter one must be more energetic or bigger, or simply there must be a higher number	C	C	Y
It is the wavelength or frequency scale to which the brightness of the spots can be compared.	A	A	Y	From their displacement with respect to the orthonormal axes you can tell the relative mass of the various particles emitted since particles with higher inertia tend to undergo less displacement under the influence of the same force. The brighter spots are particles with a larger cluster while the colour can give an indication of the energy content of individual particles. regions with more blue or violet colour indicate particles with higher energy content than those which are reddish.	D	D	Y
it represents the strength of radiation	A	A	Y	there is a particle that shows strip tracks in a straight line.	A	C	N
	M	M	Y		M	M	Y
	A	M	N	the energy and the location in the space	C	B	N
Intensity of the signal	B	A	N	It can give information about the energy and path of the particle as it passed through the detector. The brighter spots should be due to particles which released more energy.	C	C	Y
The number of the tracks.	A	A	Y	The number of them, the weight and the charge of them.	C	A	N
	Total number of statements		18		Total number of statements		18
	Compliant coding		14		Compliant coding		10
	Relative compliance		0,78		Relative compliance		0,56

How do the particles which hit the detector chip differ from each other?	Category	Category_inte rrater	Compliance	How many particles hit the detector chip?	Category	Category_inte rrater	Compliance
They have varying energies and move in different directions. Some affect smaller areas of the detector than others.	X	C	N	About 12	C	A	N
They are traveling in different directions and have different energies and sizes.	X	C	N	14	C	A	N
particles vary from one another	X	C	N	this number is random; it changes every time. there can be no certain answer.	A	D	N
They have different energies and different tracks.	D	C	N	12	C	A	N
They differ in energy, mostly.	C	C	Y	12 or 13, depending on whether you count one of the linear tracks as one or two particles	C	C	Y
They differ from the energy	C	C	Y	12	C	A	N
Location, size, intensity	B	C	N	12	C	A	N
its size, trajectory, type of interaction	B	C	N	13	C	A	N
the the particles that hit the detector ship they will be detected and they will lose thier energy.	A	C	N	two	A	A	Y
Some are lighter and move faster (i.e. longer tracks), others are more massive and slower (brigher spots)	D	C	N	I count about 13.	C	A	N
	M	N	N		M	M	Y
Some are bigger, some are smaller	B	C	N	13	C	A	N
They differ in their mass, energy content and the number of particles in each cluster	C	C	Y	Can't be counted	A	A	Y
it can be seen by how they move after hit the detector chip.	C	C	Y	4	A	A	Y
size, brightness	A	A	Y	12	C	A	N
from energy and position in the space	X	X	Y	13	C	A	N
Energy and path	X	C	N	12	C	A	N
Because they have different energies and mass.	C	C	Y	12	C	A	N
	Total number of statements		18		**Total number of statements**		18
	Compliant coding		7		**Compliant coding**		5
	Relative compliance		0,39		**Relative compliance**		0,28
				Total relative compliance			**0,57**