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RESEARCH ARTICLE

"Holes in the atmosphere of the universe" - An empirical qualitative study on mental models of students regarding black holes

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Abstract

Black holes are both interesting to many students and are part of several school and university curricula. However, it has not yet been documented in detail what kind of mental models of black holes students have. As such, this study qualitatively reports on the mental models of 53 university students, most of them with a non-physics major. The gestalts of the mental models found were mostly disc shaped holes or black spheres, though some funnels or ellipsoids were also described by the students. As for the functionality, students associated attractive functions with a black hole, though more elaborate descriptions such as time dilation or gravitational lensing and Hawking radiation were also named. All university students described a kind of black hole creation, though not all knew about their change in time and only described growth or could not give founded reasons for the change. Several participants showed potential problems by seeing their mental model as a direct replica of reality and assumed that black holes were literally holes. Conceptual problems regarding things "behind" the holes were raised. The results show that many rudimentary properties of black holes are known to university students without explicit education in that field, and a surprising amount of physics quantities were associated with them, although things like density or mass were described inadequately in several cases. Though mental models of black holes were not documented this extensively before, parallels in thinking with mental models in other areas of physics could be observed, making the findings consistent with literature.

Keywords: Black holes; Mental models; University students; Astronomy; Empirical study

1 Background & Outline

Astronomy has not only been one of the oldest subjects in the field of science education, but also one of the most interesting and motivational for both boys and girls (e.g. Holstermann and Bögeholz (2007)). The literature on how learners understand and develop concepts of astronomical topics is in some cases extensive: A lot of empirical research has been done on the topic of the earth and its shape (e.g. Nussbaum and Novak (1976), Vosniadou (1992)), the origin of seasons (e.g. Baxter (1989)), the mechanics underlying the day and night cycle (e.g. Bryce and Blown (2016), Jones and Lynch (1987)) or lunar phases (e.g. Lightman and Sadler (1993)). These topics, however, are mostly taught in primary or lower secondary education and often do not extend farther. So, while the mental models and with that also possible cognitive developments have been extensively examined by empirical studies in these areas, other areas of astronomy lack thorough descriptions. One such topic is the black hole. To our knowledge, there is only a single study (Favia et al. (2014)) that addressed students' concepts and mental models of black holes in a rudimentary fashion. As they are of recent scientific interest, for example, in the context of gravitational waves (see Abbot et al. (2016), or the first "picture" of a black hole Castelvecchi (2019)) and typical astronomical objects discussed in school classes on a surface-level in the context of stars Salimpour et al. (2021). Understanding typical mental models of black holes will prove useful and important in addressing inadequacies as well as facilitate effective further cognitive development.

The aim of this paper is to collect qualitative data on the mental models that students have of black holes and to lay out foundations for further research into this topic. However, to achieve this, we first want to establish the construct of the *mental model* used in this paper (sec.2), as it has had a variety of different applications Horst (2016). Following this theoretical description, we will extensively report on the methods used to collect our qualitative data to be transparent with the way we conducted the research (sec.3). Next, we report on the data collected (sec. 4) and document the analysis of the data set extensively (sec.5). In the end, we will summarize the main findings (sect. 6) and finish with implications for teaching and further research (sec.7).

2 Theoretical Framing

Mental models are a construct of central importance in the context of conceptual development. In the current literature, the term *mental model* is not the only one used to describe mental states of cognition, though it has proven useful in the research on students' imaginations in scientific contexts (e.g. Ubben and Heusler (2019); Horst (2016); Ke et al. (2005); Harrison and Treagust (1996)). In the present study, the term 'mental model' will be used in the same way as in Ubben (2020), p. 14, freely translated:

> *Mental models are individual types of mental modal patterns that possess a functional potential and are based on outside experiences.*

The definition entails three main aspects of a mental model, which can be characterized as follows:

1. Mental models possess a modal component, a *gestalt*, a pattern that consists of one or more modal patterns. If one takes for example the mental model of a glass of water, the gestalt component might be a cylindrical see-through shape, which is cold when touched.

2. Mental models possess a *functional potential*, meaning that there are certain things that the entity modeled can potentially do or that it can potentially be used for. In the example of our glass of water, this could be falling down or quenching your thirst.

3. Mental models are held by individuals and rely in huge parts on outside experiences. This is in line with the constructivist view on conceptual learning. The mental model of the glass of water might have been firstly built by seeing a glass of water. This also makes the model malleable, it can grow and change from new experiences, though the older versions it has been built from may still pop up under stress (compare Shtulman and Valcarcel (2012)).

The above definition of a mental model has already proven useful in the examination of mental models of quantum physics and their cognitive development (Ubben and Bitzenbauer (2022); Ubben (2020); Ubben and Heusler (2019)). As such, we also choose this definition for a first thorough collection of gestalts and functionalities of mental models of black holes and thus will make our research question more precise. The aim of this study will not only be to document mental models, it will also extensively focus on their properties gestalt and functionality separately. As such, the main questions of the present study are:

1. What kind of gestalts do mental models of black holes have in non-astronomy educated university students?

2. What kind of functions are ascribed to mental models of black holes by non-astronomy educated university students?

By investigating these two questions, we hope to get a more differentiated understanding of mental models held by various learners. Based on these two, we conducted a qualitative study meant for collecting forms of these two aspects of mental models regarding black holes from various different learners without deeper astronomical background knowledge (i.e. not having taken a university course in astronomy). In addition to these aspects with regards to black holes, we also considered some possibly more complex versions of mental models of black holes: We additionally incorporated the creation and change of a black hole during its lifespan into our study to more elaborately talk about functionalities and gestalts in detail.

It may be not immediately clear as to why we want to document gestalts as well as functionalities, as a scientist might argue that only the functionality of a black hole and its interactions with its environment are of interest. In many other areas of physics education; however, it has been shown that inadequate images - and therefore gestalts - of mental models can lead to several problems in cognitive development: The gestalt can be associated to inadequate functionalities, making the mental model insufficient in certain situations. The most prominent example for this is Bohr's atomic model, where the orbits of electrons are imagined, giving the inadequate interpretation that electrons move on trajectories (e.g. Ke et al. (2005), Petri and Niedderer (1998), Bormann (1986)). Similar problems might arise from thinking about black holes as literal holes, giving rise to questions like "Where does the hole lead?" (this hypothesis is one confirmed for several students in this present study). Another problem might be that even if the image is considered to be physically appropriate, it can be misunderstood as a literal image of gestalt rather than a metaphoric image of functionality - a problem popping out in several areas of physics education such as mental models of light rays (Galili and Hazan, 2000), of fields (Törnquist et al., 1993) or of electron spin (Taber, 2004). These over-literal interpretation have been found to be huge conceptual obstacles in conceptual development (Ubben, 2020) and might lead to fragmented knowledge (e.g. "knowledge in pieces" by diSessa (1993)). Thus, not only problems with the functions that mental models have are relevant, but also problems with inadequate gestalts. Arising from this approach of examining mental models as consisting of gestalt and functionality, descriptions for their interpretations by learners have already proposed in other fields as well (Ubben, 2020). In the discussion, we will show that the results from this study are consistent with this approach as well (see sec. 6).

In the following section, we will document our methodology that was used for collecting possible gestalts and functionalities of the mental models of students in the context of black holes as well as the steps we made to ensure the scientific quality of the research.

3 Methods

As our aim was to collect first basic qualitative data on what mental models students hold of black holes, we decided to approach the matter by using open ended questions first. In regards to functionality, describing the functional properties of black holes is sufficient to gain a first impression on what learners know in this regard. A problem, however, is to get a clear idea about the gestalts that learners associate with black holes in open ended questions. Though it seems reasonable to assume that the gestalts of the mental models will now and then emerge from the written answers, this was not deemed suitable enough to get a clear picture of the gestalts. That is why a pre-study was conducted to extract the typical images learners have and work them as archetypes into the questionnaire as a closed question. As such, we will firstly document the pre-study and its outcomes and implications for the main study. Following will be a detailed description of the scientific criteria used to ensure resilience of the data.

During the conception, implementation and evaluation of the pre- and main study, we tried to meet the quality criteria of empirical studies as well as possible. In the later sections, we will justify individual activities for this purpose several times. Due to the qualitative nature of the main and the pre-study, "classical" quantitative criteria as reliability can not be fully applied like as in quantitative studies (e.g. Döring and Bortz (2006), pp. 195 and pp. 326). It might implicate partially unjustified expectations of this criteria because an identical(!) replication of the qualitative parts is not possible (e.g. Steinke (1999)): If the study would be repeated, the same people cannot be asked again and different people will provide different answers to the open-ended questions. Since the creation of categories depends on the answers to the open-ended questions, it could also be that this is not exactly replicated, although it is quite likely that very similar conclusions can be drawn from a different group of people. The same holds true for the distribution of the answers to the closed questions.

For this reason the criterion of intersubjective verifiability (as part of reliability) is replaced by *inter-subjective transparency* of the procedure and, above all, the conclusions drawn. In order to enable this *inter-subjective transparency*, in addition to the collection and evaluation process and the reasons for drawing conclusions, all quotations as evidence (recognizable by "#" e.g. "#42") and coding systems are disclosed.

Since the coding of categories depends to a large extent on the researchers themselves, the application of the codings used were inter-rated by a person not related to the study and Cohen's Kappa was calculated and estimated by Landis and Koch (1977) which we understand as the standard reference for judging this value, to ensure *qualitative reliability* of the analysis.

The methodology of generating the questions, where the criterion of validity becomes especially important, and the process of coding is described in the respective sections.

3.1 Pre-study

As we are focusing on the two components gestalt and functionality that a mental model has by the definition we use, the first step was to examine what gestalts students ascribe to black holes. The first step in documenting the kinds of mental models held in the context of black holes is to understand which gestalts are most associated with the term, naturally. This will be done in preparation of a broader main-survey which is documented in section 3.2.

To get a first impression of what different people imagine black holes to look like, a small study was conducted where we collected the drawings of black holes of several different people. This pre-study will be described in the following sections.

Methodology

The task was simply to draw a black hole from "front view" and "side view". This was to get a closer idea of how the participants imagined a black hole in three dimensions. The expected answer for a front view was just a circle filled with black, but the side view was hypothesized to entail several different shapes, as more than one different shapes from everyday life could look like a sphere from the top (e.g. cylinder, sphere).

The study was conducted with 25 participants. Of these, 8 were students of a physics education course at a university, the other 17 were layperson.

As there is no grounded theoretical basis to form codes deductively, inductive coding is used. Open (and not necessarily final) codes are first worked out "from the data". For example, if a black hole is shown as a circle, this would be the first code, that might be applied to other drawings but not to all, where then a new code has to be created. In several steps, codes are gradually formed, combined but also separated again if necessary, until a code system has been developed that can subjectively record the data sources with regard to the question to be examined. The data is then (again) completely encoded using the encoding system that has been developed (see Kuckartz (2010), pp.75).

Data analysis

As the drawings of black holes were not too complex, categories could be extracted inductively from the drawings that were summed up under three aspects: shape, design features, coloring. We inter-rated all categories with 20 % of the data and obtained a value of .95 for Cohen's Kappa, which is evaluated as "almost perfect" Landis and Koch (1977). In the following, these categories and sub-categories as well will be reported in greater detail. Prototypical images with numbers of similar drawings can be seen in Figure 1.

Shape of a black hole:

The shape of a black hole-category encapsulates the geometrical shape that the participants of the study ascribed to a black hole. As the task was to draw a black hole from the front and from the side, deductions regarding the three-dimensional shape imagined could be drawn. Taking the front view, only two subcategories were found that could describe all drawings: circle and oval. These categories were ascribed to the drawings when the black hole was drawn as a circular or oval shape respectively.

The shape that participants drew when asked for the side-view differed more, however. The shapes found here were a circle or an oval as well, but three other shapes were also found: several participants either drew just a line or a triangle-shaped depiction. In two cases, a rectangular shape was also drawn. Taking these together, four three-dimensional shapes for a black hole were extracted: a spherical shape (both views drawn as a circle, found in 4 cases), an ellipsoid shape (one view oval and one circular or both oval, found in 10 cases), a hole/funnel/cylindrical shape (circle or oval shape front, triangular/rectangular side view, found in 6 cases) or a disc-like shape (front view circular or oval, side-view, found in 4 cases). As the cylindrical shape was only drawn in two of the 25 cases.

Design features of a black hole

Apart from the different shape the learners' drew, they in part added several details to their drawings or used other design features. Six main features could be extracted from the 25 drawings. In several cases, the black hole was drawn together with several other *objects surrounding* it, mostly being dots or scribbles in the direct vicinity of the shape. In several instances, the participants drew *lines going away* from the black hole. In other cases, the black hole was *surrounded by one or more*

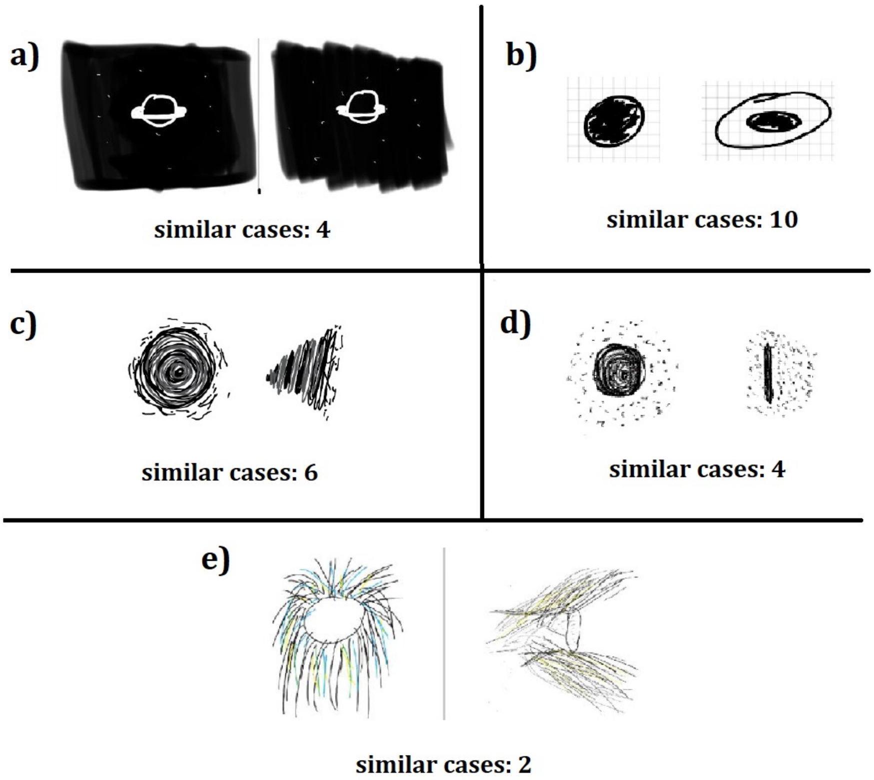

Figure 1. Several drawings of black holes by the participants. Regarding the side-view, four people drew a circle similar to a), ten drew an oval shape similar to b), six drew a funnel similar to c), four drew a line similar to d) and two a cylinder similar to e).

rings. Additionally, the way of drawing differed in three ways: In some cases, the black holes were *drawn with circular motions* (concluded from the lines in the drawings), in some cases the shape of the black hole was *colored in*, in some instances it was *not colored in*. Two of these categories could prove especially useful for determining the complexity of the mental model: The rings around the black hole and the objects around a black hole may indicate that at least the gestalt of an accretion disc may be present in the mental model.

Color of a black hole

The coloring of the black holes was another point that differed between the drawings. Regarding the shapes drawn, they were either *black* or *not colored* at all. Everything outside the shapes was either colored *red, blue, green, black* or *grey*. As these colors might have been limited by the pens or pencils used to draw the drawings, it appears to be not suitable to draw more conclusions than that the participants either think of a black hole's gestalt as being black or not conceptionalizable.

Implications for the main study

The most striking differences that were found in the different gestalts were the rough shapes of black holes in the mental models of the participants. Five main geometrical shapes were extracted that appeared to characterize the mental models. For the main study, four of the five shapes were used as possible answers to the question "5. What drawing fits your imagination of a black hole best?". The shapes used were a sphere, an ellipsoid, a disc and a funnel. The cylindrical shape was only drawn by two people and as the possible choices were supposed to be manageable, it was not incorporated. However, for people holding this gestalt, we had the option of "none of the drawings" (although later on, not a single person picked it). As the main way of drawing a black hole had been drawing it as a circle from the front, this option was the one always given for the same reasons. Additionally, the oval shapes might also have been because of lacking drawing skills, as drawing a perfect circle could prove difficult. In the end an item with five choices was generated from the pre-study, where four were the shapes and one was "none of above". The item can be seen in figure 2.

The other categories were not deemed suitable for item construction: The design features added by the participants differed widely and could not be distinctively incorporated into multiple choice items. The main idea transported by the added details seemed to have been one of an accretion disc, though this was a topic deemed to complex and might be looked at in future research. The coloring choices could not be directly traced back to the mental models, as it is unclear whether the colors were chosen for pragmatic reasons (color of pen used) or for conceptual reasons. It was, however, the case that every shape colored was colored in black. For that reason, we decided to color the shapes given black as well.

3.2 Main study

Based on the pre-study, one close-ended item for probing the possible gestalts a mental model might have was generated. However, as the present study is one of the first qualitative ones in this field, the aim was to document as many different mental models of black holes as possible. To achieve this goal and to document a preferably large amount of different conceptions, it was decided to develop and use additional open ended items together with the one derived from the pre-study. This enables a documentation of aspects of mental models that have not been known when the items were devised (see also Hollenberg (2016)). Interviews had at first been considered as well, but as the interaction between the study directors and the participants were tried to be kept minimal to eliminate possible influences and priming, this method was dismissed. By using an online

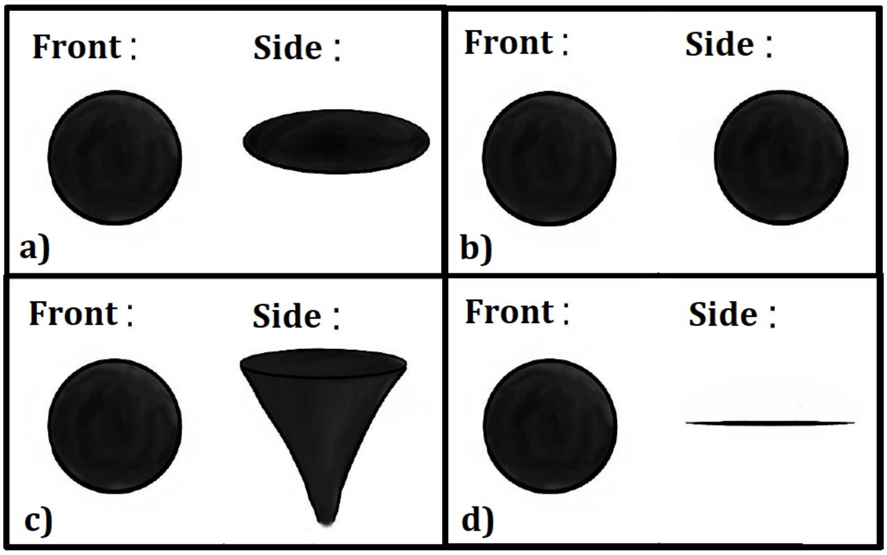

Figure 2. The possible choices given to the participants: a) an ellipsoid, b) a sphere, c) a funnel, d) a disc. Not in the figure is the choice "None of the above."

tool to present the open-ended items to the participants, it was possible to get a sufficient amount of participants, to circumvent the limitations posed by the covid-19 pandemic and to get data that was deemed satiated.

Conception and development of the survey

As the aim of the survey was to collect data on mental models of black holes, it was not relevant in what way these concepts were related to the current level of scientific knowledge. As such, the first part of the survey was to transparently inform the participants of the aims of the study as well as the fact that an honest answer was more useful for evaluation than a factually adequate one. Additionally, it was also emphasized that the black holes talked about in the survey were the ones found in space.

The items generated for probing the mental models were constructed adhering to several steps for ensuring the criteria of validity: Firstly, the questions were phrased in a way that no complicated sentence structures were used. For example, a question like "What is, in your opinion, the structure known as a black hole?" would be rephrased to "What is a black hole?". Additionally, the words used were chosen to be as basic and easily understandable as possible. Hence, in the previous example, the word *structure* was deleted as well. Lastly, suggestive questions like "In what way does a black hole change with time?" were avoided and instead more neutral questions like "Does a black hole change with time?" were chosen.

Explanation of the developed items

In the following paragraphs, the development of the several open-ended items will be documented. In table 1 an overview of the questions used will be given as well as what aspect of a mental model they were focusing on (but are not limited to).

The order of the questions as seen in table 1 was chosen deliberately. There are several things to keep in mind when ordering items (see e.g. Hollenberg (2016)). The questions are ordered from easy to hard and from concrete to abstract, starting with a general question of what a black hole is and ending with a complex question that asks the participant to explain a black hole to a child. The questions and their order can be seen in table 1. The first question (item 1, "What is a black hole?") was designed to get a first understanding of the students' mental model, to let them start thinking and give their initial thoughts. The second question (item 2, "Why are there black holes in space?") was designed to probe further elaborated aspects of the mental model and tried to address, whether the mental model was more or less dynamic and which additional functional and gestalt aspects might be linked to the mental model. Thirdly (item 3, "Describe the properties of a black hole") an item directed at functionality was given to the participants, which generally gathered the main functions coded in the mental model. The fourth question (item 4, "What has the name "black hole" to do with its properties?") addressed gestalt and functionality potentially to an equal degree. This is also a prime example of a question that can not be as thoroughly evaluated without the distinction between gestalt and functionality, as will also be shown by the answers of the participants. Item 5 was the multiple-choice item generated from the pre-study (item 5, "What drawing fits your imagination of a black hole best?") and mainly aimed at documenting the gestalts of mental models. Following, possible change of a black hole was addressed. In this item (item 6, "Do black holes change over time? Please justify your answer.), mainly the functional mechanisms of growth or loss were targeted, though of course gestalt aspects also could emerge here (e.g. growth of size vs. growth of gravitational attraction). The following question (item 7, "How can a black hole be discovered?") mainly addressed the functional aspects of discovering black holes indirectly through their interactions with other things, but answers like "looking at them" that are more gestalt oriented are also expected. Finally, the participants were asked to explain a black hole to a child (item 8, "How would you explain a black hole to a child?"). This item was devised and placed last to allow the participants to reflect upon and reiterate the most central aspects connected to their mental model.

To ensure that the criteria of validity used for developing the questions were applied properly, we let two students of physics education master classes answer the questions via a think-aloud-session (see e.g. Charters (2003), Ericsson and Simon (1984)). Additionally, we asked them for problems with understanding the questions. Before the session, the method of think-aloud was trained by solving a "Sudoku" (a mathematics puzzle) with this method. Both participants did not have major complaints regarding the questions and only minor comments were made. The corresponding phrases were adjusted together with the two participants to ensure that their remarks were dealt with appropriately. The answers and discussions with the two participants were audio-recorded with their permission and transcribed. The

Table 1. The items generated for probing students' mental models of black holes. In the first column, the questions are displayed (freely translated from German). In the second column, the topic is shown and in the last column the main aspect addressed is found.

Question	Topic	Main aspect addressed
1. What is a black hole?	Characteristics	Gestalt & Functionality
2. Why are there black holes in space?	Creation	Functionality
3. Describe the properties of black holes	Characteristics	Functionality
4. What has the name "black hole" to do with its properties?	Characteristics	Gestalt & Functionality
5. What drawing fits your imagination of a black hole best?	Characteristics	Gestalt
6. Do black holes change over time? Please justify your answer.	Change	Functionality
7. How can a black hole be discovered?	Characteristics	Functionality
8. How would you explain a black hole to a child?	Characteristics	Gestalt & Functionality

transcripts were analyzed by three different neutral people that were in no way part of the study. Their task was to judge whether the question was answered in a way that we intended to (by giving them answers generated by us that we deemed suitable) and thus to ensure a high validity of the questions. In the end, they agreed that all questions were answered in the way we expected them to be answered.

After this process of developing the items and ensuring that they work appropriately, the survey was deemed usable for the study. In the following section, the data from the study will be discussed in greater detail.

4 Data Description

The main study was conducted via an online survey and was taken by 52 university students (of which 41 completely answered all questions). It was decided to ask university students as the topic of black holes might not be known to younger people in sufficient enough detail for productive evaluation and because they already finished mandatory education. Of all the participants (21 male, 31 female, none diverse), only two had taken a university class in astronomy or astrophysics. This fact has to be kept in mind when later analysing the results, as the mental models collected are not those of people considered experts. Of the participants, six were studying physics, 18 studied other STEM sciences (like Chemistry), 25 studied a subject different from STEM sciences (like Law) and four chose not to indicate their university subject. Again, this distribution suggest that the participants are - save perhaps for the physics students - not experts regarding black holes. As the background information collected was to be kept at the minimum to not cause participants to abort answering the survey, no other questions in this directions were asked.

The data obtained from the open-ended questions is analyzed later in the article in sect 5. Therefore, only the quantitative data will be reported more extensively: From all the participants choosing the shape of a black hole that is closest to their mental image, none chose that they did not imagine a gestalt that was not presented in the possible drawn answers. Three people reported imagining a black ellipsoid, 13 imagined a black sphere, 14 imagined a funnel/hole and 20 imagined a black disc. The implications of this will be discussed later, though in light of the small amount of people answering, no generalizations as to ratios of the gestalts held will be made and only qualitative comparisons will be made.

5 Analysis

In this section, the process of data analysis will be documented, reported and discussed. There were two kinds of data gathered: Small amounts of quantitative data (from item 5, see fig 2), but mainly qualitative data. As the quantitative data is not suitable for the standard analysis methods due to its small sample size, the ratios are not anything to be generalizable to greater populations. However, some questions arise from them that will be discussed.

The qualitative data; however, was extensively analyzed via a qualitative content analysis by developing codes in regards to the factors gestalt and functionality as explained in the section of the pre-study. Technically every code was always assigned to a whole answer to one of the questions as a rule to make evaluation more resistant to technical mistakes while inter-rating. To ensure reliability, again, we chose to inter-rate 10% of the data set with a person not related to the project and calculated Cohen's Kappa for the categories. Its value was .88, which is to be deemed as "almost perfect" by Landis and Koch Landis and Koch (1977). As such, the reliability of the data analysis was ensured. The developed codes and their definition as well as some example statements are shown in the tables at the subsections as part of the criteria of *inter-subjective transparency*. All quality analyses were done by using MaxQDA Software (2019). All answers from the survey can be found in supplementary material 1.

5.1 Gestalt of a black hole

Apart from the quantitative results, aspects concerning the gestalt of black holes were also described in some surveys without being explicitly asked for. These were also categorized and are presented here. Together with the data from the pre-study, they will be used to answer Research Question 1. The aspects mentioned relate to the shape of the black hole itself, the shape of the black hole's environment, and the shape of the progenitor. The categories with examples can be seen in table 2. All student answers are freely translated from German. We tried to present the meaning of the answers and their phrasings as faithfully as possible in this paper, though there might be aspects lost in translation we are not aware of. To ensure that nothing was lost, we asked a native speaker in English to check the translations and iron out any problems. Still, it might be of merit to replicate the study in English to check for consistency of the answers.

A first observation to note from these categories, is that although it was said by some persons that a black hole is "a large area in the universe in which nothing exists" (#76), others were e.g. of the opinion "The black hole has a very high mass, concen-

Table 2. The categories coded in the context of visual gestalts of black holes. The categories are roughly coding the gestalt itself, the gestalt in the vicinity of the event horizon and the gestalt of stars that are the precursors of black holes. In the categories, *black hole* is abbreviated *BH* for simplicity's sake.

Category [number of codings]	Definition	Example statement
Gestalt of a BH - Color [14]	In the text passage, the "color" or how a BH appears to an observer is described (Black is coded as a color as well, although it technically is not).	"Light is so strongly attracted that it cannot get out, appears black." (79), "Black circle in the middle of a bright ring [...]" (#108)
Gestalt of a BH [5] - Shape	In the text passage, the shape of a BH is described.	"Round, like a vortex" (68), "A hole that swallows everything without [us] knowing where it ends up." (#41)
Gestalt of a BH [4] - spatial extent	In the text passage, the spatial extent of a BH is described.	"big, dark, dimensionless" (115), "The black hole has a very high mass, concentrated in a small volume." (#38)
Gestalt of a BH - no developed image [1]	In the text passage, no concrete visual image of a BH can be described.	"How a black hole looks, I really don't know at all, but I think it doesn't look like a black hole .... That's really all I think I know." (#36)
Gestalt of a BH surroundings (rings or objects) [5]	In the text passage, a ring or rim is that is visible around the black body or concrete objects (e.g. celestial bodies) described.	"You can see the border because of the rays of light that just managed to escape the black hole." (#87), "Stars that are sucked in orbit the black hole and the orbit keeps shrinking." (#127)
Gestalt of a BH precursor - star [22]	In the text passage, the a star is described as the precursor of a black hole, implying a gestalt of a star when thinking of a precursor.	"A collapsing star that attracts everything around it." (#107)
Observability of a BH [6] - telescope	In the text passage, it is said that a black hole can be seen through a telescope.	"With very powerful telescopes." (#110)
Observability of a BH [4] - seeing blackness	In the text passage, it is said that a black hole can be seen directly as a black or dark spot.	"Since it is dark, things may disappear in this direction." (#68)
Observability of a BH [2] - other	In the text passage, it is said that a black hole can be seen directly by another way.	"Probably very difficult. Maybe visually or with wave spectra from the precursor sun." (#72)
Label - color [22]	In the answer to (item 4) the label is ascribed to the color of the black hole.	"Look like black holes." (#66)
Label - shape [6]	In the answer to (item 4) the label is ascribed to the shape of the black hole.	"It is also round, so it resembles a hole." (#40)
Label - unspecific, not related to gestalt [3]	In the answer to (item 4) the labelling is not specifically explained or explicitly not connected to the gestalt.	"I don't know, but I think it has nothing to do with his black hole appearance." (#36)

trated in a small volume." (#38). The former idea was coded here in more answers with 6 namings compared to 4 of the latter. In addition, the "coloring" of the black hole has been discussed by 14 people. Here, all were unanimous: black holes "are black" (#61), "appear black" (#79) or it was said "I imagine it dark there, hence black" (#83). Also, the form of a black hole was described by some in passing remarks. In 5 cases, a black hole has actually been described as a hole in the literal sense: "A black hole is a small hole in space from which nothing can 'escape'." (#113). This can be taken as a reference to a replica conception (see Ubben (2020), Treagust et al. (2002)), i.e., a conception in which the black hole is understood as a replica of a black hole in the literal sense. However, it is interesting to note that all 4 participants who answered the question on shape in addition to this statement chose the sketch that depicts the black hole from the side as a line, although the funnel sketch would better fit the classical optical representation of a hole. One respondent also stated "I really don't know [what a black hole looks like] at all" (#36), so a not much developed conception of the shape was also found. The opposite case of an exclusively developed idea of the shape, however, also occurred: "From a physics perspective, I can't imagine anything like that. For me it looks like a black downward spiral." (#45).

In addition, there was evidence in 5 cases that the mental model of the participants, in terms of gestalt, included the environment of a black hole. This referred to objects in the vicinity of the black hole: "A very large number of stars around them as they have such a large pull." (#112) and/or a visible ring around it: "? black circle? in the middle of a bright ring" (#108). Lastly concerning the shape, it should also be mentioned that the black hole was often described as a "dead star" (i.e. #106), so that also the shape of the progenitor can be assumed to be integrated into the mental model of a black hole in regards of dynamic aspects. But this becomes even clearer in the section about the formation of black holes (see e.g. table 7).

Conclusions

The results evaluated here can be compared with those obtained from the pre-study (section 3.1) on gestalt. In doing this, several similarities but also some differences can be identified: First of all, the categories that appeared in general (sphere, ellipsoid, disc, funnel) can be noted as similarities. Additionally, in both studies, objects and rings in the surroundings of the black hole were sketched/described. Also, in the preliminary study, most of the sketches used a black color scheme. Due to the black representation also frequently described in this survey, this color choice can thus be interpreted as a decision of the participants in the preliminary study. It can also be deduced from the data obtained here that the four shapes of black holes, which were most frequently drawn in the preliminary study, are also accepted by the respondents of the online survey.

It is to be emphasised that no statements to the quantitative differences between the pre- and main-study can be made, though it might be useful to look at them qualitatively and using the quantitative differences to generate new hypotheses for future research: In the preliminary study, by far the largest proportion (10 out of 25) sketched the black hole from the side as an oval, while it was only rarely depicted as a line (4 out of 25). At first glance, this is not consistent with the results of the online survey, in which the largest proportion agreed with the side view of the black hole as a dash (20 out of 50) and very few (3 out of 50) agreed with the oval view. It has to be seen in further studies whether this discrepancy is due to the small sample size and thus attributable to statistical randomness or if there is another explanation. If one allows the interpretation of these representations as different perspectives of the black hole in the shape of a round disk, these results could in the future possibly be explained: In both studies the participants could have imagined the black hole as a disk. In the preliminary study, in which a black hole was to be drawn, many might have sketched the inclined perspective representation of a round disk (oval), since sketching a completely lateral representation (line) might have been perceived as too "extreme". In the online survey, the respondents who imagine the black hole as a round disk then saw both possible perspectives and decided in majority for the representation of the line, because this is exactly the lateral representation of a disk.

Twelve people (and thus half as many as those describing an indirect observability) presented in their remarks a possibility to observe black holes directly. In half of these cases the possibility of observation through a "telescope" (e.g. #101) was mentioned. Four participants described being able to observe them "due to the fact that everything is completely black at that point" (#38). The comments of 2 other respondents also suggested the idea of direct observability, but have been assigned to the other subcategory, such as "Probably very difficult. Maybe visually or with wave spectra from the precursor sun." (#72).

The notion of a black hole as a 'hole' identified here was also tested by Favia et al. with the statement "black holes are actual holes in space" (Favia et al. (2014), p. 39) and identified as a notion that is usually discarded during an astronomy course. This is still consistent, as only two participants did visit such a course. However, it remains an open question in this study how exactly the idea of a black hole as a hole fits together with the shape as a disk (lateral representation as a line). One explanation would be that the black hole is imagined as a hole in the wall between two rooms and not as, for example, a hole in the ground. However, this is very speculative and cannot be deduced from the evaluation of the written answers alone.

5.2 Functionality of a black hole

While the gestalts of the mental models being limited in number, we found quite plenty different functionalities ascribed to black holes. We decided to document the many differing aspects named by the students, although some might be seen as too thorough. For example, the way of *attraction* was differentiated into the categories of *attracting*, *pulling inside* and *absorbing*, as they describe similar but different ideas. Key statements and observations of these categories as well as noteworthy statements will be taken and discussed in the conclusion of this subsection.

Attractional functionalities

Attraction can be stated to be seen as a central property of a black hole, since this topic could be coded in 43 of the 53 surveys. Of these, in 25 cases there was talk of "great[er] gravity" (e.g. #101) or effects related to this type of attraction: "gravitational lensing" (e.g. #64). In the remaining surveys, the attraction was described rather unspecific and without a concrete cause. Here it was stated, for example, that it "swallowed a lot" (#113) or that it has "So strong [of an] attraction that everything that comes close is attracted and disappears" (#106) without this being further specified. The corresponding categories and key examples can bee seen in table 3.

In connection with attraction, 20 participants also described that what is attracted cannot escape the black hole. 7 respondents linked this to a certain radius and described e.g. " nothing within a certain radius around the center of mass can leave this radius" (#103) or mentioned the keywords "event horizon" (#87) or "Schwarzschild radius" (#92). The remaining 13 explained a little bit more unspecifically that nothing can escape from the (inside of the) black hole, without formulating a concrete border: "Light that enters a black hole does not come out there" (##40).

Furthermore, the attraction was described with different expressions, which were classified here into three different categories. The first category, "absorb," represents that what is attracted becomes a part of the black hole. Only statements containing this verb, such as "absorb all known matter" (e.g. #72) fall into this category. However, the occurrence of this category is hardly noteworthy with 4 cases. The category "suck in" describes the "taking in" of attracted matter. This included expressions such as "to suck up things" (e.g. #109) or "attracts and can swallow everything from matter" (e.g. #121) and others, which were used by over 30 respondents and thus the majority. The third category, "attract," included terms such as "a collapsing star that attracts everything around it" (#107), which describe being attracted to the hole. These were used by just under half as many respondents as formulations in the "suck in" category. However, it was not uncommon for respondents to switch flexibly between these terms, making the distinction perhaps a bit too specific. In further studies, it might be interesting to use these three terms as answers for a multiple choice question.

In addition, the respondents named different "things" that are (or can be) attracted by a black hole. The surveys could be coded into different categories (see table 3). Among these, 15 respondents named only material things that a black hole attracts, such as "They can suck in matter or swallow stars." (#110). Only very rarely, exclusively non-material things have been named: "Concentrated mass in space, the gravity of which is so great that light can no longer escape and the light is bent" (#108). Here it is conceivable that material things are not explicitly mentioned, but are nevertheless part of the mental model in connection with attraction. Most frequently (in 19 cases), it was assumed that a black hole attracts both material and non-material entities. This was either both explicitly mentioned: "attracts materials in the environment (by gravity?) [...] Light absorbing" (#120) or the phrases suggested that both matter and light were meant: "whereby everything is "sucked in", even light" (#63). In the last category, "nonspecific," respondents were coded which exclusively used statements such as " hole that devours everything without knowing where it ends up" (e.g. #41), without "everything" being specified in the course of the answer. Here, it could not be traced what was included in this label.

Conclusions

First of all, it is not surprising that references to the property of a attraction could be found in 43 of 53 surveys. On the other hand, however, it is interesting that this property was not mentioned at all in 10 surveys, although these cases are nevertheless in the minority. Some of these surveys consisted of answers to only a few questions, but even in surveys in which all questions were answered, this trait was not mentioned in some cases.

More than half of the answers that did mention an attraction, described it in the context of gravity. Here, however, it was not always clear whether the meaning of this terminology was known when it was used: There are several answers in which the participants mentioned gravity, but did not describe or even mention the mass of the black hole (as a cause for said gravity).

The description of an unspecific attraction was also assigned if only the property of the black hole to "swallow" things was described. However, whether this formulation actually describes a process of attraction could not always be judged. So, with such a description, it is also possible that the concept of a black hole that swallows things (e.g. the way a crocodile swallows its prey) could exist. As is known, the crocodile does not attract its prey first, but swallows it simply "on the spot", if it comes too close to it.

Furthermore, it is questionable how consciously the words were chosen to describe the attraction process. For example, although the distinction between the categories "attract", "suck in" and "absorb" seems to make sense in principle, the fact that in many interviews several of the categories could be assigned means that it can be assumed that the choice of terms does not always reflect the respondent's own conception. In addition, some of the answers in which the category "suck in" could be coded indicate a connection to the statement tested by Favia et al. "black holes are like huge vacuum cleaners, sucking things in" (Favia et al. (2014) p.39). An example of such a fit would be the statement, "a component of outer space into which things can be sucked " (#116).

In answers speaking of what is attracted to the black hole, four different categories were identified, but it can be assumed that upon further investigation there were essentially only two categories. On the one hand the attraction of only material and on the other hand the attraction of material and non-material. Answers from the category only non-material could probably be assigned to the latter and those from the category non-specific to one of the two categories. However, this conjecture would require further testing.

Functionalities directly related to physics

Apart from the previously presented property of attraction, still other properties were named, which can be assigned to common physical properties, which are presented in the following and can be seen in table 4. Frequently, physical properties were named to describe the "nature" of the black hole. In particular, the mass and density of a black hole were mentioned. The mass was described by 17 people. Of them, 2 were of the opinion the black hole is an infinitely heavy mass point (e.g. #62) and the rest attested a very high mass (e.g. #38) to it or that it is very heavy (e.g. #40). It is already clear in the first quotation that density was sometimes also described in connection with mass. Sometimes, however, only a large mass was attributed without addressing the density or the density was addressed without evaluating the "size" of the mass. 18 participants commented on the density of a black hole. Of these, however, 6 held the opinion that there was no density at all and described the black hole as "a space in which no matter exists." (#110) or "a large area in the universe in which nothing exists" (#76). However, this is followed by 8 respondents who attributed a "high density" (#108) to the black hole and 4 who even spoke of infinitely high density (e.g. #73). In addition, in connection with the mass and/or density, in 6 cases the strong space-time curvature (e.g. #62) was also stated (or not quite so formally: "Does space bend around them?" (#58)).

Furthermore, five respondents described an influence of the black hole on time. Three times it was said that "time passes more slowly in the vicinity of the black hole" (#101) and in three other cases time was reported to stand still: "I believe that when you find yourself in the black hole, you don't get older a day, time is practically not moving forward." (#36).

In addition, properties related to radiation/light were listed in the interviews. These often referred to the emission of radiation/light. Eight respondents described that black holes "emit certain radiation (Hawking radiation?)" (#43) and mostly mentioned Hawking radiation in this context, as here. Mostly (in 18 cases), however, it was emphasized that black holes do not emit radiation (by which mostly light is meant) by formulating this (rarely) directly (e.g. #88) or it was (more often) paraphrased by the attractive force and the impossibility of escape of light: "once it has crossed the event horizon, even light cannot escape." (#87). Partly, other "interactions" with light were described or indicated as well. There was e.g. the notion that the black hole is "light-impermeable" (#127) or "a mass in which there is no light and from which nothing comes out. " (#109). These expressions often also indicate misconceptions known from geometrical optics (see e.g. Hubber (2006)).

In some cases, the black hole was also associated with kinematic properties. Three respondents were of the opinion that black holes "may possibly rotate" (#103) or have an "angular momentum" (#44). In one statement it was even said they

Table 3. The categories coded in the context of attraction of black holes. In the categories, *black hole* is abbreviated *BH* for simplicity's sake.

Category [number of codings]	Definition	Example statement
Attraction with gravity given as the cause [25]	In the text passage, gravity is named as the reason for the attraction.	"the gravity of which is so great that light can no longer escape and the light is bent." (#108)
Attraction without cause given [18]	In the text passage, an attraction is described, but no cause is given.	"Everything that gets in there somehow disappears." (#113)
Kind of attraction - suck in [32]	In the text passage, the attraction is described as sucking things into the black hole.	"They can suck in matter and swallow up stars." (#110)
Kind of attraction - attract towards [15]	In the text passage, the attraction is described as just pulling towards the black hole.	"So a black hole attracts all matter." (#63)
Kind of attraction - absorb [4]	In the text passage, the attraction is described as sucking things into the black hole and absorbing them.	"black holes absorb light." (#107)
No escaping [20] - generally from within	In the text passage, it is indicated that nothing can escape from inside of a black hole.	"A black hole is a small hole in space from which nothing can "escape". " (#113)
No escaping - at set radius [7]	In the text passage, it is indicated that at a set radius, nothing can escape the black hole or that there is an event horizon or Schwarzschildradius.	"A black hole is an object whose mass is so great that even light cannot escape gravity within the event horizon." (#85)
Things attracted - immaterial and material things named [19]	In the text passage, it is stated that both immaterial and material things are attracted by a black hole. This was also coded when "everything" was said to be attracted and light was given as an example of that.	"An incredibly strong attraction that even attracts light." (#107)
Things attracted - only matter named [15]	In the text passage, it is only stated that material things are attracted by a black hole. This was also coded when "everything" was said to be attracted but only material examples were given.	"They can suck in matter or swallow stars." (#110)
Things attracted - only immaterial things named [2]	In the text passage, it is only stated that immaterial things are attracted by a black hole.	"Concentrated mass in space which has a gravity so high that light can not escape anymore." (#108)
Things attracted - not specified [6]	In the text passage, it is stated that "everything" is attracted without specifying details.	"So strong attraction that everything that comes close is attracted and disappears (?!)." (#106)

are "agile" (#116) and have accordingly some momentum. Furthermore, three physical properties, which were mentioned repeatedly (but only by two participants), were that black holes "condense masses very strongly" (#101) or are "electrically charged" (#41).

Conclusions

Often, the physical properties of mass and density were described. That in the context of the first property a large or infinite mass was often ascribed to the black hole is obvious, since many described the attraction as gravity and with it usually a large mass is associated. That so many also referred to the density of a black hole, on the other hand, is more surprising and might be interpreted as an indication of a more advanced mental model. However, the answers in which the black hole was described as "density-less" must also be taken into account. Such views were also generally held by students until they attended an astronomy course, as is consistent with the survey by Favia et al. The statements "black holes are empty space" (Favia et al. (2014), p.38) or "black holes do not have mass" (ibid., p.39) are similar to these. Favia et al. also tested the statement "we could travel through time in a black hole" (ibid., p.39), whose degree of retention was calculated to be slightly lower. Although this notion could not be found in the context of the investigation in this study, the influence of the black hole on time was also partly described here. The ideas described in this survey seem to be less "naive" than the idea of simple time travel, also hinting at more advanced models are the mentioned physical properties in connection with electromagnetic radiation, which were also coded quite often. Also, only one person stated that black holes could move, implying a more dynamic view of the black hole in space compared to other more static, localized views.

Other properties of a black hole

Apart from the physical properties outlined above, properties were also named which are not to be assigned to physical subject areas. Such properties are discussed in this section and can be seen in table 5.

Nine people asked held the view that black holes are "mysterious" (#116) or a "A space / area in space that has not yet been explored much" (#122). This great unknown is often related to the inside: "Unknown what happens to the matter that disappears in it." (#112) or the area "behind" the black hole: "Behind them there is something that may still be unknown " (#46). (Whereby one participant is also sure: "After that there is nothing at all" (#83)). The person also states that they are "a hole in the atmosphere of the universe." (#46), which almost sounds metaphorical.

In addition, eight participants stated that the black hole is capable of making things disappear: "Everything that gets in there somehow disappears" (#113).

Three other respondents, on the other hand, were of the opinion that the black hole "pulls in and destroys things in space" (#42) or even more detailed: "Decompose matter into its basic building blocks." (#72). Accordingly, the black hole has also been described as "dangerous" (#42) in one of these surveys.

Lastly, black holes were also described in one case each as "dimensionless" (#115) or it was said "They have negative mass (does it exist?)" (#110). These are concepts which sound like physics, but appear more as guesses.

Conclusions

The categories coded as "other properties", such as "mysterious" or "making things disappear", often sound like properties inspired by science fiction because of the formulations used here. They seem to be more guessing than knowing or not heavily founded on previous knowledge.

In this context, the latter property of making things disappear can also be seen as an indication that the notion of "consumption", as it occurs in other physics topics such as energy consumption (e.g. Opitz and Harms (2016)), is also found in the black hole topic area. Just as in electric-teaching the light bulb is often seen as a consumer of electricity, the black hole could be understood here as a consumer of the things that enter it without changing itself, being a functionality found before in other mental models.

(Indirect) Observability of a black hole

From the answers to the question about possibilities of the discovery of a black hole, the idea of visual observability is inferred. The evaluation of these answers resulted in the three categories listed in table 6. Seven answers, which were assigned to the category of "no idea", were placed into one subcategory each: Three of the respondents here represented that they "had no idea" (#121), while the answers of seven participants were classified as non-adequate and thus could not be assigned to any of the other categories. Examples are "by light" (#117) or "in space" (#108).

Twenty-four, and thus most of the answers, described an indirect observability of black holes, which can be understood as a kind of process oriented possibility of discovery. Among these, 13 addressed observability through interaction with celestial bodies, stating, for example, "possibly through the trajectories of planets, comets etc." (#40). Six persons described the effect of black holes as gravitational lenses and that these cause an observable effect: "No idea. Perhaps through corresponding refraction of light in the universe, from which one could deduce a correspondingly high gravity" (#43). Eleven people whose answers were assigned to the indirectly observable category mentioned other possibilities to infer black holes by indirect observation. These were partly (physically) very specific, like e.g. "gravitational waves and the orbit of stars." (#85) to large parts however also very unspecific, like e.g. "analysis of the particles / matter in the environment, gravity" (#120) or "spectroscopy" (#39).

Last, it should be noted that the categories "directly observable" (see sect. 5.1) and "indirectly observable" are not disjoint. This can be seen from the fact that three respondents named both ways to observe a black hole directly- and a black hole indirectly.

Conclusion

With regard to the evaluation of observability, the first thing to discuss is the classification in the category "no idea". People whose answers were classified in this category do not necessarily have a non-developed imagination. They could also have had problems formulating an answer or no motivation to formulate an answer. In addition, the decision to place an answer in the "no idea" category or one of the "other" category was sometimes difficult. For example, the answer "spectroscopy" (#39) was assigned to the subcategory "other" in the category "indirectly observable", although the answer is also in parts hazy and therefore inadequate and could have been guessed. On the other hand, the answer "With the help of light signals" (#71) was assigned to the category "no idea", although behind this could also be the idea of an indirect possibility of detection.

A crucial reason for the question about detection was the statement tested by Favia et al. "black holes can be seen visually, like seeing a star or planet." (Favia et al. (2014), p.39). Through the responses in the "directly observable" category, the occurrence of this notion was also confirmed, although it occurred more marginally than the "indirectly observable" category.

However, this quantitative difference should also be interpreted with caution, since the question did not directly ask whether one could visually see a black hole. Thus, some who

Table 4. The categories coded in the context of functionalities of black holes related to physics. In the categories, *black hole* is abbreviated *BH* for simplicity's sake.

Category [number of codings]	Definition	Example statement
Properties (physics) - density, high density [8]	In the text passage, the black hole is described as having high density.	"Very heavy Relatively small volume" (#40), "Concentrated mass in space." (#108)
Properties (physics) - density, no density [6]	In the text passage, the black hole is described as being something immaterial where nothing can exist.	"A space where no matter exists." (#110), "A huge area in space in which no light is reflected and there is nothing at all. So neither atoms nor smaller particles." (#69)
Properties (physics) - density, infinite density [4]	In the text passage, the black hole is described as having infinite density.	"Singularity. Infinite mass on an infinitely small point." (#62), "The entire mass of a black hole is concentrated in a single point with an infinitely high density [...]" (#73)
Properties (physics) - mass, high mass [15]	In the text passage, the black hole is described as having a high mass or weight.	"Very heavy." (#112)
Properties (physics) - mass, infinite mass [2]	In the text passage, the black hole is described as having an infinite mass or weight.	"Singularity. Infinite mass on an infinitely small point." (#62)
Properties (physics) - influence on time, slow down time [3]	In the text passage, the black hole is described as slowing down time.	"time passes more slowly around it." (#43)
Properties (physics) - influence on time, stop time [3]	In the text passage, the black hole is described as stopping time.	"[...] and time is stretched. [Time] stops at a certain distance from the center." (#60)
Properties (physics) - emit no radiation [18]	In the text passage, the black hole is described as emitting no radiation (me.g. light).	"No light comes out." (#43)
Properties (physics) - emit radiation [8]	In the text passage, the black hole is described as emitting radiation (e.g. Hawking radiation).	"may radiate (Hawking radiation)." (#103)
Properties (physics) - interaction with radiation [2]	In the text passage, the black hole is described as interacting with radiation in some way.	"It is also light-impermeable." (#127)
Properties (physics) - bending space-time [6]	In the text passage, the black hole is described as bending space-time. This code is also given when only spatial curvature is named.	"Does space bend around them? (#58), "Strong space-time curvature." (#62)
Properties (physics) - rotate [3]	In the text passage, the black hole is described as rotating or having angular momentum.	"may possibly rotate." (#103)
Properties (physics) - compress [2]	In the text passage, the black hole is described as being able to compress things.	"condense masses very strongly." (#101)
Properties (physics) - high energy [2]	In the text passage, the black hole is described as having high energy.	"a lot of energy in play." (#57)
Properties (physics) - electrically charged [2]	In the text passage, the black hole is described as having electric charge.	"Are electrically charged and large." (#41)
Properties (physics) - move [1]	In the text passage, the black hole is described as moving or having momentum.	"Agile." (#116)

Table 5. The categories coded in the context of functionality of black holes that address other properties. In the categories, *black hole* is abbreviated *BH* for simplicity's sake.

Category [number of codings]	Definition	Example statement
Other properties - mysterious inside/ behind [9]	In the text passage it is said that the inner part of a black hole is unknown or mysterious or that there is an unknown area "behind" the black hole.	"Unknown what happens to the matter that disappears in it." (#112), "Maybe because you know so little about it and you don't know what's behind it?" (#106), "A hole in the atmosphere of the universe." (#46)
Other properties - disappearance of matter [8]	In the text passage it is said or implied that a black hole vanishes things.	"Unknown what happens to the matter that disappears in it." (#112)
Other properties - destructive [3]	In the text passage it is said that a black hole is destructive.	"Something that pulls in things in space and destroys them." (#42)
Other properties - incomprehensible [2]	In the text passage properties of a black hole are described which are not comprehensible.	"They have negative mass (is that a thing?)." (#110)
Other properties - dangerous [1]	In the text passage it is said that a black hole is dangerous.	"dangerous." (#42)

Table 6. The categories coded in the context of functionality of black holes. In the categories, *black hole* is abbreviated *BH* for simplicity's sake.

Category [number of codings]	Definition	Example statement
Observability - surrounding celestial bodies [13]	In the text passage it is described that black holes can be observed indirectly via the surrounding celestial bodies.	"Influencing orbits." (#92), "And the objects that are drawn in are extremely hot, so it's pretty hot around the holes." (#38)
Observability - gravity lensing [6]	In the text passage it is described that black holes can be observed indirectly via gravity lensing.	"also by the curvature of light due to the gravitational force of the black hole." (#88), "Gravity lensing." (77)
Observability - other [11]	In the text passage regarding observability (item 7) it is described that a black hole can indirectly be observed but it does not fit into the other categories how this is done.	"gravity waves" (#85)
Observability - no idea [7]	In the text passage regarding observability (item 7) it is not described how a black hole can be discovered or the answer is confuse.	"At the end of space." (#83)
Label - functionality of black [23]	In the answer to (item 4) the label part "black" is ascribed to the similar function of black things (not emitting/reflecting radiation).	"There is no light! It is not clear to me which one it specifically affects, and whether there is no radiation at all?" (#84)
Label - functionality of a hole [12]	In the answer to (item 4) the label part "hole" is ascribed to the similar function of a real hole.	"Hole: something is sucked in like something falls into a hole." (#76)
Label - functionality of unknown [6]	In the answer to (item 4) the label is taken as a metaphor for insufficient knowledge (as it is metaphorical, this is understood as entailing functionality not gestalt).	"Because you don't know what's behind it." (#117)
Label - replica [3]	In the answer to (item 4) the label is taken as a literal description (also regarding gestalt, but the category is placed here for convenience sake).	"Maybe they are called holes because they suck up things and you used to think they were holes." (#109)

exclusively mentioned possibilities of indirect detection might still have the idea that a black hole is directly observable. In addition, it is conceivable that by asking such a question, for some participants the answer "telescope" seemed too trivial and for this reason they formulated an alternative answer in the area of indirect observability.

5.3 Labeling of a black hole

One of the hypotheses formed from research in other areas of mental models was that the label "black hole" might be taken literally and only ascribed to the gestalt Therefore, we divided the answers in this category into a gestalt oriented one (see table 2) and a functionally oriented one (see table 6). To the question "What does the name "black hole" have to do with the properties of a black hole?", three respondents answered very unspecifically, such as "Probably not much" (#46). Among the remaining participants, however, essentially four different strands of argumentation, could be identified.

In the fewest (three) cases, arguments were made in the sense of a gestalt replica idea, as was done, for example, in "with good telescopes you can see a hole in the middle." (115). Slightly more participants (six), on the other hand, were of the opinion that a black hole is so named "because you know so little about it" (#106), so that thus the unexplored/mysterious aspect was argued with, taking the name more metaphorically. Thirty-three and thus most of the respondents justified the origin of the name with the functionality of the black hole. This referred in 23 cases to (interactions with) light, which function as the reason for the designation "black". Examples are "they are black because they contain no light" (#109) or "attraction of photons and thus extinction of light" (#121). Twelve times, the functionality also referred to interactions with objects, which mostly justify the designation "hole": "Due to the property of "sucking in" matter, the term hole actually fits very well." (#110). Twenty-five and thus a somewhat fewer amount of participants argued with the shape of a black hole. In this context, 22 persons referred to the "color" justifying the naming, such as "black area in space" (#39) or "light entering a black hole does not come out of there and therefore it is perceived as black." (#40). The designation "hole" was justified by six interviewees with additionally using with the form, e.g., "it is also round, so it resembles a hole" (#40). This means, that there were many cases where both gestalt (black) and functionality (hole) were seen as name-givers.

Conclusions

Only a few of the responses evaluated here provided evidence that purely gestalt ideas result from the name "black hole". These were mainly answers in the category replica. Most, on the other hand, argued more from the (known) properties, and related these to the conceptualization, suggesting that the conception was not (primarily) influenced by the term. Despite this, the name hints at both functional as well as gestalt ideas, which make the black hole quite an interesting case of a label encompassing both these aspects, where one of the two (black) is taken literally (although this is of course reasonable).

5.4 How come black holes into being?

In this category, we coded the answers regarding the creation of black holes. As it was not easily possible to directly extract the gestalts that the students thought of when describing the creation of black holes, the answers given seem to lean more on a functional side. Nonetheless, it is likely that e.g. describing the death of a star is accompanied by the image sequence of a star dying in the students' mind. Further implications of this will be discussed in the outlook (sect. 6). The codings extracted from the data can be seen in table 7.

Inductively, the descriptions of the formation of black holes could be classified into three different superordinate categories.

Table 7. The categories coded in the context of creation of black holes. The answers are mainly from item 2, but in other categories the birth has been described as well.

Category [number of codings]	Definition	Example statement
From stars - process directed inwards [10]	In the text passage, a black hole creation process directed inwards from a star is described.	"Stars don't burn indefinitely, and when their time comes they die out or collapse." (#107)
From stars - process directed outwards [7]	In the text passage, a black hole creation process directed outwards from a star is described.	"Because stars explode." (#110)
From stars - unspecific [7]	In the text passage, a black hole creation process from a star is described in an unspecified way.	"They are created when stars decay." (#37)
Not from stars - process directed inwards [6]	In the text passage, a black hole creation process directed inwards in some way is described, but not related to a star.	"A mass attracts more and more mass because of gravity and at some point becomes so large that it represents a black hole." (#40)
Not from stars - process directed outwards [1]	In the text passage, a black hole creation process directed outwards in some way is described, but not related to a star.	"Because of the expansion of the universe over the years." (#76)
Not from stars - unspecific [5]	In the text passage, a black hole creation process is described, but not related to a star, in an unspecified way.	"I think black holes came into being at some point in evolution." (#116)
No idea [15]	In the text passage, a black hole creation process is not known.	"I don't know." (#106), "Still unexplained." (#44)
Other [1]	In the text passage, a black hole creation process ascribed to other means.	"They arise by chance, for example, when two very massive neutron stars collide." (#63)

These are primarily ideas about the formation that are related to stars or for which no connection to stars is recognizable.

However, in 15 cases, the responses were placed in the category indicating a non-developed idea about formation. These are going to be addressed here first. There were, again, two possible reasons for the placement in this category. The first reason occurred most frequently with 9 responses and is the more obvious one where a participant directly shared that they had no idea about this and did not know whether black holes were formed or not, such as "Good question, next question." (#36). The reason that the remaining six respondents were also placed in this category is because they did not provide an adequate answer to this question. Examples of such responses include "Far from the earth" (#46) or ""Swallow" matter" (#125), indicating confusion with the question, possibly misreading the item.

Of those who described a black hole formation, most (#22 students) thought that it was related to stars, so the process was in the context of a rather an unambiguous shape in these cases. However, this category could still be broken down into the three subcategories by the processes described there. With 10 cases, most frequently formation in connection with stars undergoing inwardly directed processes were described. Into this category fell processes such as collapsing or imploding of stars: e.g., "Because large dying suns collapse in a supernova" (#60) or "implosion of stars after they are burned out" (#92). Seven, and thus slightly fewer respondents, described outward processes such as the expansion or explosion of stars: e.g., "because stars explode?" (#75) or "suns that use up their fuel only expand and then eventually collapse and form a black hole. " (#72). As can be guessed from the last quotation, the first two categories are not necessarily disjunct from each other, because in two cases both an inward and an outward directed process were described. Lastly, there are 7 participants who described non-specific or non-directional formation processes related to stars, such as the more general "the black holes are created when stars die." (#84) or "because stars burn up at some point, an extremely strong pull is created " (#117).

"Only" 12 persons described formation processes which are in no explicit connection with stars. However, these could also be divided into the subcategories of inwardly directed, outwardly directed and unspecific processes. With 6 respondents, most of them named inwardly directed processes here as well. These all described processes in which matter "comes together". Mostly these were ideas like "a mass attracts more and more mass because of gravity and at some point becomes so large that it represents a black hole" (#40) but also a deviating variant is to be mentioned: "They arise by chance, for example, when two very massive neutron stars collide" (#63). Only one respondent named an outward directed process, namely the formation "because of the expansion of the universe over the years" (#76). Significantly more respondents described non-specific processes for the formation of black holes. The five responses placed in this category are very diverse. Examples are answers like "I don't quite understand the question. After all, you could just as easily ask why the earth exists. I think that black holes arose at some point in evolution." (#116) or "for me the black hole appears there somewhere and you don't know what's in it" (#71).

Conclusions

First of all, in the context of this discussion, it is necessary to address the answers that indicated an undeveloped idea of the formation of black holes. The answers of almost 1/3 of the respondents who answered this question have been put into this category. The fact that the conception about the origin goes rather into the depth of the mental model was recognized also before. However, the fact that such a large proportion has no (adequate) answer to this question is surprising. Even though these answers were justifiably placed in this category, it still cannot be clearly established that the surveyed students actually do not have a developed conception. It is also conceivable that the respondents could not or did not want to articulate themselves appropriately, for example. In addition, some responses indicated that "where" was read instead of "why" and therefore the question was not adequately answered with responses such as "at the end of space" (#83).

Nevertheless, based on this result, it can be concluded that the formation process gives rise to many interesting conceptions. Take, for example, notion that black holes form because of the expansion of the universe: This might indicate the concept that black holes form because there is "tension in the fabric of space-time, so it rips and leaves a hole" (which is our try to explain some of these answers like (#76) or (#71). It may also be that "they were always there" might have been a concept here that was not articulated, though this is conjecture.

Nevertheless, many more adequate answers to the question were also formulated of which the great majority had probably in mind the shape of a star in connection with the formation of black holes. However, one cannot be always sure that it is actually imagined, like it is described. In particular, when categorizing the outward processes in which an explosion was described, it is not always clear whether the respondents actually envisioned an explosion or rather described this based on an incorrect choice of words. In addition, in some of the answers, indications of a typical student conception could be found: Phrases like "suns that use up their fuel" (#72) or "stars that eventually burn up" (#117) point to the idea that "stars are burning gases", which is a consumption-idea as well (e.g. Opitz and Harms (2016), Favia et al. (2014)).

Lastly, the answers to formation unrelated to stars are to be discussed. The inward processes describing mass(es) coming together have not been known as an idea before, but are very logical in the argumentation: if a respondent imagines a black hole as a gravitational acting mass, but they have no connection to mental models of stars, this argumentation is very plausible. More difficult to interpret are those answers that were classified as "unspecific". Some of those answers also indicate a not (distinctly) developed idea. Two of these answers, however, point to ideas about the black hole, which were also tested by Favia et al. in the form of statements. Here it is to be mentioned "for me the black hole appears somewhere" (#71), which fits to the statement "black holes create themselves from nothing" (Favia et al. (2014), p.38), as well as the idea "perhaps also other dimensions that will be opened up" (#57) as a hint to the idea "black holes are doors to other dimensions" (ibid., p.39). However, these can be taken as exceptional cases in this work.

5.5 Do black holes change?

In this category, we coded the answers regarding the change of black holes. As with the formation of black holes, it was not easily possible to directly extract the gestalts that the students thought of when describing the change of black holes, the answers given seem to lean more on a functional side. Nonetheless, it is likely that e.g. describing the growth of a black hole is accompanied by the image sequence of a black hole expanding in the learners mind. Additionally, some statements refer directly to gestalts, which we indicated by a star in the category. Further implications of this will be discussed in the outlook (sect. 7). The codings extracted from the data can be seen in table 8.

The answers to the question about change could be deductively divided into the (disjunctive) categories "change" and "no change". However, there were also people who do not seem to have a developed idea about this process and answered, for example, "don't know" (#106). With 36 respondents, the vast majority of participants were of the opinion that a black hole changes with time. Only in six cases was the change of a black hole denied. If the change was denied, then in most cases no (comprehensible) reasons were given. Only in two answers, the statements pointed to a conception in which the black hole is understood as not too "saturating": "No, it just keeps sucking in matter, cannot be "saturated"" (#68). However, since otherwise (also due to the small number of cases) no further insights can be drawn from these answers, the ideas about change will be focused on in the following. In the case of ideas about change, three different categories of ideas could be inductively derived from the answers. Here, a distinction is made primarily between the categories of "growth" and "loss", which will be described in detail in a moment. With nine persons, however, a non-negligible part of the respondents also gave unspecific answers regarding a change. These were answers like "I could imagine that the black hole would change after an eternity, because it "swallowed" a lot and this has an impact on the changes." (#113) from which it is not clear how exactly it changes. Such unspecific answers could also be an indication of an undeveloped or underdeveloped idea about the temporal development of a black hole.

Twenty-three participants described the change of the black hole in connection with growth. With 18 cases, most of the participants were of the opinion that the black hole grows or becomes bigger: "Maybe it grows when it attracts mass" (#92) or "black holes can become bigger" (#44). Statements such as these were interpreted in terms of the increase in expansion as an aspect of the shape of a black hole. In addition, 5 people described an increase in mass "Since it "soaks up" everything from its environment, I would suspect that it will become more massive over time. That it changes its shape or that it has a limited lifespan I would deny (or in that sense it is not known to me otherwise)." (#87). Here, however, only statements were coded in which an increase in mass was explicitly mentioned and not only, as in the example above (#92), a growth due to attracted masses. In two interviews, moreover, an increase was described in terms of the strength of the black hole: "Maybe it pulls more and more mass into itself and becomes denser and stronger." (#60).

Eleven respondents described a decrease in relation to the development of a black hole, which is less than half the number who described an increase. Of these, six respondents thought that the decrease referred to the expansion of a black hole and that it would eventually become smaller and/or disappear, changing shape: "A black hole gets smaller and smaller until it no longer exists. Otherwise space would be full of black holes." (#39). Also, it was explained in three cases that the black hole loses mass: "I think that even a black hole can lose size over time, due to what is known as Hawking radiation ..." (#88) and likewise was described in three cases that the energy decreases: "Increases in mass from the environment. Loses energy from Hawking radiation" (#62).

In six cases, an increase and a decrease of the black hole was described together. If these participants also describe a "temporal change", often, on shorter term an increase and on longer term a decrease has been outlined: "It can grow as long as matter moves towards it, if matter is in a stable orbit, matter cannot fall into the black hole. Black holes disappear over very long periods of time as the Hawking radiation "tunnels out"" (#64).

Justifications for a change were also provided in most cases, of which the five most common categories are briefly presented here. In 17 cases, a change, mostly the increase, was justified by the "absorption function" of a black hole (of matter): "Yes it grows because it attracts more and more mass." (#40). Rarely (in 2 cases), the increase (of the expansion) has been focused on the expansion of the universe: "Yes, the universe is expanding, so are the holes" (#76). The decrease of the black hole was justified with 7 cases most frequently with the Hawking radiation: "Yes, due to the Hawking radiation, the black hole evaporates over time, reducing its mass" (#63). In addition, in 2 cases a collapse of the black hole was described in connection with the decrease: "I could imagine that at some point it would reach a size where it would become unstable and then collapse." (#38). Finally, mostly unspecific described changes were justified by 4 respondents by the fact that everything changes with time: "As everything changes over time, the black hole will also gradually change, progress, renew and maybe even dissolve" (#71).

Table 8. The categories coded in the context of change of black holes. The answers are mainly from item 6, but in other categories the change has been described as well. If gestalt properties are mainly addressed, the item will be marked by a star (*)

Category [number of codings]	Definition	Example statement
Growth - get bigger* [18]	In the text passage, a black hole is described as growing.	"They are getting bigger. The more they take, the bigger they get." (#107)
Growth - get stronger [2]	In the text passage, a black hole creation process ascribed to other means.	"Maybe it pulls more and more mass into itself and becomes denser and stronger." (#60)
Growth - get more mass [5]	In the text passage, a black hole is explicitly described as gaining mass.	"A black hole 'grows' when it can hold more mass. However, a black hole loses energy over billions of years because it radiates with Hawking radiation." (#85)
Loss - get smaller/disappear* [6]	In the text passage, a black hole is described as getting smaller and/or disappearing.	"I have no idea, but I can already imagine. Possibly disappear again." (#120)
Loss - lose energy [3]	In the text passage, a black hole is described as losing energy in any way.	"Loses energy from Hawking radiation." (#62)
Loss - lose mass [3]	In the text passage, a black hole is described as losing mass in any way.	"Yes, because it can gain in mass, for example, but - if I'm not mistaken - it can also lose weight with Hawking radiation." (#103)
Unspecific [9]	In the text passage, a black hole is described as changing, but not how in the context of growth or loss of properties.	"It may well be that it changes its shape by changing the various gravitational forces. Maybe electrical forces are also involved." (#121)
Reasons for change - intake [17]	In the text passage, a black hole is described as changing (mostly growth), because they have an "intake property".	"I could imagine that the black hole would change after an eternity, because it "swallowed" a lot and this has an impact on the changes. " (#113)
Reasons for change - Hawking-radiation [7]	In the text passage, a black hole is described as changing (loss), because they send out Hawking radiation.	"Loses energy through Hawking radiation." (#62)
Reasons for change - everything changes [4]	In the text passage, it is argued that black holes change because everything changes.	"I think so, since all things change over time and the black hole is subject to a lot of movement from attraction " (#116)
Reasons for change - universe expansion [2]	In the text passage, it is argued that black holes change (growth) because the universe expands.	"Yes, the universe is expanding, so are the holes." (#76)
Collapse [2]	In the text passage, it is argued that black holes change (loss) because they collapse.	"Yes, at some point it collapses or disappears." (#37)
No change [6]	In the text passage, it is said that black holes don't change.	"I don't think so, because it shouldn't grow due to what it absorbs and it arises and persists due to a one-time explosion / force" (#111)
No developed concept [5]	In the text passage, it is said that there is no idea on the topic.	"I don't know." (#37)

Conclusions

The results sketched above in the context of the change in black holes are not surprising in most cases. Here, it is understandable that some persons have not yet developed a mature idea about this aspect. That might be because the explanation and understanding of the change (as a dynamic process of growth and loss) of a black hole from a still immature mental model is quite complex (due to few points of contact in everyday life).

The answers in which a change was denied can also be understood on the basis of the existing literature. If a black hole does not change over time, then it cannot vanish in logical consequence. This also fits to the misconception of "black holes last forever", which was found to be quite resistant by Favia et al. (2014). However, whether the respondents actually assumed an infinite lifetime in the case of a negated change of the black hole cannot be understood at this point.

Moreover, the idea of those who exclusively described an increase of the black hole also fits to the aforementioned idea, since a finite lifetime would also have to be likely linked to a decrease. That this idea was so often co-described, is also comprehensible in view of the frequently mentioned property of attraction and was therefore also mostly justified with the "absorption function". Also, Favia et al. tested to the category of exclusive increase a statement which was still affirmed on average even partly after an astronomy course: "black holes get bigger forever and nothing can stop them from doing so" (Favia et al. (2014), p.39). Since the English word 'big' can be translated as both 'big', 'strong' and 'heavy', it is not clear in this case to which aspect of the increase this notion refers. In German, the language in which the study was conducted, these aspects can be linguistically distinguished from each other, which is why this was done. Thereby the expressions 'becomes bigger' or 'grows' were assigned to an increase of the expansion of the black hole. However, it cannot always be clearly interpreted whether the participants actually had the idea that the black hole is expanding with these formulations. This is also the case when using such expressions in quotation marks as: "A black hole 'grows' when it can hold more mass" (#85), which are then not unambiguous.

On the other hand, more surprising and not matching with the current literature are the answers that listed just a decrease or both an increase and decrease (and thus a more complex mental model) as change. In three cases, in which only a decrease was described, again (as with the property of "disappearance") evidence for a consumption idea was found, since, as in the following example, no reason for the decrease was given: "I have no idea, but I can already imagine. Possibly disappear again." (#120). Interesting is also the reasoning of the expansion of a black hole with the expansion of the universe, as if the black hole was a painted (instead of glued) circle on a balloon, which is blown up. It also fits to this interpretation that the black hole in both cases was also described as empty space in space and not as a celestial body.

Finally, the reasoning of the change by the fact that everything changes is to be emphasized. This reasoning is to be understood as a logical reference of the experiences made in the everyday life to the "unknown" object of a black hole. In this interpretation, the explanation "Everything changes" fits to the theory "knowledge in pieces" of diSessa diSessa (1993), from whose point of view this explanation could be interpreted as one of the p-Prims postulated there, since these are simple building blocks of cognition.

5.6 Central properties of a black hole

To get a rough idea which of the properties of a black hole are deemed as central, we asked the participants to tell us how they would explain a black hole to a child. Through this final question, we hoped for summaries of the central points that the participants associated and deemed important in the context of black holes. The results can be seen in table 9.

When asked to explain a black hole to an elementary school child, six subjects said they did not want to formulate an explanation, such as "I wouldn't try." (#41). The remaining explanations were evaluated for content in such a way that the explanations were assigned to the properties explained in them as categories. These were then interpreted as characteristics that are perceived as central by the explainer.

The trait of attraction, by a wide margin over the other traits, was explained most frequently by a total of 22 respondents. An exemplary explanation is "something that pulls in and destroys things in space " (#42). In connection with attraction, analogies were also mentioned in some cases, such as "vacuum cleaner" (#101), "cyclone" (#116), "magnet" (#120), or "drain" (#62). There were 12 explanations that used a literal hole-shape to explain a black hole, where the hole was a "rift" (#111), a "cyclone" (#116) or a "hole" (#72). The third place in this ranking goes to the explanation using the (high) weight of a black hole, such as "area in the universe that is very heavy and very strong" (#44), with 11 cases. Here, also a comparison to the earth was partly mentioned: " Just like the earth pulls you to the ground" (#40). This is followed in number of occurrences by the explanation via an interaction of the black hole with light, which could be found in 9 explanations, as for example in "it is black because it swallows up all the light and thus everything becomes dark" (#121). In seven answers the property of the black hole to hold onto attracted objects was explained. An example of this is "and it even attracts the sun's rays and never lets them go away" (#40). Analogies were also described in connection with this property, such as a "trash can from space that cannot be emptied" (#64) or a "big hole in the ground" (#43). Six respondents also referred to the density of a black hole in their explanations, half of them explaining a non-existent density and the other half explaining the large density of a black hole: "A huge nothing" (#58) vs. "and when you put so much mass together, and even squeeze a lot of it together, then the attraction is huge" (#77). Making up the rear is the statement that the black hole "can make things like stars disappear within" (e.g. #115), which was formulated in only four surveys.

Conclusions

The explanations for an elementary school child including the characteristic of attraction is consistent with the answers to previous questions. This speaks for the fact that the characteristics listed here, may indeed be seen as the most central (considering our sample). Also, the second place took a gestalt-oriented literal explanation of a hole in space, which also shows that a gestalt was held in comparably high regard in an explanation.
However, these conclusions are also only valid with restrictions: It is possible that some central aspects were deemed too complicated for primary students, such as the curvature of space-time around a black hole or Hawking radiation. This could explain, for example, why a high density was used less frequently in the explanations, since the construct of density is difficult to grasp even for older students (see e.g. Xu and Clarke (2012)).

6 Discussion

This study qualitatively reports on the mental models of 53 university students of which most do not have a background in physics. The gestalts of the mental models found were mostly disc shaped holes or black spheres, though some funnels or ellipsoids were also described by the students. As this black sphere is the gestalt most closely representing the real world-entity, many

Table 9. The categories coded in the context of important aspects of black holes. The answers are mainly from item 8, but in other categories the change has been described as well. If gestalt properties are mainly addressed, the item will be marked by a star (*)

Category [number of codings]	Definition	Example statement
Attraction [22]	It is explained that black holes attract things in some way.	"This point attracts all things around you, comets, planets and also light." (#38)
Literal hole* [12]	In the text passage, a black hole is described as a literal hole, tear or whirlpool.	"A hole in which everything falls into what is in the area and it does not come out again." (#127), "A kind of cyclone that is very far away and can attract things." (#116)
Weight [11]	In the text passage, a black hole is described as having weight.	"A trash can from space that cannot be emptied and which is very heavy." (#64)
Interacts with light [9]	In the text passage, a black hole is described as interacting with light.	"Then it can even happen that even the light cannot go away." (#77)
Holding tight [7]	In the text passage, a black hole is described as not letting things escape anymore.	"And it even attracts the sun's rays and never lets them go away." (#40)
Density [5]	In the text passage, a black hole is described as having some kind of density.	"That inner part is still super heavy and squeezed together to a very small point. " (#38)
Make things disappear [4]	In the text passage, a black hole is described as making things disappear.	"A rift in space in which everything disappears that is drawn into it." (#111)
Other [2]	In the text passage, a black hole is described as having other properties than those above.	"That is a big nothing, the universe is over there" (#83), "And they are so great that they can even stretch the time." (#60)
No explanation [6]	In the text passage, a black hole is not explained.	"I wouldn't do that until I had a little more knowledge of the subject." (#36)

inadequate or not thought through gestalts were extracted. Predictably, we found that several students associate a literal hole structure to the black hole.

As for the functionality, students associated attractive functions with a black hole, though more elaborate descriptions such as time dilation or gravity lensing and Hawking radiation were also named. These, however, were only given on a rudimentary basis in general and only very few students explained these more advanced functionalities adequately (i.e. not just naming them).

On one hand, in open-ended questions, only the statements written down can be evaluated, possibly missing out on other aspects of the mental models at hand. There were statements that indicated that the persons asked had not thought about questions before, like "I do not know.", but we cannot for sure say whether there were aspects of the students' mental models we did not capture with our method. On the other hand, we reached a point of saturation with the answers given, implying that in the context of this study, we got all or almost all possible answers and thus (almost) all possible gestalts and functionalities associated with the mental model of a black hole.

All in all, comparably few adequate mental models have been documented. There were aspects of both gestalt and functionality that were not developed sufficiently and several common findings from mental models in other areas of research have been found. With black holes, understanding the mental models as direct replicas of reality was seen in several participants, which is consistent with findings from other areas of (physics) education (e.g. Ubben (2020), Pluta and Duncan (2011), Grosslight et al. (1991), Treagust et al. (2002)). Additionally, the notion of "consumption" which has been found in several cases in the context of energy Opitz and Harms (2016) was found as well - participants thought that black holes just make matter disappear.

Also, when looking at more elaborate mental models such as those incorporating birth, change or detection, many were only developed little. The image of a star is likely to be closely associated to black holes and their birth, showing that at least in some cases, these two mental models might be connected in cognition. Also, several participants did not think that black holes changed over time, which points towards a more or less static mental model (though functions regarding attraction had been named). It is also interesting that the detection methods for black holes were in part "looking through a telescope", which might be related to recent news of a "first picture of a black hole".

Although only aspects of gestalt and functionality have been categorized in the present study, in some cases the interpretations of these two aspects by the participants shines through. When comparing several statements to recent research in other areas of physics education (Ubben (2020), Ubben and Heusler (2019)), several types of understanding can also be seen in the context of black holes in rough shapes, which are consistent with previous research in mental models of quantum physics. The types are characterized by two scales, one expressing how much the gestalt of the mental model is seen as adequate when compared to the real thing (*fidelity of gestalt*, FG) and one expressing how much the functions of the mental model are adequate in describing what the real thing does (*functional fidelity*, FF). As these were purely empirical descriptions of mental models in quantum physics, it was only a hypothesis that one could find these ways of understanding in other areas of mental models as well.

In the context of black holes, we found several statements where this model is also fitting, giving first direct qualitatively empirical support for it being more generally applicable: There are people, who do not have any idea, what a black hole does and what it looks like. One such case were the statements from (#36), who described not knowing how black holes looked like and only vaguely recounts effects on time (which are incorrect). As such, their mental model does not show to have either high fidelity in gestalt or functional fidelity. There are people that only have images of how black holes look in their minds. One such person would be (#61), who only continuously described black holes as "black", not indicating knowing any functionality, making the functional fidelity quite low and the fidelity of gestalt rather high (even if only being a rough gestalt from the descriptions). There are also people having an understanding of their mental model which corresponds to a dual type understanding: Statements like "A hole in the sky that cannot be seen with the naked eye and is capable of making things like stars disappear. It also absorbs parts of space debris" (#115), can be roughly placed

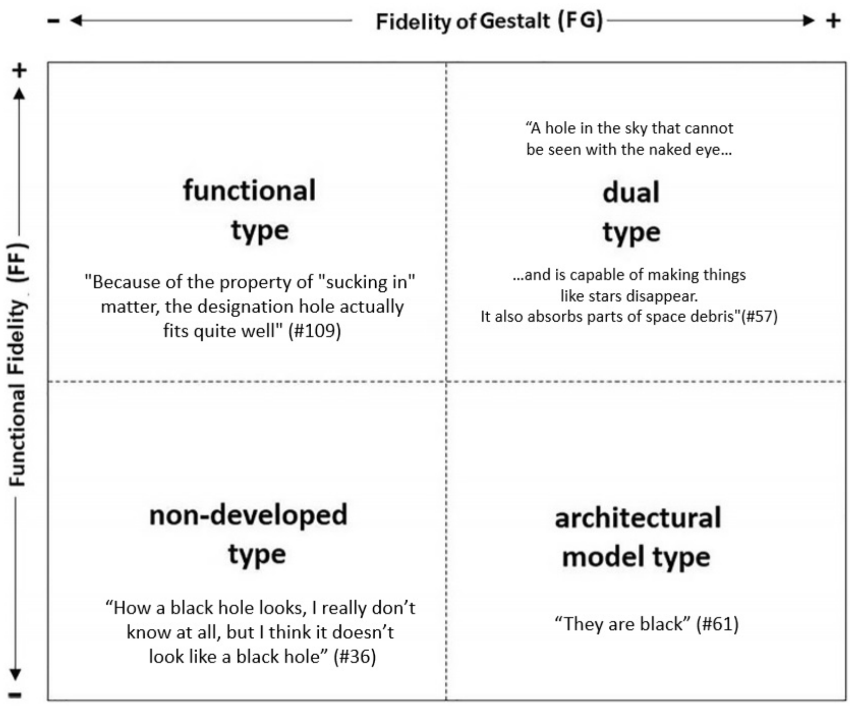

Figure 3. The types of understanding adapted from Ubben and Heusler (2019). Exemplary answers are placed in the categories of understanding most suitable for the statements.

into this category, as the gestalt "hole" and the functionality "swallows" are both seen and talked about as if they were like that in reality. In these cases, the students seem to not fully appreciate the model character of mental models. Finally, there are people who solely focus on the functionality of black holes as well: "Because of the property of "sucking in" matter, the designation hole actually fits quite well" (#109). This statement solely relies on the functional aspect of a black hole and thus only implies high functional fidelity and low fidelity of gestalt (as the "hole" name is seen as abstract and thus functional).

These statements encapsulate notions that align with the types of understanding previously extracted in the context of mental models of atoms Ubben and Heusler (2019). The exemplary remarks for all four types of understanding can be seen in figure 3. Though comparable types of understanding have been isolated in the statements of the participants, more research in this direction is needed to further confirm these observations and perhaps even show typical patterns of conceptual development. Perhaps even self-reflective surveys regarding these types might give new insights, as will be tested elsewhere.

7 Potential implications

The documented gestalts and functionalities found in this study are extensive and diverse. Though not much has been said about their adequacy, there were some mental models that had an inadequate gestalt (e.g. literal hole), inadequate functionalities (black holes have no mass) or both. Several future research could be built on these findings. Firstly, the plethora of inadequate aspects in mental model might provide fruitful grounds for developing distractors for a concept inventory test. As previously mentioned, the only items we are aware of are by Favia et al. (2014) and only have options to agree and disagree (and all being labelled as misconceptions by them). Thus, the generation of multiple choice questions from this study and the application to conceptual evaluations of learners is the next logical step based on the data in this study, which will be reported on elsewhere.

Secondly, this study lays the foundation for further examinations of mental models in the context of black holes in general. The method we used proved to generate the much needed knowledge for future research.This means making a distinction between answers regarding gestalt and functionality did not only lead to the documentation of new mental models, it also emphasized that these to factors seem to be both of critical importance in mental model research and should always be kept in mind in our opinion: Take for example item 4, where this approach made a clean distinction between the answers possible and hinted at misconceptions with regards to overly literal interpretations and more. Contrary to other areas of physics (e.g. quantum physics or electrodynamics), this way of interpreting might be more easily addressed and not pose a great obstacle, though this conjecture would have to be tested in further research, such as interview studies, where participants who think of the gestalt of a hole are asked to apply this gestalt to several situations (e.g. flying with a spaceship to the structure from directly below or what is "behind") and evaluate their consistency.

Additionally, the framework of using gestalt and functionality as the two main factors in research on mental models proved useful. As this was the first study explicitly incorporating these two aspects into the structure and evaluation of mental models, it stands to question whether this approach was useful. In our opinion, it aided in the documentation and provided us with not only many new aspects of mental models of black holes but also almost naturally triggered statements that heavily indicated different kinds of interpretation regarding gestalt and functionality. This supports the types of understanding previously extracted by Ubben and Heusler (2019) in quantum physics and hints at them being a suitable model for describing understanding (of mental models) as was previously suggested Ubben (2020).

Based on the research presented here, we hope to provide a foundation for studying mental models of black holes and their interpretation as well as other astrophysical concepts (such as the Big Bang, which will be shown elsewhere). By doing this, we also hope to better spot inadequate aspects of mental models and aid facilitating conceptual change or enhancement by addressing them directly, so that students understand black holes as more elaborate than simply "holes in the atmosphere of the universe".

8 Availability of supporting data and materials

The data set of the answers can be obtained by contacting the authors when desired.

9 Declarations

The authors declare that they have no conflict of interest.

9.1 Ethical Approval (optional)

For this type of study, no formal consent was required.

9.2 Consent for publication

The data provided in this survey was collected completely anonymously and can not be traced back to the participants. The participants were informed about this at the beginning about the study.

9.3 Competing Interests

The authors declare that they have no competing interests

9.4 Funding

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9.5 Authors' Contributions

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References

Abbot, B., Abbott, R., Abbott, T., R., A. M., and et al. (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical Review Letters*, 061102-1. https://doi.org/10.1103/PhysRevLett.116.061102.

Baxter, J. (1989). Children's understanding of familiar astronomical events. *International Journal of Science Education*, 11:502–513. https://doi.org/10.1080/0950069890110503.

Bormann, M. (1986). Das Schülervorverständnis zu Elektronen. *Vortraege der DPG in Gießen 1986*, 1:502–513.

Bryce, T. G. K. and Blown, E. J. (2016). Manipulating Models and Grasping the Ideas They Represent. *Science and Education*, 25:47–93. https://doi.org/10.1007/s11191-015-9802-6.

Castelvecchi, D. (2019). Black hole pictured for first time — in spectacular detail. *Nature*, 568:284–285. https://www.nature.com/articles/d41586-019-01155-0.

Charters, E. (2003). The Use of Think-aloud Methods in Qualitative Research: An Introduction to Think-aloud Methods. *Brock Education*, 12:68–82. https://doi.org/10.26522/BROCKED.V12I2.38.

diSessa, A. (1993). Towards an epistemology of physics. *Cognition and Instruction*, 10:105—-225. https://www.jstor.org/stable/3233725.

Döring, N. and Bortz, J. (2006). *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften*. Springer, Berlin/Heidelberg.

Ericsson, K. A. and Simon, H. A. (1984). *Protocol analysis: Verbal reports as data.* The MIT Press, Cambridge.

Favia, A., Comins, N. F., Thorpe, G. L., and Batuski, D. J. (2014). A direct examination of college student misconceptions in astronomy: a new instrument. *Journal and Review of Astronomy Education and Outreach*, 1:A21–A39.

Galili, I. and Hazan, A. (2000). Learners' knowledge in optics: interpretation, structure and analysis. *International Journal of Science Education*, 22:57–88. https://doi.org/10.1080/095006900290000.

Grosslight, L., Unger, C., Jay, E., and Smith, C. (1991). Understanding models and their use in science: conceptions of middle and high school students and experts. *Journal of Research in Science Teaching*, 28:799–822. https://doi.org/10.1002/tea.3660280907.

Harrison, A., G. and Treagust, D. F. (1996). Secondary Students' Mental Models of Atoms and Molecules: Implications for Teaching Chemistry. *Science Education*, 80:509–534. https://doi.org/10.1002/(SICI)1098-237X(199609)80:5<509::AID-SCE2>3.0.CO;2-F.

Hollenberg, S. (2016). *Fragebögen: Fundierte Konstruktion, sachgerechte Anwendung und aussagekräftige Auswertung*. Springer VS, Wiesbaden.

Holstermann, N. and Bögeholz, S. (2007). Interesse von Jungen und Mädchen an naturwissenschaftlichen Themen am Ende der Sekundarstufe I - Gender-Specific Interests of Adolescent Learners in Science Topics. *Zeitschrift für Didaktik der Naturwissenschaften*, 13:71–86.

Horst, S. (2016). *Cognitive Pluralism*. The MIT Press, Cambridge.

Hubber, P. (2006). Year 12 students' mental models of the nature of light. *Research in Science Education*, 36:419–439. https://doi.org/10.1007/s11165-006-9013-x.

Jones, B. and Lynch, P. (1987). Children's conceptions of the earth, sun and moon. *International Journal of Science Education*, 9:43–53. https://doi.org/10.1080/0950069870090106.

Ke, J. L., Monk, M., and Duschl, R. (2005). Learning introductory quantum physics: sensori-motor experiences and mental models. *International Journal of Science Education*, 27:571–594. https://doi.org/10.1080/09500690500186485.

Kuckartz, U. (2010). *Qualitative Inhaltsanalyse. Methoden, Praxis, Computerunterstützung*. Beltz Juventa, Weinheim.

Landis, J. R. and Koch, G. C. (1977). The Measurement of Observer Agreement for Categorical Data. *Biometrics*, 33:159–174. https://doi.org/10.2307/2529310.

Lightman, A. and Sadler, P. (1993). Teacher predictions versus actual student gains. *The Physics Teacher*, 31:162–167. https://doi.org/10.1119/1.2343698.

Nussbaum, J. and Novak, J. D. (1976). An Assessment of Children's Concepts of the Earth Utilizing Structured Interviews. *Science Education*, 60:535–550. https://doi.org/10.1002/

sce.3730600414.
Opitz, S.; Blankenstein, A. and Harms, U. (2016). Student conceptions about energy in biological contexts. *Journal of Biological Education*, 51:427–440. https://doi.org/10.1080/00219266.2016.1257504.
Petri, J. and Niedderer, H. (1998). A learning pathway in high-school level quantum atomic physics. *International Journal of Science Education*, 20:1075—-1088. https://doi.org/10.1080/0950069980200905.
Pluta, W. J.; Chinn, C. and Duncan, G. R. (2011). Learners' Epistemic Criteria for Good Scientific Models. *Journal of Research in Science Teaching*, 48:486–511. https://doi.org/10.1002/tea.20415.
Salimpour, S., Bartlett, S., Fitzgerald, M. T., McKinnon, D. H., Cutts, K. R., James, C. R., Miller, S., Danaia, L., Hollow, R. P., Cabezon, S., Faye, M., Tomita, A., Max, C., de Korte, M., Baudouin, C., Birkenbauma, D., Kallery, M., Anjos, S., Wu, Q., Chu, H.-e., Slater, E., and Ortiz-Gil, A. (2021). The gateway science: a review of astronomy in the oecd school curricula, including china and south africa. *Research in Science Education*, 51(4):975–996. https://doi.org/10.1007/s11165-020-09922-0.
Shtulman, A. and Valcarcel, J. (2012). Scientific knowledge suppresses but does not supplant earlier intuitions. *Cognition*, 124:209–215. https://doi.org/10.1016/j.cognition.2012.04.005.
Software, V. (2019). *MAXQDA 2020 [computer software]*. VERBI Software. Available from maxqda.com, Berlin.
Steinke, I. (1999). *Kriterien qualitativer Forschung. Ansätze zur Bewertung qualitativ-empirischer Sozialforschung*. Juventa, Munich.
Taber, K. S. (2004). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education*, 89:94–116. https://doi.org/10.1002/sce.20038.
Treagust, D., Chittleborough, G., and Mamiala, T. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education*, 24:357–368. https://doi.org/10.1080/09500690110066485.
Törnquist, S., Pettersson, K.-A., and Tranströmer, G. (1993). Confusion by representation: On student's comprehension of the electric field concept. *American Journal of Physics*, 61:335–338. https://doi.org/10.1119/1.17265.
Ubben, M. S. (2020). *Typisierung des Verständnisses mentaler Modelle mittels empirischer Datenerhebung am Beispiel der Quantenphysik*. Logos, Berlin.
Ubben, M. S. and Bitzenbauer, P. (2022). Two Cognitive Dimensions of Students' Mental Models in Science: Fidelity of Gestalt and Functional Fidelity. *Education Sciences*, 12:163. https://doi.org/10.3390/educsci12030163.
Ubben, M. S. and Heusler, S. (2019). Gestalt and Functionality as Independent Dimensions of Mental Models in Science. *Research in Science Education*, pages s11165–019–09892–y. https://doi.org/10.1007/s11165-019-09892-y.
Vosniadou, S. (1992). Mental Models of the Earth: A Study of Conceptual Change in Childhood. *Cognitive Psychology*, 24:535–585. https://doi.org/10.1016/0010-0285(92)90018-W.
Xu, L. and Clarke, D. (2012). Student difficulties in learning density: A distributed cognition perspective. *Research in Science Education*, 42(4):769–789. https://doi.org/10.1007/s11165-011-9232-7.