Neutron Stars: An Infographics Poster

Master’s thesis

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ABSTRACT

Neutron stars are a timely and immensely interesting topic to learn about; through reading about them, one can come to understand the basic principles of the universe, grasp the meaning of recent scientific breakthroughs and successfully avoid plentiful misconceptions and hoaxes. However, for an educated adult to read and learn about neutron stars, one has to either go through superficial and often dubious pop-science articles on one end of the spectrum or deep and complex papers and course books intended for astronomy experts at the other end. Both of these extremes offer little graphic support to help the reader form mental models of the introduced concepts and fail to serve the needs of educated novices interested in the topic. There is a gap for material in the middle of the spectrum; where the target audience is thoughtfully approached with structure, language and visualizations, while their feedback being part of the design process. In this thesis I explore what kind of value can an Information design approach bring to adult novices interested in neutron stars. For that purpose, I create an information design poster about neutron stars. I frame the target audience of the poster with the use of personas, and after an extensive study of the phenomena, appropriately structure and produce textual and visual content. I refine the poster through various feedback sessions and conduct a qualitative evaluation session with users who fit the persona characteristics set at the beginning. The results of the evaluation session indicate that using a user centric information design approach to communicate about complex astronomical phenomena brings value to the target group; the users feel the content is sufficiently tailored to their needs and are content that a wider overview of astronomical phenomena is included. The comparisons used help them bridge the barrier of unimaginable numbers, and their interest in neutron stars rises after interaction with the poster. By including the users in the design process, and making an effort to understand their background, content can be produced that meets the needs and expectations of the target audience. This way, losing readers can be avoided by accurately estimating background knowledge if the target audience while supplying sufficient visual cues to help them navigate through complex phenomena.

Keywords: infographics, poster, augmented reality, information design, structure

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GLOSSARY AND DEFINITIONS

Neutron star - is the collapsed core of a star much larger than our sun, that ended its life by exploding in a supernova.[1] It is the densest form of matter we can directly observe.[2]

Pulsar – is a special type of a neutron star that pulses radio waves and other electromagnetic radiation at very regular intervals.[3]

Magnetar – is a special type of a neutron star with a magnetic field of extreme strength, normally thousand times the magnetic field of a normal neutron star.[4]

Information design - for the purpose of this thesis I refer to Information design as an umbrella term for any design of "external representations" that facilitates better learning and understanding.[5]

Infographics - a type of information design serving to communicate visually to a general, non-specialist audience. It stems from a journalistic tradition.[6]

Data visualization - visually represented information that is of quantitative nature.[7]

Scientific visualization - the "visual representations of scientific data", the data being of physical nature, and the representation being interactive.[8]

Information visualization - a visual representation of data, however only applicable to "computer supported" visualizations.[9]

Augmented reality – is a technology overlaying virtual objects over reality, by blending the real and virtual, being interactive and shown in three dimensions.[10]

1 Max Camenzind, *Compact Objects in Astrophysics: White Dwarfs, Neutron Stars and Black Holes* (Berlin Heidelberg: Springer-Verlag, 2007), 137.

2 Camenzind, *Compact Objects in Astrophysics*, 649.

3 Paweł Haensel, A.Y. Potekhin, and D.G. Yakovlev, *Neutron Stars 1: Equation of State and Structure* (New York: Springer-Verlag, 2007), 34–40.

4 Camenzind, *Compact Objects in Astrophysics*, 648.

5 Stuart Card, Jock D. Mackinlay, and Ben Shneiderman, *Readings in Information Visualization: Using Vision to Think*, (San Francisco: Morgan Kaufmann Publishers, 1999) 6–7.

6 Masud et al., "From Data to Knowledge: Visualizations as Transformation Processes within the Data-Information-Knowledge Continuum." *14th International Conference Information Visualisation* (2010): 447.

7 Michael Friendly, "A Brief History of Data Visualization." in *Handbook of Data Visualization*, ed. Chun-houh Chen et.al. (Berlin: Springer-Verlag, 2008), 15-56.

8 Card, Mackinlay, and Shneiderman, *Readings in Information Visualization*, 6–7.

9 Masud et al., "From Data to Knowledge," 447.

10 Azuma, "A Survey of Augmented Reality." *Presence 6*, no.4 (August 1997): 335-385.

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1 INTRODUCTION

Purpose

> *"Pulsars ... have the potential to reveal such diverse aspects of the Universe as the nature of spacetime and the fundamental properties of matter ... [they] are a treasure of knowledge about the physical universe ..."*
> (Geoff McNamara)[11]

11 Geoff McNamara, *Clocks in the Sky: The Story of Pulsars* (Chichester: Praxis, 2008), 12.

Pulsars, as well as other types of neutron stars, are important objects used for testing astrophysical theories that cannot be tested on Earth. However, also non-scientists can benefit from learning about them: they can serve as a vessel to learn the fundamentals of astronomy, star formation and underlying principles of the universe. With this knowledge one can grasp the meaning of scientific breakthroughs as they happen and successfully avoid hoaxes* and misconceptions.

* For example, the chain email claiming Mars will reach the size of the moon, that has been continuously resurfacing since 2003. See: science.nasa.gov/science-news/science-at-nasa/2010/25aug_marshoax/

This thesis is written in hope of motivating the production of deeper entry level scientific material targeted at the often-overlooked novice adult and encouraging the producers of these materials to use learnings from the Information design field to the mutual advantage of them and their readers. The motivation is also in line with Aalto University's A!OLE project to future-proof education, by creating "engaging, interactive digital solutions"[12], since one of the key themes is the use of augmented reality.[13]

12 Tomi Kauppinen and Lauri Malmi, "Aalto Online Learning - A Pathway to Reforming Education at the Aalto University," EUNIS 2017 Proceedings (June 2017).

13 Kauppinen and Malmi, "Aalto Online Learning - A Pathway to Reforming Education at the Aalto University,".

As a spill-over effect this thesis could facilitate a better understanding and use of available open source software to support complex topics for educators. Since the chosen topic of neutron stars is so complex, the findings can be used as guidelines for approaching other, similarly complex material presented on a poster with a general target audience.

Problem statement

For an educated adult to read and learn about neutron stars, one has to either read through superficial and often dubious pop-science articles on one end of the spectrum or deep and complex articles or course books intended for astronomy experts at the other end. Both of these extremes offer little graphic support to help the reader form mental models of the introduced concepts and fail to serve the needs of educated novices genuinely interested in the topic.

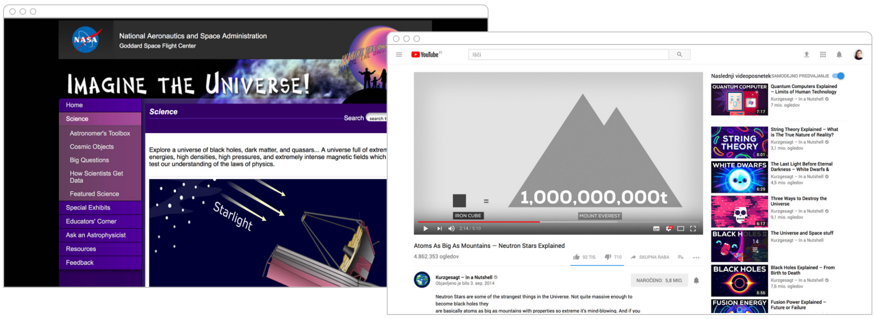


Figure 1: An example of pop-science material on the topic

(left: NASA Imagine the Universe website; right: Kurzgesagt Youtube channel)

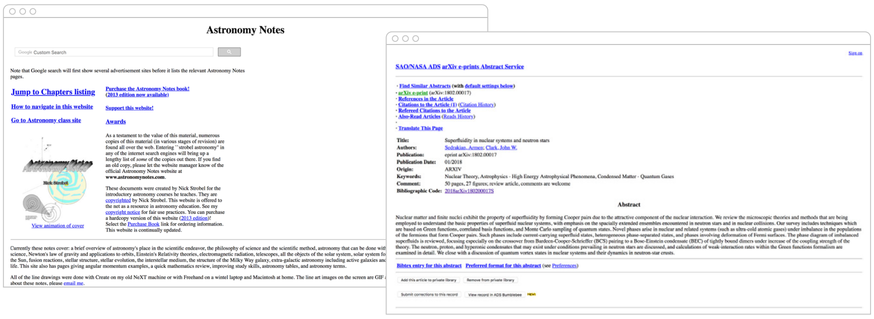


Figure 2: An example of material intended for astronomers or astronomy students

(left: Astronomy notes website by Nick Strobel, right: NASA ADS website).

This thesis is addressing the gap by creating educational material at the middle of the two extremes: material not assuming prior education in an astronomy related field, while not being too basic, condescending and superficial. Instead it offers both depth, as well as a good starting point from which to delve deeper into the topic. The created material thoughtfully approaches the target audience with structure, language and visualizations, while also including their feedback as part of the design process. Since "*[a]n infographic is a multi-section visual representation of information intended to communicate one or more specific messages*"[14] I decided to take infographics as a starting point for the work to follow.

14 Alberto Cairo, The Truthful Art: *Data, Charts and Maps for Communication* (San Francisco: New Riders, 2016), "What We Talk About When We Talk About Visualization", Safari Books Online.

Research question & scope

This thesis explores:

What kind of value can an information design approach bring to adult novices interested in neutron stars?

To answer that question, I create an infographics poster about neutron stars. I start by framing the target audience of the poster with the use of personas. After an extensive study of the phenomena, I appropriately structure and produce textual and visual content. I refine the poster through various feedback sessions and conduct a qualitative evaluation session with users who fit the persona characteristics set at the beginning. I discuss the learnings from the evaluation session that can be useful for designers undertaking a similar task and provide an agenda for further research on the topic.

The decision to design a paper poster instead of a screen-based infographic, stems from research findings of paper continuously winning the preference of students over screen for study material[15]. Students learning from paper seem to outperform those learning from screen[16] especially when the study time is self-regulated[17]. Therefore, to ensure an as pleasant as possible experience, I focus on a paper-based infographics poster that is enhanced with web-based content available through smartphones.

15 Rakefet Ackerman and Morris Goldsmith, "Metacognitive Regulation of Text Learning: On Screen Versus on Paper," *Journal of Experimental Psychology: Applied* 17, no.1 (2010): 18-32.

16 Anne Mangen, Bente Walgermo, and Kolbjorn Bronnick, "Reading Linear Texts on Paper versus Computer Screen: Effects on Reading Comprehension," *International Journal of Educational Research 58*, (2013): 61-68.

17 Ackerman and Goldsmith, "Metacognitive Regulation of Text Learning: On Screen Versus on Paper," 18-32.

Thesis structure

The thesis is structured as follows:

The **Literature review** chapter offers an overview of learnings from the information design field that are relevant for creating an infographics poster.

The **Approach** chapter is divided into three parts: the first part illuminates the *planning phase* of studying the topic, structuring the content and developing personas; the second part focuses on the *production* of textual and visual content. It describes challenges of dealing with astronomical scales, and touches upon technologies used and the visual language developed; the third part concludes the chapter with the *evaluation* sessions and their results.

The **Reflection** chapter reviews the findings from the evaluation sessions, critically evaluates the methods and discusses which approaches work best, which do not, and what are the future steps for both improvement and research.

The **Conclusion** offers a summary of the findings and novelties presented in this thesis.

2 LITERATURE REVIEW

To be able to answer the research question a wide research on existing approaches is necessary in order to be able to use the most suitable ones in the production part of the thesis. This literature review is presenting relevant learnings from the field of Information design that can be applied to the visualization poster, with a focus on **structural approaches**. The literature is selected according to prominent authors in the field dealing with structure, whose learnings can be applied to an explanatory graphic "based around a specific and focused narrative".[18]

18 Andy Kirk, *Data Visualization: A Successful Design Process*, (Birmingham: Packt Pub, 2012), 33.

Shneiderman proposes guidelines for visual design in a form of a mantra: "Overview first, zoom and filter, then details-on-demand".[19] His mantra serves as a reminder that designers should enable the user to: first gain a quick overview of the information presented, to focus on specific parts of interest, to ignore the irrelevant bits and lastly to delve deeper into topics they* wish to explore.

19 Shneiderman, "The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations." *Proceedings 1996 IEEE Symposium on Visual Languages*, (1996): 336-343.

* I shall be consistently using 'they' instead of 'he' or 'she' as the pronoun of choice for a third person in singular.

Shneiderman points out that the information seeking mantra can be understood as a list of tasks users are trying to achieve when using information visualizations. He explores these tasks further, by narrowing the area of interest to computer-based information visualizations and adds three more tasks the designer should allow the user to achieve. The user should be able to: see connections between separate objects, reverse their steps and extract the desired information.[20]

20 Shneiderman, "The Eyes Have It," 336-343.

Even though Shneiderman's guidelines focus on computer-based information visualizations, when slightly reframed, they may prove just as valuable when crafting an information design poster:

Overview first: The user should get an overview on the topic of the poster already from a distance.

Zoom and filter: The act of walking towards the poster could be reinterpreted as zooming-in, while skimming different sections and deciding on which to read could be considered filtering.

Details-on-demand: Focusing on sections of the poster that spark interest and reading those carefully.

Evident connections: On the poster, the relations and connections between the content must be obvious and clear.

Step reversal: Step reversal is not an issue in a static poster. This guideline refers to interactive, computer-based visualizations, where users require to retrace their steps.

Extraction: The task of extraction is something specific to the computer as a medium although it could be valuable to rethink within the constraints of a printed poster.

Rather than focusing on aspects of usability **Kosara** explores journalistic story structures and discovers that the most widely used structure is the inverted pyramid, which reveals the main point in the beginning and then supports it with additional details further on. This structure is widely used in data visualization, even though its suitability is under debate.[21] Kosara proposes another structure, which is based on Cohn's comic story structures, but reworked to fit data stories. He proposes first stating a **claim**, or a **question**, then providing **evidence** and **facts**, and in the end connecting the evidence with the original claim or question to form a **conclusion**.[22]

21 Shneiderman, "The Eyes Have It," 336-343.

22 Robert Kosara, "An Argument Structure for Data Stories." *Short Paper Proceedings of the Eurographics/IEEE VGTC Symposium on Visualization (EuroVis),* (2017).

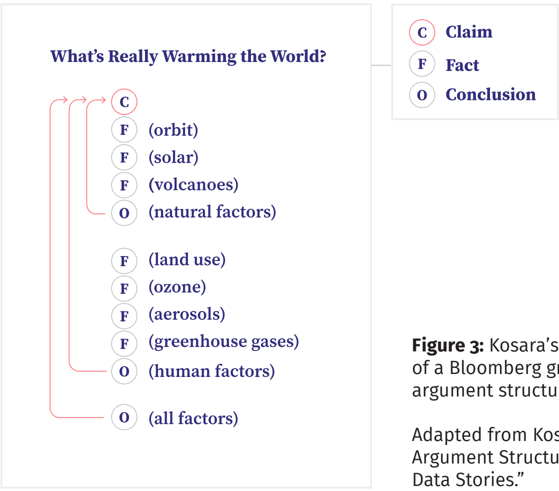


Figure 3: Kosara's analysis of a Bloomberg graphic argument structure.

Adapted from Kosara, "An Argument Structure for Data Stories."

Kosara's suggestion can come to play effectively on the poster about neutron stars: starting the poster with claims about the extremity of neutron stars could attract a user's interest and entice them to invest in understanding the reasons causing these phenomena. Interspersing evidence throughout the poster, could be, although not exactly following Kosara's proposal, an effective way of keeping users interested. This is important because the users would only be able to satisfactorily support the initial claims if they reach the end of the poster.

Wurman takes yet another approach to structure. He suggests that despite there being no limit on the amount of information in the world, there is a limited amount of **ways to organize** it. He states that there are ways to organize information: **location**, **alphabet**, **time**, **category** and **hierarchy** (shortened to LATCH)[23]. The types can also be nested within each-other: organizing the large structure with one, and smaller

23 Richard Saul Wurman, *Information Anxiety 2 (Indianapolis: Que,* 2001), 40–47.

sub-structures with another type of organization. Looking at the same information through different organizing types yields a deeper understanding of that information as one can identify its underlying structures.[24]

24 Wurman, *Information Anxiety 2*, 40–47.

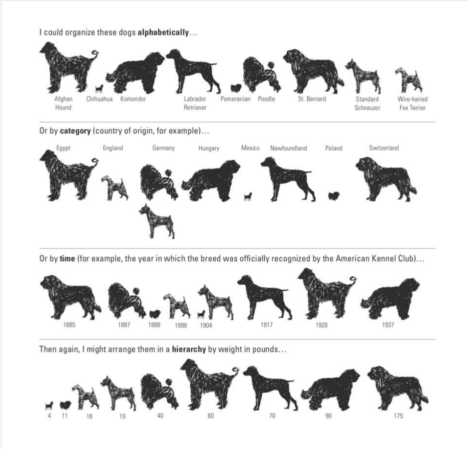


Figure 4: Wurman's example of LATCH theory on reorganising dog breeds.

Figure from: Wurman, 45.

Reorganizing the information or filtering it on demand could prove useful for the topic of neutron stars; however, the medium of the poster does not easily allow that. Building the structure based on categories, or as Wurman also suggests, structuring them per "different **questions** to be answered"[25], could work well with Kosara's proposal to start with **claims**. Those claims could encourage the user to ask those questions. Framing the rest of the content according to those same questions could provide a clear organizational structure.

25 Wurman, *Information Anxiety 2*, 41.

Cairo approaches the topic of structure similarly as Shneiderman, stating that a successful information graphic should **present**, **compare**, **organize** and **correlate**. He builds upon Louis Sullivan's idea "form follows function" but restructures that idea to "functions constrain forms"[26], meaning that the **tasks** or problems the users are trying to solve should define the form of the object or information graphic. He encourages defining a narrow set of goals when designing, to effectively limit the available design choices of the visualization.

26 Alberto Cairo, *The Functional Art: An Introduction to Information Graphics and Visualization* (Berkeley: New Riders, 2013), 36.

As **Ware** puts is:

> *"Effective design should start with a visual task analysis, determine the set of visual queries to be supported by a design, and then use color, form, and space to efficiently serve those queries."*[27]

27 Colin Ware, *Visual Thinking for Design* (Burlington: Morgan Kauffman, 2008), 21.

Lidwell, Holden and Butler expand Cairo's and Ware's notion of a successful graphic: they further discuss structure in terms of **instructional strategies**.[28] They list four instructional strategies: advance organisers, chunking, inverted pyramid and storytelling; and illuminate their different purposes and use cases:

28 William Lidwell, Kritina Holden and Jill Butler, *Universal Principles of Design* (Gloucester: Rockport, 2003), 19.

Advance organisers are short snippets of content offering the user important background information before presenting the main content. They either explain important fundamental concepts or compare the user's existing knowledge to the new information about to be presented.[29]

29 Lidwell, Holden, and Butler, *Universal Principles of Design*, 18.

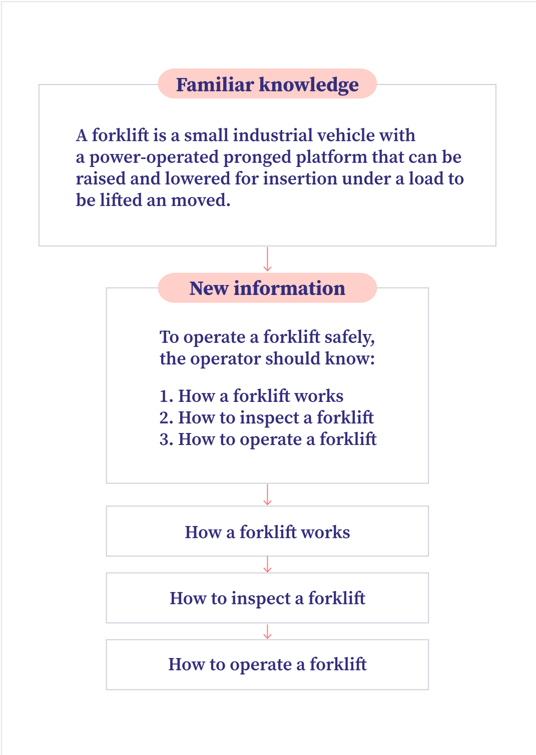


Figure 5: An example of an advance organiser.

Adapted from: Lidwell, Holden, and Butler, 19.

Chunking combines snippets of information into larger units to ease processing and remembering. For this strategy to be effective it is advised to use a maximum of four to five larger units or *chunks*.[30]

30 Lidwell, Holden, and Butler, *Universal Principles of Design*, 38–39.

The **Inverted pyramid** method structures information from most to least important by presenting *critical* information first and continuing with *elaborative* information. This method is widely used in journalism.

The **Storytelling** method engages users using six base elements: a setting, characters, plot, invisibility, mood and movement. These elements provide the audience with orientation, empathy, engagement, immersion, sentiment and stimulation.

The strategies of Lidwell, Holden and Butler are widely adaptable to the poster design task of this thesis. Advance organisers, for example, can take into account the prior knowledge of the user to explain underlying astronomical information when needed, while chunking can provide clearer narrative and visual structure. The inverted pyramid could be used to explain the most important fundamentals before delving into specifics of neutron stars. Some aspects of storytelling, especially the setting, plot and mood, could provide background information, keep the user engaged and take into account their state of mind.

Illuminating another aspect of storytelling, specifically for the field of data visualization, **Kosara and Mackinlay** encourage using the inherent properties of stories, such as time, to create structure in the visualizations.[31] Setting events and facts onto a **timeline**, can provide information about their **causality** relationship even when the timeline is not progressing linearly. Kosara and Mackinlay present stories as an effective technique to make data easier to understand for the users.

31 Robert Kosara and Jock Mackinlay, "Storytelling: The Next Step for Visualization." Computer 45, no. 5 (May 2013): 44-50.

On a different note **Segel and Heer**[32] review features of storytelling from another perspective. They place the features onto the spectrum between author-driven and reader-driven approaches. The **author-driven** approach structures the story flow in a linear way. It has a concrete message to convey and limits interaction, which makes it suitable for educational videos, comics, training materials and similar mediums. The **reader-driven** approach on the other hand, does not have an exact order of reading. Instead it enables readers to interact with the visualization without having a clear message to convey. This approach is suitable for visual analysis tools for example. According to the spectrum of author- and reader-driven approaches Segel and Heer identify three types of structures: the martini glass, the interactive slideshow and the drill down story.

32 E. Segel and J. Heer, "Narrative Visualization: Telling Stories with Data." *IEEE Transactions on Visualization and Computer Graphics 16*, no.6 (November 2010): 1139-1148.

The **martini glass** structure starts with an author-driven approach, leading the reader linearly through an introduction to the topic and subsequently opening up into a reader-driven approach, where the reader can freely explore the data.

The **interactive slideshow** structure is linearly structured, however offers exploration within its linear sections or slides, thus combining the author and reader-driven approaches.

The **drill down story** structure is heavily reader-driven and lets the reader choose which part of the theme they wish to explore.

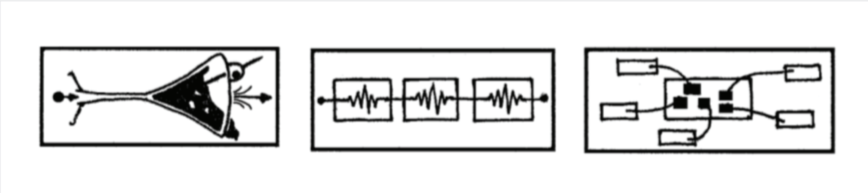


Figure 6: Martini glass, interactive slideshow and drill down story structures.

Figure from Segel and Heer, "Narrative Visualization: Telling Stories with Data."

The predominantly author-driven structures, such as the martini glass or interactive slideshow could fit the explanation poster, since its purpose is communicating about a topic, which needs to be delivered in a linear fashion due to its complex nature. The martini glass approach would mean loosening up the linear approach once the necessary fundamentals have been communicated, allowing the reader to choose the subsequent topics according to their preferences. Following the interactive slideshow approach, the poster could be structured into linearly ordered sections, offering user interaction from within each section.

The author-driven versus reader-driven approach dichotomy of Segel and Heer appears across information design literature: Alberto Cairo[33] calls it the presentation and exploration component and Andy Kirk exploratory versus explanatory data visualization[34]. Regardless of how it is named, the choice of which approach to use might be the most fundamental decision an information designer makes in the design process.

33 Cairo, *The Functional Art*, 12.

34 Kirk, *Data Visualization*, 35.

Regardless whether the content is author- or reader-driven, **Holšánová** expresses the importance of understanding how readers perceive visual forms of communication, and how they derive meaning from it.[35] She stresses that **visual form and content** is only one of three facets of meaning making, the other two being the reader's **personal characteristics** and the **context** within which the reader encounters, perceives and interprets the visuals. By demonstrating that people are only able to focus on one visual section at a time, she emphasises the necessity of guiding the reader through the content. She furthermore demonstrates how readers' behaviour changes depending on the structure of the infographic: **serial** structures guide the attention of the user in a linear path and **radial** structures demand the user to continuously choose entry points. Holšánová concludes that the latter is not suitable for conveying complex topics, since readers tend to lose interest when they need to continuously make decisions while reading.

35 Jana Holšánová, "In the Eye of the Beholder: Visual Communication from a Recipient Perspective," in *Visual Communication*, ed. David Machin (De Gruyter Mouton, 2014), 331-355.

Figure 7: Reading paths.

Image from Holšánová, "In the Eye of the Beholder: Visual Communication from a Recipient Perspective," 331-355.

What Holšánová calls the serial and radial structures, Koponen, Hildén and Vapaasalo term **linear** and **open** structure.[36] They furthermore extend these categories by opening up possibilities of linear structures containing open structure sections and vice versa. The idea of one larger structure entailing another, smaller one is in line with **Ware**'s research on human perception.[37] Ware suggests using large- and small-scale structures to enable users to navigate a design efficiently. The **large-scale structure** helps organising main sections of the design, while **the small-scale structure** organises the structures inside the main sections, to secure a level of distinction between similar sections.

Ware's approach is especially valuable in an infographics poster, where multiple sections are displayed side by side, needing both the larger-scale structure to inform about the relationships among sections, as well as that deeper level of structure to help with distinction between them. Combining that principle with **Lidwell, Holden and Butler**'s proposal of using the Gutenberg diagram as a layout framework with text heavy and homogeneous designs[38] might prove as a good starting point for the task at hand.

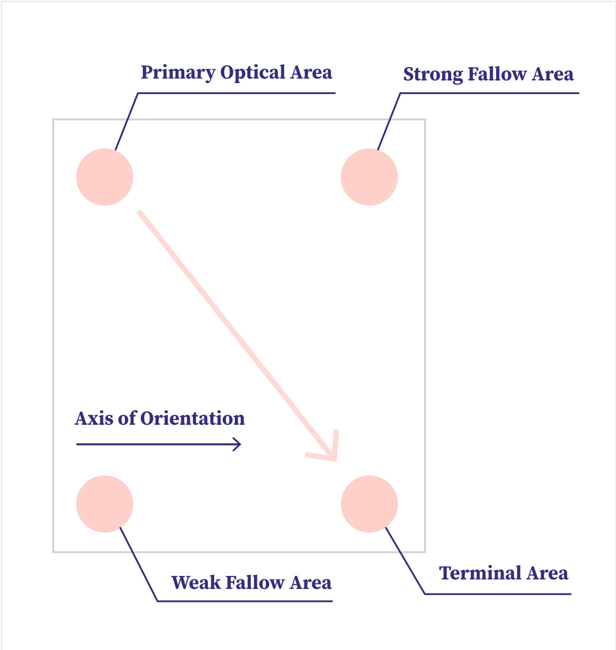
36 Juuso Koponen, Jonatan Hildén, and Tapio Vapaasalo, *Tieto Näkyväksi : Informaatiomuotoilun Perusteet* (Helsinki: Helsinki: Aalto-yliopisto, 2016), 59.

37 Ware, *Visual Thinking for Design*, 40–41.

38 Lidwell, Holden, and Butler, *Universal Principles of Design*, 118–19.

Figure 8: Gutenberg diagram.

Adapted from Lidwell, Holden, and Butler, *Universal Principles of Design*, 18.



These structural approaches do not seem to contradict one another, rather they enlighten the challenge of narrative and visual structure from different perspectives and for diverse purposes. In order to communicate effectively, deciding whether to grant the user the freedom to explore the topic from entry points of their choice versus structuring the story linearly has to be supported with premeditated approaches to both structure and visuals. The design decisions need to be planned with careful attention to the user, their perception, characteristics and the context they are viewing the work in. In addition to these, the thesis focuses on including the user in the design process, considering different levels of prior knowledge and exposure to both the topic communicated and expectations of the format of a poster.

3 APPROACH

This chapter details on the design process of the poster. It starts with the **planning phase** of studying and structuring the content, creating personas and producing the text. It continues with the **production phase,** exploring and setting requirements for the media used and creating the visual aspect. The chapter concludes with the **evaluation phase** describing the iterative feedback received and final evaluation session with users that fit persona characteristics.

Planning phase

~ Study

To understand the phenomenon of neutron stars and to be able to explain it in understandable terms, I needed to extensively study not only the chosen topic, but also the surrounding **fundamentals** of astronomy, such as: star formation, stellar evolution, classification of stars, nuclear fusion, hydrostatic equilibrium, stellar structure, astronomical units and conventions. I periodically dived deeper in finding out, for example, why stars shine. This required understanding two types of nuclear fusion along with the very basics of special relativity.

The research on the topic started **overview first**, through educational videos, hours on end spent on Wikipedia, online lecture notes of astronomy professors, NASA's articles, press releases and pop-science articles. My first goal was to tie the basic principles together and understand the overall picture by gathering basic information, structuring it in my notes and developing a **mental model** of the phenomenon. When reaching the point of understanding the grand scheme, along with the neutron stars' place in it, I started structuring the **narrative flow** of the visualization.

~ Structure

While learning about neutron stars, I realised the importance of understanding particular **fundamental concepts** first, before attempting to grasp others. This finding had early implications on the structure: information needs to flow **linearly**, at least to a certain degree, to ensure that the reader possesses the required base on which to build upon when receiving new information further down the line.

I noted down the concepts and snippets of information I wanted to convey about neutron stars on separate post-it notes. To construct a sensible flow of information, I kept reassembling the notes until the story arguments flowed in a consecutive and understandable fashion. It was important, for example, that the reasons behind the neutron star's immense gravity, such as atom collapse, came first and its effects, such as gravitational lensing*, followed afterwards.

* Gravitational lensing - when an object behind the neutron star can be visible because the gravitational pull bends the light around a neutron star.

Figure 9: Preliminary structuring using post-its

While structuring a functional flow of information, I encountered several 'chicken or the egg' causality dilemmas. One particularly difficult decision to make was whether *nuclear fusion* should come before *stellar evolution* or after. The initial structure placed fusion first since it is the underlying process of the evolution. However, placed this way, the lack of vocabulary offered by the stellar evolution becomes evident when explaining the nuclear fusion in depth. I tested both options with schoolmates and found that beginning with stellar evolution produces less confusion.

After coming to understand which sections of the content need to be in sequential order and which can be freely moved around, I focused on structuring the poster itself. I took note of Kosara's take on story structure in visualizations and his proposal of an argument structure that states a *claim* first, continues with *facts* which can be interspersed with *explanations* and ends with a *conclusion*.[39] As a background research for my own structure I also collected a corpus of educational videos, popular science articles and encyclopaedia entries which were made for a similar target audience as my work. I analysed this corpus by encoding it with Kosara's framework to see what argument structure they follow, and if that structure could apply to my poster as well.

39 Kosara, "An Argument Structure for Data Stories,".

Material	Argument structure
"Neutron Stars: Crash Course Astronomy #32" video by CrashCourse	F F C F F F F ... F O
"Atoms As Big As Mountains - Neutron Stars Explained" video by Kurzgesagt - In a Nutshell	C F C F F F F ... F O
"What is a Neutron Star?" video by NASA Goddard	C F F F F F F ... F O
"Neutron Stars: Definition & Facts" online article by space.com	F F F F F F F ... F F
"Neutron Stars, Pulsars and Magnetars Explained" video by Top5Quantum	F F F F F F F ... F O
"What are neutron stars? (Astronomy)" video by Socratica	C F F F F F F ... F O
"Gravitational Waves 101 | National Geographic" video by National Geographic	F F F F F F F ... F F
"Neutron Stars" online article by National Geographic	F F F F F F F ... F F
"How Gravitational Waves Work (Infographic)" online article by space.com	C F F F F F F ... F F
"Hubblecast 103: Hubble observes source of gravitational waves for the first time" video by HubbleESA	C F F F F F F ... F O
"Neutron-Star Collision Shakes Space-Time and Lights Up the Sky" online article by QuantaMagazine	C F F F F F F ... F F
"Squishy or Solid? A Neutron Star's Insides Open to Debate" online article by QuantaMagazine	C F F F F F F ... F O

C Claim/Question
F Fact
O Conclusion

Figure 10: The argument structure of analysed material

Like my initial solution, plenty material followed the inverted pyramid structure, as is to be expected for journalistic pieces. Nevertheless, in an attempt to grab attention of the users, I reworked the structure of the neutron star poster according to the proposed framework:

I start with five claims about neutron stars, to entice the reader into learning more. I chose claims I found intriguing myself and fairly straightforward:

- When discovered, neutron stars were briefly thought to be extraterrestrial intelligence.[40]
- Only 0.1%[41] of all stars[42] are neutron stars.
- They measure only about 20 km in diameter.
- Despite their small size, their masses equal up to three masses of our Sun.
- Their density can be compared to and even exceeds that of an atomic nucleus.

40 Alan John Penny, "The SETI Episode in the 1967 Discovery of Pulsars," *The European Physical Journal H 38*, no.4 (September 2013): 535–47.

41 Camenzind, *Compact Objects in Astrophysics*, 269–72.

42 Strobel, *Astronomy Notes*, 8.

These claims offer the reader a quick overview of how unusual this phenomenon is, begging the questions of **why** and **how** neutron stars evolve to such extremes. I follow up with interspersed explanations and facts, with implicit conclusions that tie back to the original claims. All the while taking care that the sequence of the educational story is in the correct order.

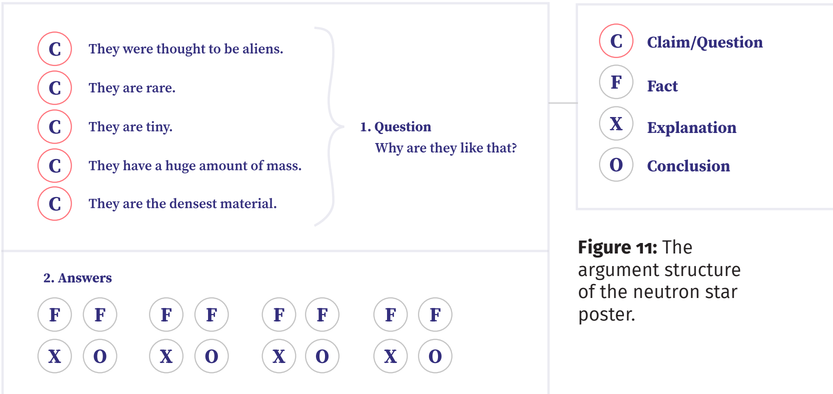
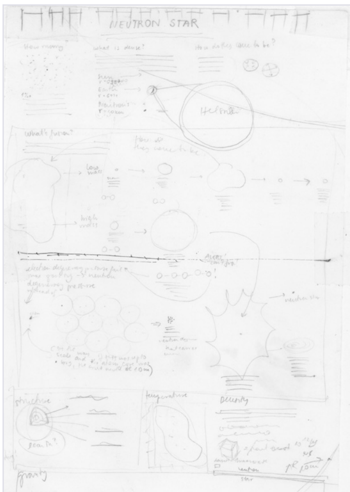


Figure 11: The argument structure of the neutron star poster.

Figure 12: One of the first sketches of the poster.



At this point in the planning phase I omitted some of the content I initially planned to include, such as: neutron star collision being the **source of heavy elements**, inner and outer core of the neutron star going through several **nuclear pasta phases** and neutron stars in **binary systems**. When restructured, these topics were not tying back to the initial claims and therefore seemed both out of place and overly deep for the first-time reader.

At the end of the planning phase, the poster was in the shape of wire-frames: structure was set in place, textual place holders with collected content distributed and first visualisation sketches in place.

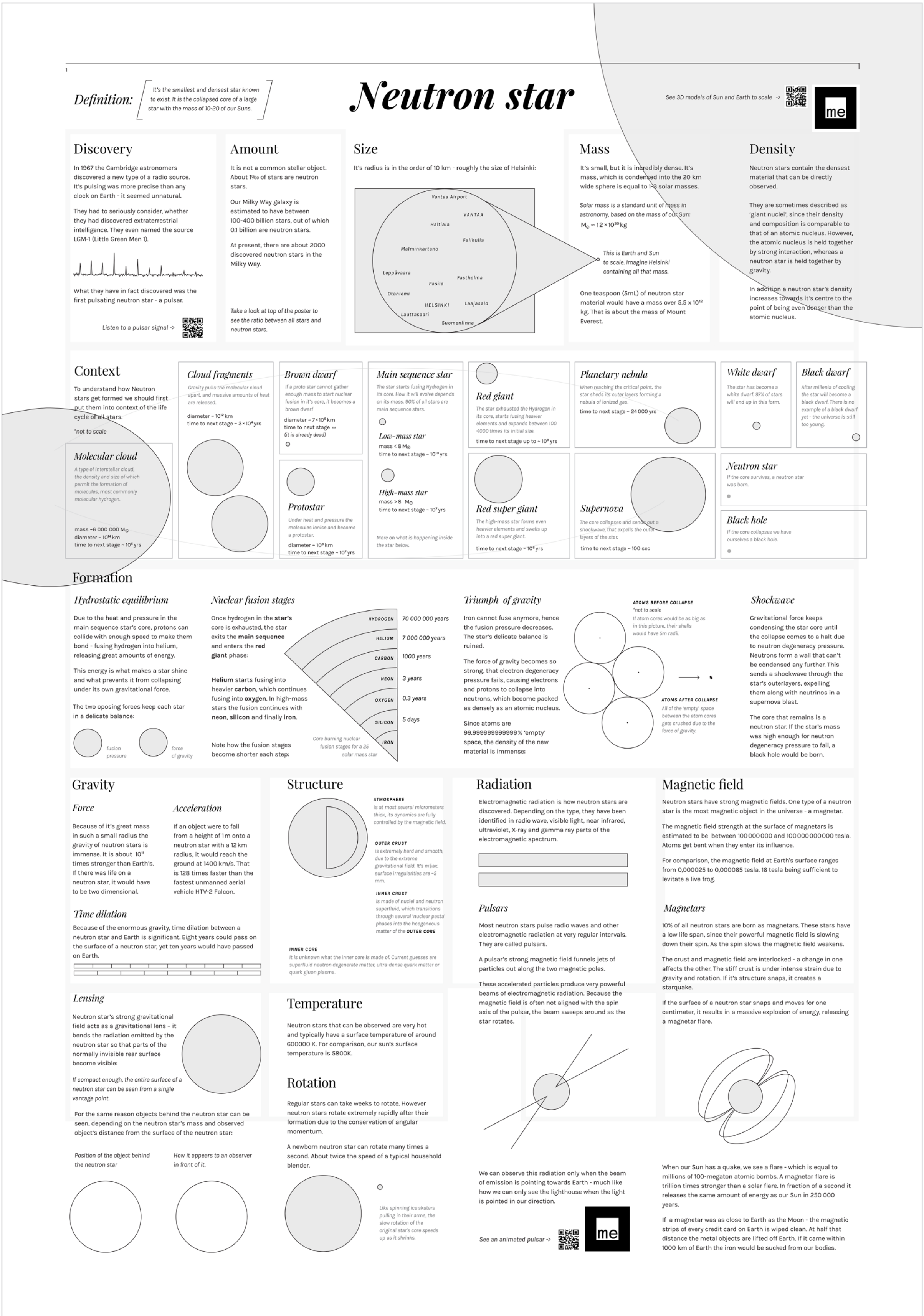


Figure 13:
Wireframe phase of the poster.

~ Personas

While cutting out excess content I recognised the need for developing **ad-hoc user personas** [43], to verify the decisions I was making. Ad-hoc personas, opposed to data-driven personas, are based on assumptions instead of data, and are used when data isn't readily available: for example, at the start of a new service or project, with no existing user base to survey.

43 Donald Norman, "Ad Hoc Personas & Empathetic Focus," in *The Persona Lifecycle: Keeping People in Mind Throughout Product Design*, ed. John Pruitt and Tamara Adlin (San Francisco: Morgan Kaufmann Press, 2006) 154-57.

Adlin and Pruit propose clarifying the goals of the endeavour before starting the persona development. [44] Focusing on persona creation within organisations, they suggest six perspectives to explore: business goals, brand goals, user experience goals, value propositions, differentiators and persona effort goals.

44 John Pruitt and Tamara Adlin, *The Persona Lifecycle: Keeping People in Mind Throughout Product Design* (San Francisco: Morgan Kaufmann Press, 2006), 28, ProQuest Ebrary.

Out of the above, I found **user experience goals** and **differentiators** to be the perspectives directly applicable to the task of this thesis. I wrote down specific **user experience** goals of the poster prototype:

- To communicate clearly about the neutron star phenomenon;
- To inspire interest in astronomy and overcome possible fear of the topic;
- To make the learning process joyful and visually pleasing.

I supported those goals with key **differentiators that set the poster apart from** existing material on the topic of neutron stars:

- The poster is produced based on learnings from Information design;
- It is tailored for a target group by methods focusing on the user and user-experience.

Under the assumption that the poster would be used in the settings of an exhibition in an astronomy museum, in a school hallway, a waiting room, or as an art-print hung in an office or home, I explored the different interactions, wishes and state of mind different personas would have, when interacting with the poster in those settings. Some would already know the basics about neutron stars and be curious to learn more, some would already know a lot on the topic and would be interested to spot mistakes, others would be drawn in by the visuals and learn something unexpected without any existing knowledge on the topic while some might not be interested in the poster at all. When clustering these imagined relations to the poster, the **level of existing knowledge** seemed to be a good way to classify the personas. Since I defined the target audience as adult, educated and interested in learning about neutron stars, I discarded the cluster of people not interested in the topic.

I decided to use the **persona matrix** developed by Markku Reunanen,[45] which proved to be a helpful way of capturing an efficient set of three user personas within two selected ranges of characteristics. Since I was interested in how people with varying prior knowledge levels would perceive my poster, one of the defining characteristics I chose was the **level of expertise**. For the second defining characteristic I chose **age** since I am curious about how to serve the needs of the adult audience of different ages.

45 Markku Reunanen and Jeroen Carelse, Dynamic Visualization II course at Aalto University, January, 2016.

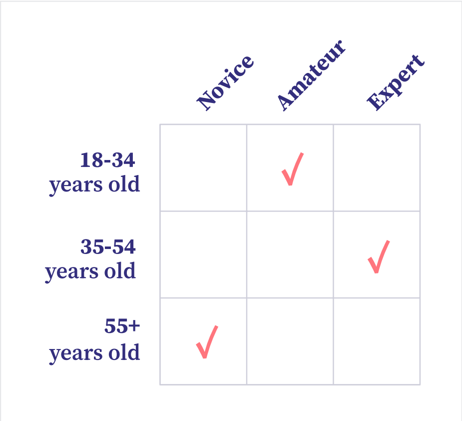


Figure 14: Persona matrix depicting age and level of expertise

I continued developing the persona skeletons, which evolved further into persona foundation documents[46]. This involved coming up with persona names, their level of importance for the design task at hand, writing what they would say, making a paragraph long description of each of them, coming up with questions they might have and their possible interests in the topic.

46 Pruitt and Adlin, *The Persona Lifecycle*, 13–37.

Figure 14: Primary persona.

Image from: userpersonaimages.com (Creative commons licence).

Persona name:
Ruben the novice

Level of importance:
Primary persona

Demographics:
56 years old
Business analyst

Quote:

"There is an underlying logic to everything."

Short description:

Ruben saw Neil deGrasse Tyson presenting the basics of astronomy on the Cosmos series on television, he was very interested in the series, but was left with many questions. He has an inquisitive mind and is always keen on learning more about the world and its underlying laws and systems.

Questions about neutron stars:

What are they? What other kinds of stars are there? Why do stars shine?

Most relevant parts of the poster:

The stellar evolution and processes inside main sequence stars.

Persona name:
Jaakko the amateur astronomer

Level of importance:
Primary persona

Demographics:
26 years old
BA in chemistry

Figure 15: Primary persona.

Image from: userpersonaimages.com (Creative commons licence).

Quote:

"There is so many things I'd like to know about the world."

Short description:

Jaakko lives at the student campus, shares his flat with two roommates and studies hard towards his master's degree. He is an amateur astronomer, follows ESA on Twitter and sometimes takes part in events organised by the astronomical society. He has heard about neutron stars, but never properly looked into them.

Questions about neutron stars:

How do neutron stars come to be? Why do they exist?

Most relevant parts of the poster:

Placing neutron stars in the life-cycle of all stars;
Reading about how extreme neutron stars are.

Figure 17:
Secondary persona

Image from: userpersonaimages.com (Creative commons licence).

Persona name:
Jenni the expert astronomer

Level of importance:
Secondary persona

Demographics:
41 years old
PhD in Astrophysics

Quote:

"The outer-space is such an inspiring place to explore."

Short description:

Jenni is a professional astronomer at an observatory. She loves what she does. As a child series such as Star Trek were the ones spurring her interest in the outer-space. She is observing in a team of astronomers from all around the world, who combine their knowledge in reports they write together.

Questions about neutron stars:

How to make more people interested in these topics?

Most relevant parts of the poster:

How is the phenomenon explained, are there misconceptions?

Creating believable personas helped to make the end users more relatable and easier to keep in mind while producing the content. In the Evaluation phase chapter, I shall delve into the qualitative evaluation session with four users fitting within the set persona demographics, to see how they **perceive** the poster, what kind of **value** it brings them and how the work could be **improved** to better serve their needs.

Production phase

~ Writing

After settling for the structure, the context of the poster and persona creation, I started writing down the content of the poster. As I was writing I focused on keeping the language and tone of voice clear and to the point, while still retaining a sense of neutrality common to scientific writing. I tried to keep the personas in mind while writing, to avoid the pitfall of pop-science articles, which tend to resort to sensationalistic language, likely underestimating the intelligence of their non-specialist readers.

During this phase I noticed more gaps in my knowledge. More background research was needed to understand the concepts and to be able to express them clearly. I did many iterative cycles of writing content, finding gaps, researching the gaps and rewriting the content.

Figure 18: Image of an iterative cycle: writing, gap, researching the gap, writing...

To verify the content of the poster, I contacted Joni Tammi, the head of Aalto Metsähovi Radio Observatory, who kindly reviewed the poster, giving me feedback and suggestions for improvements. Some of this feedback illuminated some problematic numerical values, however, most was of pedagogical nature: on how to phrase particular sections in a clearer fashion. Sourcing credible numerical values turned out to be exceedingly challenging since astronomy course books often elude exact numerical ranges for temperatures, time, size and mass, while pop-science articles and lecture notes fail to provide any sufficiently reliable sources for their numerous numerical facts. To tackle this issue, Joni Tammi pointed me towards the *Digital Library for Physics and Astronomy* by the *High Energy Astrophysics Division at the Harvard-Smithsonian Centre for Astrophysics. This* proved to be a great source of survey articles, where I could find many of the elusive values, but required a lot of effort on my part to decode the scientific language and equations.

~ Unimaginable numbers

While writing the content I realised it is filled with unimaginable numbers and size differences. The explanation of the *stellar evolution,* for example, is teeming with extreme numerical ranges: the adulthood stage of an average star lasts twelve trillion years, while their supernova explosion lasts a few minutes; or the radius of the sun measures roughly 696,000 km, while the radius of a neutron star only reaches about 10 km. The comparison of the Sun and the neutron star is essential in conveying the density of the neutron star: it is very difficult to visualise, however, due to the difference in size.

People outside of science, technology, engineering or mathematics professions, have a hard time grasping numbers outside of human experience: in nano- or astronomical-scales. They are able to place large numbers in the correct order, however have trouble making useful mental models of them.[47]

47 lyse Resnick, Alexandra Davatzes, Nora S. Newcombe and Thomas F. Shipley, “Using Relational Reasoning to Learn About Scientific Phenomena at Unfamiliar Scales,” *Educational Psychology Review 29,* no.1 (March 2017): 11-25.

Resnick, Davatzes, and Newcombe suggest that there are two ways of reasoning about such values. The first reasoning technique is to **divide the big scale into smaller sub-scales**, to be able to mentally compare both the individual parts and their sum.[48] In astronomy this concept can be witnessed by the use of solar mass as the standard way of communicating the mass of other stellar objects, instead of using nonillions and septendecillions of kilograms. Some information I found was expressed in mass of Jupiter or Earth, or even kilograms. Utilising the concept of unitizing I calculated all the mass differences of stars into solar mass.

48 Resnick, Davatzes, Newcombe and Shipley, “Using Relational Reasoning to Learn About Scientific Phenomena at Unfamiliar Scales,”.

$$M_{SUN} \approx 2 \times 10^{30}\ \mathrm{kg}$$

Figure 19: Solar mass unit.

The other reasoning approach described by the same authors is using similarities between the human and extreme scales: mapping an already known concept onto the new one, like an **analogy**. For this approach to work, the familiar or *analogous* concept needs to have corresponding structural connections to the unfamiliar one. This can become problematic if the person is unfamiliar with the analogy used, or if the differences between the analogous and base concept are too stark and overshadow the underlying similarities.[49] I used the analogous approach when writing content on the density of neutron stars. Since neutron stars are the densest material we can directly observe,[50] finding a familiar concept for an analogy proved to be very difficult. For the poster I calculated several analogies for the weight of 1 cubic centimetre of neutron star or neutronium (on Earth). However, the analogies I calculated ended up being equally hard to imagine as the base concept. One sugar cube or 1 cm^3 of neutronium would weigh equal to:

49 Resnick, Davatzes, Newcombe and Shipley, "Using Relational Reasoning to Learn About Scientific Phenomena at Unfamiliar Scales,".

50 Camenzind, *Compact Objects in Astrophysics*, 137.

- **714,285,714** Volkswagen Golf cars;
- **16** storey stacks of Volkswagen Golf cars arranged next to each other over the entire land area of Finland;
- **4,5** storey stacks of transport trucks arranged next to each other over the entire land area of Finland;
- **1,512,859** of the heaviest locomotives;

A common analogy used in literature to describe neutron stars is that a teaspoon worth of neutronium equals the estimated mass of Mount Everest.[51] However, that remains equally problematic, since grasping the size of Mount Everest is also outside of human experience. During my research I came across a comparison that likened a neutron star's density to a Boeing 747 airplane, compressed to the size of a grain of sand[52]. I found this attempt much easier to grasp, since it is showing extreme densities on a human scale. I checked the calculation and found that one small grain of neutron star material would weigh about the same as the biggest airplane in Finnair's fleet – the Airbus A350-900.

51 Kirshner, "Supernovae and Stellar Catastrophe," in *Understanding Catastrophe*, ed. Janine Bourriau (Melbourne: Cambridge University Press, 1992): 21.

At this point I realized that visualizing these vast differences would be even more challenging than presenting them in a textual form. A poster has both an upper and lower limit of the size of objects printed on it. Big objects are limited by the surface area of the selected paper, while small objects are limited by both the capabilities of the printer as well as the eyesight of users.

I found it essential to show the vast difference in size between a neutron star and the Sun to help the user imagine how much mass is condensed in the small radius of a neutron star. Every single example of the learning material I was using for learning and sourcing fell short to frame the size of the sun in comparison to the neutron star. The authors deemed that readers were familiar with the size of the Sun and used it as the familiar concept to build upon. However, when calculating the size differences for the purpose of the poster, the results perpetually shifted my understanding on the topic and proved to be invaluable when attempting to grasp the extremes of neutron stars.

However, any poster is too small to show the natural size difference in size between a neutron star and the sun: if the neutron star was printed as 0.1 millimeters in size, the Sun would still stretch for 696 meters. This can be avoided by making a **scale shift** – first comparing the neutron star with the Earth, and then reframing the scale to compare the Earth to the Sun, which I resorted to on the poster. Another solution would be to use logarithmic scales, which are used in the part of the poster about the magnetic field. These tactics still fail, however, to address an important problem of the visualization: comparing the three-dimensional volumes on a two-dimensional plane. The same problems are encountered on phone and tablet screens.

~ Augmented reality

To mitigate the problems of three-dimensional content being printed on two-dimensional paper, I thought of enriching the poster using augmented reality - **AR**. This way I could show the comparison of volumes of stars, as well as the motion of pulsating neutron stars – *pulsars*. I decided to use augmented reality only in these two instances on the poster, since these were the only cases AR would bring a valuable new perspective instead of being an unnecessary embellishment. These two instances were still feasible in both the technological framework I was working with and with the level of technical skills required.

Aside from these two, I had many more ideas of using augmented reality that could be valuable to include in the poster. *Gravitational lensing* and *light deflection,* for example, two effects of the immense gravity of neutron stars, would be wonderful to illustrate with augmented reality. The user would see how gravity bends both the light emitted from the neutron star as well as the light surrounding it. Depending on the mass of the neutron star the visual effect of gravitational lensing can be quite extreme: the entire surface area of the neutron star can become visible from a single vantage point.[53]

53 Ute Kraus, "Light Deflection Near Neutron Stars," *Relativistic Astrophysics*, ed. Harald Riffert et.al. (Wiesbaden: Vieweg+-Teubner Verlag, 1998), 66-81.

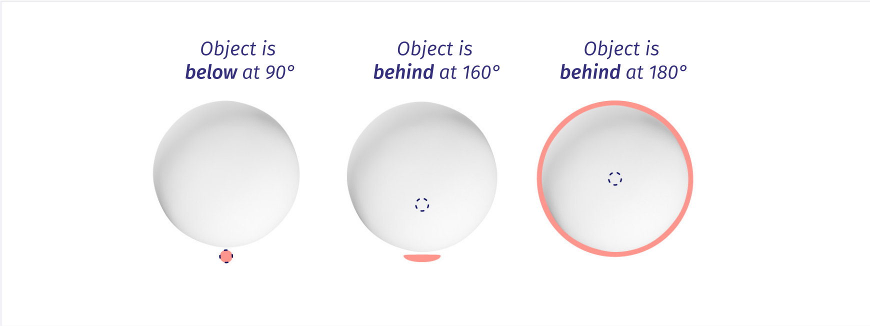


Figure 20: Gravitational lensing on neutron stars.

Adapted from: Kraus, "Light Deflection Near Neutron Stars," 66-81.

The effect of light deflection causes objects behind the neutron star, that would be otherwise hidden, to become visible.

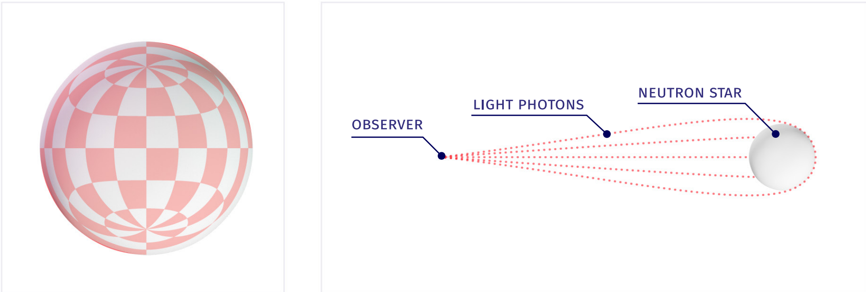


Figure 21: Light deflection on neutron stars. Left: first person view, each chequer represents 30° of the surface. Right: side view.

Adapted from: Kraus, "Light Deflection Near Neutron Stars," 66-81.

With augmented reality the user could move around the neutron star and see the effects warping the surroundings. This feature, however, along with other similarly demanding ones, remains in the list for future development.

After settling on using augmented reality, the search for an appropriate software started. I explored the capabilities of **Unity*** game development software and looked into using it in combination with **Vuforia**** and **ARKit***** extensions.

* Unity game development platform unity3d.com

** Vuforia AR platform vuforia.com

*** ARKit AR platform by Apple developer.apple.com/arkit

Both of the extensions had shortcomings – Vuforia is not able to map the surroundings, and ARKit is unable to recognize markers and vertical planes. To overcome this, I required the extensions to assist one another. Though this sounds like a straightforward task, it would require extensive developing and workarounds. At time of making this project the next release of Vuforia and ARKit were expected, promising to solve these issues. Spending excessive amounts of time learning and developing it thus seemed pointless.

Using this set of software, the augmented reality would be bound to an app in order to work on smartphones and tablets. Restrictions apply in installing apps outside of the official app stores, and proficient knowledge in app creation and time is required to publish apps officially. ARKit is also only available on newer Apple devices. Using this set of software would thus hinder the accessibility of the augmented reality content.

Figure 22: Test of Vuforia.

I considered using Microsoft's **HoloLens*** mixed reality smart-glasses. After testing its capabilities, I was disappointed by its narrow field of view. The benefit of not having to hold a device, but instead having hands available for interaction, got overshadowed by the shortcomings in contrast, field of view and most of all steep pricing. The problem of the software being proprietary and bound to an app applies here as well, with the added drawback of specific hardware required.

* Microsoft HoloLens mixed reality technology microsoft.com/hololens

I also invested in a **HoloKit****: an open-source mixed reality platform that uses a low-cost cardboard headset, into which the user inserts their smartphone. However, it did not function as advertised. Upon inserting a smartphone into the headset and looking through it, the plain, onto which the content was projected, kept being misplaced – with the content floating midair. After testing it with different smart-phones, I discarded the idea of using the HoloKit.

** HoloKit mixed reality holokit.io

In the end I decided to use **AR.js*****: an open-source based augmented reality toolkit, that enables viewing augmented reality content through web browsers on smartphones. It works on a wide variety of phones without the need to download apps. The user simply opens the website where the content is hosted, enables camera access and points their phone towards a marker onto which the augmented content is displayed.

*** Augmented reality for the web github.com/jeromeetienne/AR.js

Since the AR.js toolkit is a work-in-progress, I encountered many technical issues and bugs kept appearing along the way. Unlike Vuforia, AR.js has severe limitations as to what kind of custom images may be used as markers: the obligatory black square is visually hindering, as well as the high-contrast, low-detail requirements of the image inside it. There is little information available on how to prepare images effectively, which meant plenty of trial and error to make the toolkit work even remotely as desired. Even though my initial plan was to hide the markers in the content of the poster, this toolkit sadly did not allow such an approach – the marker resulted as a separate quite striking element on the poster. At the time of writing, the toolkit also did not allow QR codes to be part of the marker, which further hindered my plans of integrating the augmented reality in a subtler manner.

	Unity + Vuforia	Unity + ARKit	HoloLens	HoloKit	AR.js
Open source	×	×	×	✓	✓
Works on a broad range of devices	✓	×	×	×	✓
Easy to develop	✓	✓	×	×	✓
Uses markers	✓	×	✓	×	✓
Detects planes	×	✓	✓	✓	×
No separate apps or hardware	×	×	×	×	✓

Figure 23: Comparison of different software.

Since I am hosting the augmented reality content on my personal website, I had to update the website with an SSL certificate* to be able to utilize users' cameras. After having this framework in place, it was simple to introduce also other types of web-based content. I obtained an **audio recording** of a pulsar, which I thought could serve as a wonderful illustration of the discovery of neutron stars: when discovered, astronomers initially thought they had found evidence of extraterrestrial intelligence, since they were receiving incredibly precise radio wave pulses. A participant at a feedback session reported feeling goose bumps while listening to the recording, commenting that it fit their idea

* Secure Sockets Layer certificate is needed to establish a secure, encrypted connection. Without it, web browsers automatically block camera requests needed for the display of augmented reality.

of an alien sound. I became curious if the recording could serve as a means of remembering the surrounding content of the poster.*

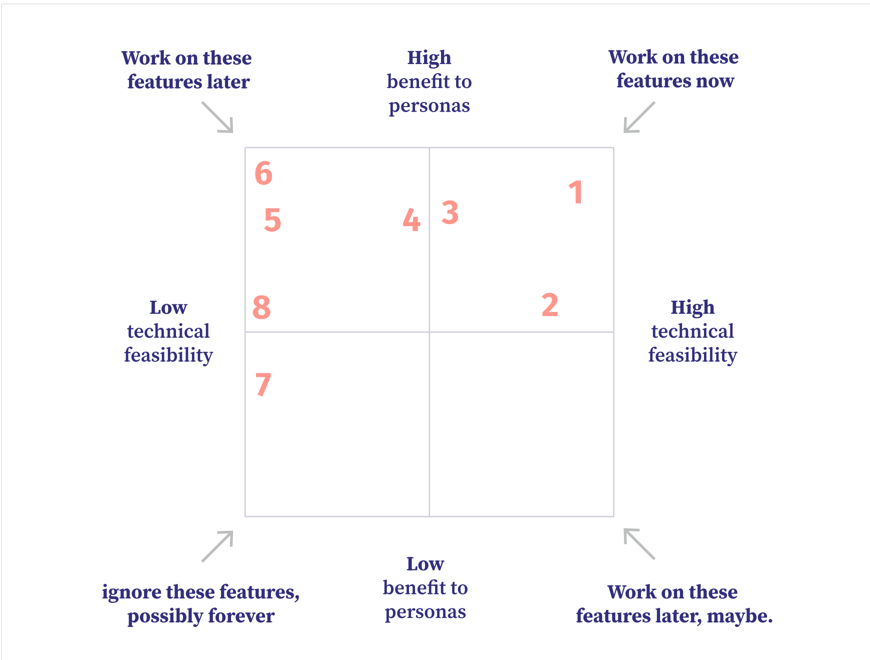
* You can listen to the recording at: marijaerjavec.com/neutron-star/sound

To make the decision which features are worth pursuing using the selected technological framework, I marked them on a “Feature-value versus technical feasibility plot”.[54] I only selected features that had high benefit to personas as well as high technical feasibility and could be produced in the time constraints of a master thesis project.

1 Size comparison of Earth and the Sun.
2 Sound of pulsars.
3 Quiz to test knowledge before and after.
4 Rotating pulsar animation.
5 Refraction visualization in AR.
6 Lensing visualization in AR.
7 Leaning into a model of a neutron star to see ts structure.
8 Showcasing the effect of mass to the outcome of the stellar evolution.

Figure 24: Features used.

Diagram adapted from Adlin and Pruitt, 129.



~ 3D models

To display visual content using web based augmented reality and to produce visuals for the poster prototype, I needed to create 3D models of the astronomical objects discussed in the prototype. Creating them, however, required learning the basics of a 3D computer graphics program. I chose **Blender*** since it is free and open-source and purchased courses from Udemy** to learn it quickly and efficiently.

* Free and open source 3D creation suite Blender blender.org

** Online learning platform Udemy udemy.com

I produced and rendered eight 3D models: a structural model of a pulsar, a magnetar, neutron star's core cross-section, neutron star's structure, sphere representing stars, molecular cloud, and cloud fragments. The last two mentioned models would require some more work to be sufficiently similar to the actual objects, and more objects should be produced: the planetary nebula, supernova and black hole.

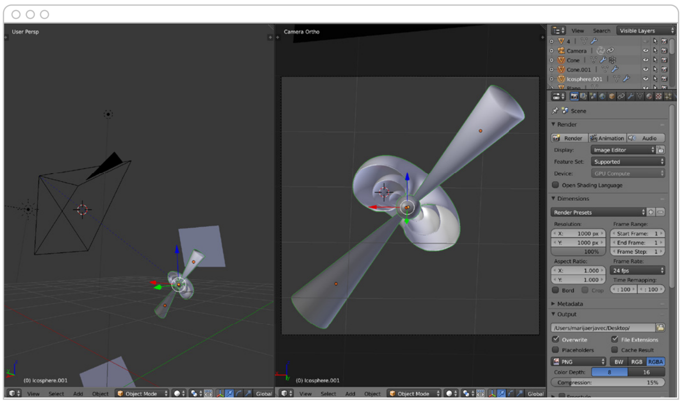


Figure 25: Pulsar model being created in Blender.

I polished the renderings in Adobe Photoshop CC*** and placed them into Adobe Illustrator CC****, where I combined the textual and visual content onto one poster.

*** Adobe Photoshop imaging app adobe.com/products/photoshop

**** Adobe Illustrator vector graphics app adobe.com/products/illustrator

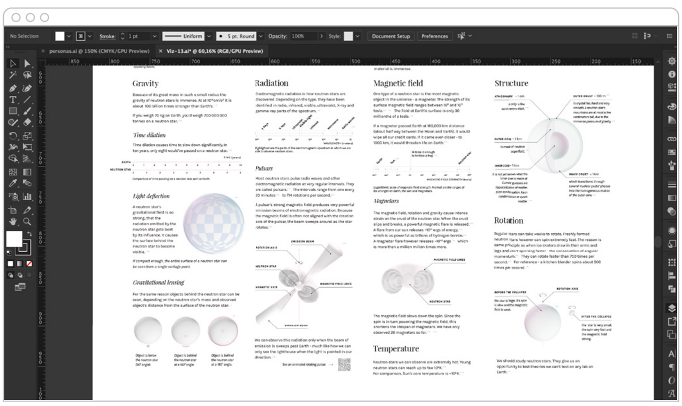


Figure 26: Tuning of visuals in Adobe Illustrator.

~ *Visual language*

The expert astronomer participant in the evaluation session remarked:

> *"I kind of find those artistic impressions of astronomical objects quite annoying because we don't have pictures of them. Okay, it's nice that somebody tries to draw them but it's not the truth."*

These words summarize my approach to the visual aspects in the poster. Artistic renderings of phenomena, that have never been imaged with a photograph, often try to imitate the appearance of photographs to the extent that it is hard to discern what is an actual photo and what is not.

Figure 27: A comparison of an image of Crab nebula taken with the help of telescopes and an artist's impression of a neutron star merger.

Credit: NASA/CXC/SAO(left) and NASA's Goddard Space Flight Center/CI Lab (right).

Also, most astronomical photographs are composites of different wavelengths, stacked on top of each other to reveal intricate interplay of structure of astronomical objects, and therefore by no means represent how the objects would appear to a human eye.

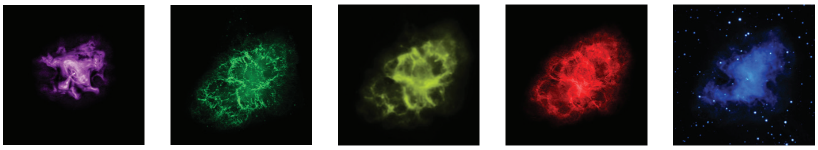


Figure 28: Separate images of the Crab nebula in X-ray, optical, Infrared, radio and UV wavelengths.

Credit: NASA/CXC/SAO

Figure 29: An image of the Crab nebula, composited from many images from telescopes capturing different spectra.

Credit: NASA/CXC/SAO

Even when naturalistic depiction isn't the main objective, pop-science posters still appear with a dark background imitating a night sky. I found that to be confusing and misleading, and tried to go as far as I could from those depictions, and from the canonical approach popular information graphics take. The decision taken corresponds to Tufte's idea to "*[m]aximize the data-ink ratio, within reason*"[55] and only use ink to introduce new information.

55 Edward R. Tufte, *The Visual Display of Quantitative Information* (Cheshire: Graphics Press, 2001), 96.

Since "*[a]esthetic designs are perceived as easier to use than less-aesthetic designs*"[56] my goal was to create an aesthetically pleasing poster, with some implications of scientific credibility, while still not being overly dry.

56 Lidwell, Holden, and Butler, *Universal Principles of Design*, 20.

The typography has evolved through the design process until I settled upon **Fira Sans**, for its wonderful legibility, slight narrowness which proved helpful with the amount of text on the poster, its open licence and availability for both print and web use. I paired it with **Playfair Display** – also an open licensed font, which brings a contrast to the Fira Sans and serves as an homage to the scientific posters I encountered as a child. Albeit this reference to the school poster was later not so well received by one participant in the evaluation session, which I tried to mitigate with changing the colour scheme to a slightly more vibrant one. I also included **Source Serif Variable** font for the equations.

Evaluation phase

In this section I am writing about the various **feedback** sessions held along the design process. After that I layout the plan for the **evaluation session** and **report** from it. I discuss the findings of this evaluation in the next chapter called Discussion, where I critically discuss the methods, approach and results of the evaluation phase and tie those back to the research question.

~ *Preliminary feedback*

During the design process I continuously showcased the poster and its progress. In addition to fellow Visual communication design students who gave ample feedback on the visuals and structure, I showcased the poster multiple times at the Aalto Online Learning group meetings to receive feedback on the structure in the sketching phase, test the interactive content of the poster and gather impressions. Out of those sessions I received feedback on the flow of the information and got acquainted with the issues of using the interactive content: people often did not have updated phone software which would enable AR content on their phones, Apple users often wouldn't realise they have integrated QR scanners in their camera and would start looking for QR code readers in the App store. The AR.js library used for the AR content has bugs that hinder the experience and there wasn't any instruction on the screen once the QR code has been scanned, to instruct people where to point their devices onto. There wasn't much I could do to improve the AR.js library itself, however, I updated the interactive content prototypes with instructions on how to use them, using confirmation as a "technique for preventing unintended actions by requiring verification of the actions before they are performed"[57]

57 Lidwell, Holden, and Butler, *Universal Principles of Design*, 54.

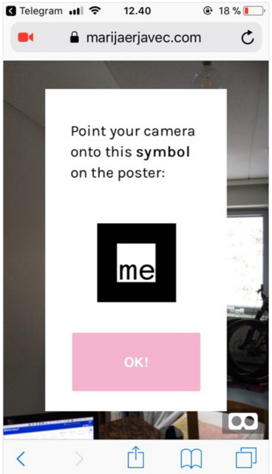


Figure 30: Designed pop-up to guide users where to point their devices.

I also took the opportunity to showcase a version of the poster in the Learning @Aalto Gala event, where I observed how people **interacted** with the poster in a busy setting, what people are **attracted** to, how much time they **invested** in interacting with the poster and what **kind** of people approached it.

There were three main reasons people approached the poster: for some the title was enough to grab their attention since they were astronomy enthusiasts themselves; some didn't know much about astronomy but got intrigued by the visuals and others witnessed people interacting with the digital content of poster and wanted to try it out themselves.

An amateur astronomer expressed interest in having more information in the section of Life cycle of stars about masses and timespans of different states of stars, which I ended up including in the final version of the poster. I also learned that displaying the poster in a frame with a glossy plastic cover makes it difficult for phones to display augmented reality content projected on top of the poster.

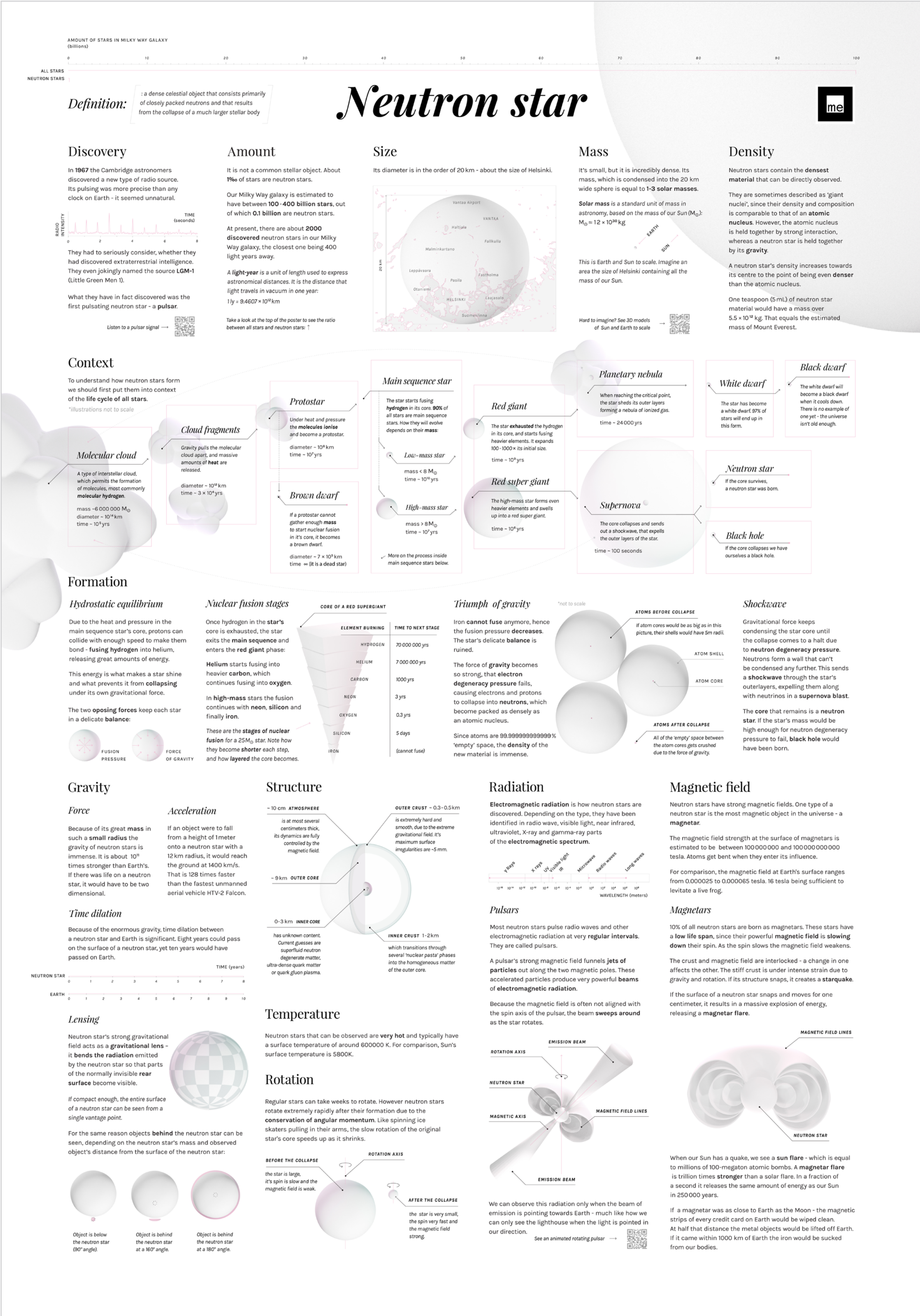


Figure 31: The poster as on December 20th 2017

~ Method

To plan the official evaluation session, I returned to the personas developed in the Planning phase section of this chapter and used them as a *"recruiting profile for participants"*[58].

58 Pruitt and Adlin, *The Persona Lifecycle*, 154.

I surveyed the available techniques for the evaluation session and found the concurrent think aloud, retrospective think aloud, concurrent probing and retrospective probing techniques[59] as most promising. Since I was interested in the thought process of the users as they are going through the poster, and precise usability measurements are not the primary goal of these sessions, I chose the **concurrent think aloud technique**. This technique requires the user to verbalise their thought processes as they are interacting with the poster or completing the tasks requested from them. However, the interaction measurements, such as time needed to complete a certain task for example, are not precise when using this technique, since the users spend time verbalising their thoughts during the session in addition to interacting with the prototype being tested.[60] In contrast, the **retrospective think aloud technique** supposedly yields more reliable measurement results, since the users do not report their thoughts as they interact, but instead debrief after their interaction. However, since the reporting can start to up to an hour since the interaction the users may have a hard time recollecting their thoughts. Since I am more interested in the users thought process I chose the former technique and decided to pair it up with **concurrent probing questions** – asking participants to clarify their thoughts or elaborate on them, where needed.

59 "Planning a Usability Test," U.S. Department of Health and Human Services, accessed March 31, 2018, https://www.usability.gov/how-to-and-tools/methods/planning-usability-testing.html.

60 U.S. Department of Health and Human Services "Planning a Usability Test."

After settling for the techniques to use in the evaluation, I prepared a plan for the session, using the Research-Based Web Design & Usability Guidelines[61]. I set up: the exact **scope**; the **purpose** of the session with listed **concerns** I have, the **questions** I'd like to answer with the session, the **goals** that I'd like to reach with the poster; the **schedule** and location; breakdown of each **session**; **equipment** that will be used; **description** of the type and amount participants I will be looking for; the **tasks** the participants will carry out; the **data** I am interested in collecting from the participants and the sessions. The sections are described in more detail in the next few pages.

61 "Running a Usability Test," U.S. Department of Health and Human Services, accessed March 31, 2018, https://www.usability.gov/how-to-and-tools/methods/running-usability-tests.html.

Scope:

Evaluation sessions testing the Neutron star info-graphics poster prototype as of 22 March 2018

Purpose:

Concerns

Do the participants understand the sequence they should be reading the poster in?
Do the participants understand the visuals?
Do the participants find the visuals helpful?
Can participants understand the explanations?
Is the poster clear?
Do the users find the AR content?
Are they interested enough to take out their phones to see the web content?
Are they able to play the web content with their own phones?

Questions

What can be improved?
Does the poster bring any value to the participants?
Do the participants learn anything new?
Are the participants inspired to learn more about neutron stars in the future?
Do the participants enjoy reading the poster?
What were the participants' expectations?
Were the participants' expectations met?

Goals

Do the participants feel that the content is tailored to their needs?
Did the poster spike an interest in the topic of neutron stars or information design approaches?
Did they learn something about the basics of astronomy that they didn't know before?

Schedule and location:

Four sessions scheduled, one session per persona.

The location is Aalto University premises in Otaniemi: Harald Herlin Learning center at Otaniementie 9 or Aalto ARTS building at Miestentie 3.

Ideally the schedules would be similar for all personas, however, the time of day and hour depending on participants' preferences.

Sessions:

Each session lasts one hour:

Intro (5 minutes)

Welcoming, explaining who I am, what is this project for, what the participants' tasks are, explaining the think aloud technique, asking for permission to record, and ensuring the participation is anonymous. Before starting the testing, thanking them for volunteering, and stressing that it is the poster undergoing a test, not their performance.

Warm up (5 minutes)

Asking the participants to familiarize themselves with the poster, skim through, find parts that seem more interesting and get the overall idea of the poster. Meanwhile I observe their initial reactions without instructing them to report their thoughts yet. After they have seen the poster I ask for initial impressions, how they would go about reading the poster and if there was some part they were particularly interested in.

Interaction (30 minutes)

The participants explore the poster using the think aloud technique. If necessary I ask probing questions for clarifications. If the participants encounter problems that they cannot overcome, I step in and help out, marking that as a major usability issue in the poster. If the participant is very detail oriented I encourage them to focus on certain areas of the poster to stay within the time constraints, and vice versa, if the participant only skims through, I ask them to read a section they previously indicated was more interesting.

Self-reporting survey (10 minutes)

The participants fill out a survey answering questions about their demographics, usability, visuals, interactive elements and structure of the poster, as well as their feelings while and after interacting with the poster and about the topic.

Debrief (10 minutes)

Extra time reserved for possible additional questions and comments of the participants in an informal conversation. This time can also be used as a safeguard in case the participant was late to the session. Questions asked in this part are what the most annoying parts of the poster are, which are the most memorable parts, and asking for feedback.

Equipment

The poster is hung on a wall, a backup iPhone SE is ready for reaching the web-based content, an audio recorder set in place, refreshments prepared, and equipment for filling out the questionnaire: pens, survey papers, chair and table.

Participants

The three participants, one participant per session. Pre-developed personas are used as a recruiting profile:

- Persona 1: 18-34 years old, amateur astronomer
- Persona 2: 35-54 years old, expert astronomer
- Persona 3: 55+ years old, novice.

Gender does not play any importance in recruitment process, they should however be interested in learning about neutron stars or be curious about astronomy in general. I also require them to have lived in Finland for at least 3 months to have familiarized themselves with the size of Helsinki.

Data form the participants:

- Age of the participant.
- Completed level of education.
- Self-reported astronomy knowledge level

Multiple choice questions:

- Ease of reading the poster.
- Ease of understanding the poster's textual content.
- Ease of understanding the poster's visual content.
- Ease of understanding the poster's interactive content.
- Ease of using the interactive content.
- Ease of understanding the phenomenon of neutron stars.
- Ease of finding information on the poster.
- Clarity of the poster.
- How pleasant is the process of reading the poster.
- How pleasant is the interaction with the poster.
- How well chosen was the level of knowledge offered by the poster.
- How joyful was the exploration of the poster.
- How visually pleasing is the interaction with the poster.
- Was there fear about the topic beforehand? If yes, has it been overcome?
- Is there newly found inspiration to read more on the topic of neutron stars?

Open questions about the session.

- What is most annoying aspect of the poster prototype?
- What are the most memorable aspects of the prototype?
- Any other feedback on the poster?

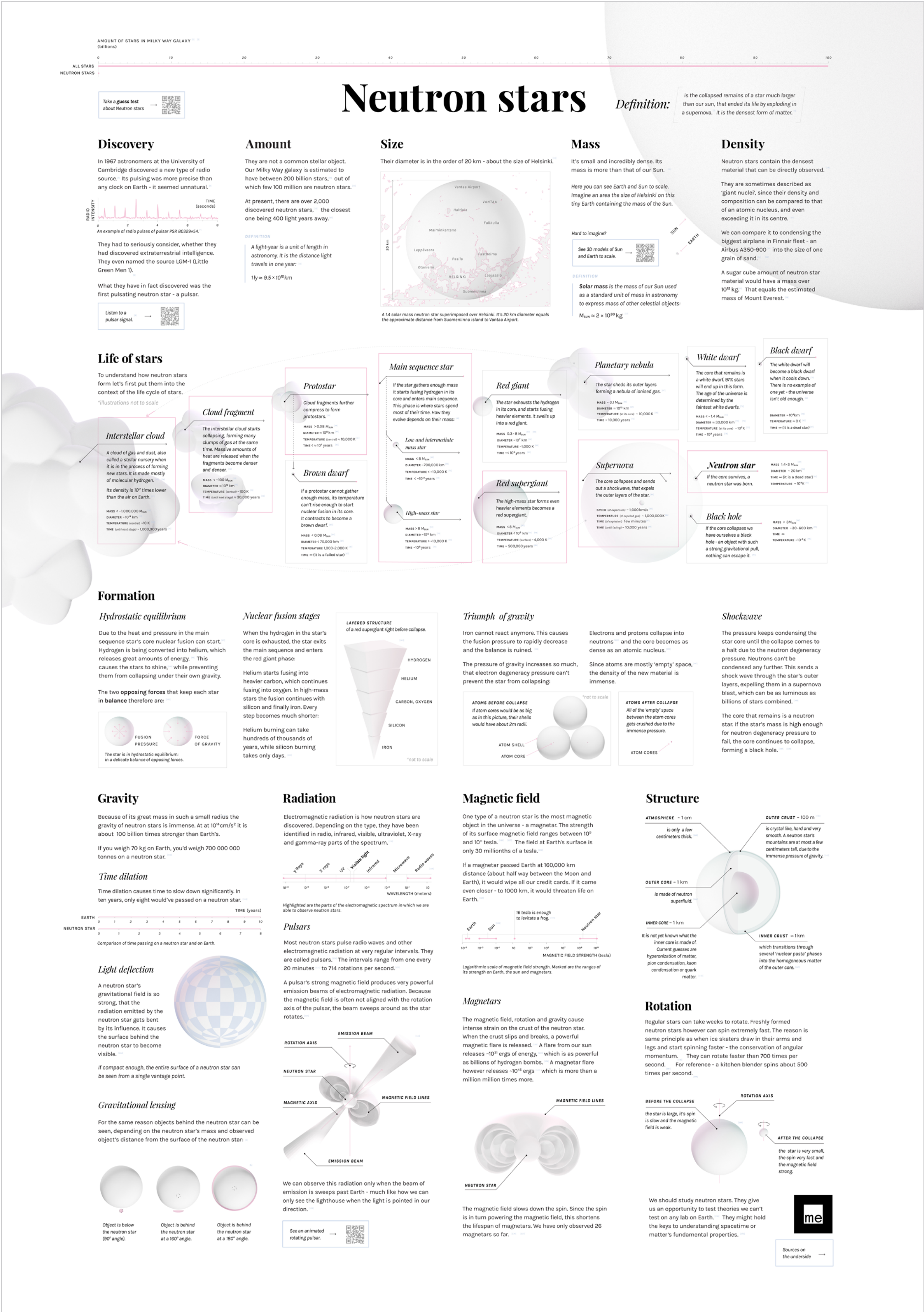


Figure 32: State of the poster at the evaluation phase

~ Sessions

After planning, I contacted people that fit the persona requirements. I arranged sessions with three participants fitting the amateur astronomer and expert astronomer personas in both their level of expertise and their age ranges. However, I couldn't secure a time with a novice older than 55 years as per the third persona, instead I tested the poster with a novice in the mid age range.

The sessions went according to plan and yielded insightful results. Even though the participants are all highly educated, living in Finland and have a common albeit varying interest in neutron stars, their exploration approach of the poster varied greatly. Some took time to meticulously read through sections being deeply interested in detail and others glanced through the poster, felt overwhelmed by the amount of text and instead focused on the visuals, trying to find supporting textual information something sufficiently caught their attention. In addition to the consistent feedback on some issues, there was also quite opposing views and ideas when it comes to the usefulness of the comparisons, clarity of particular visuals and on the structure of the poster.

~ Results

This section starts with an overview of **usability** feedback: touching upon which design choices proved challenging and could be improved; and continues with the participants' overall experience and **sentiment** of interacting with the poster.

The participants were coming from different study fields: some in arts others in sciences. The sample size is too small to make any general conclusions, however it was interesting to observe how people from science backgrounds tended to follow the poster **linearly**, when arts students delved into the poster through visually most **salient features**. Another interesting bit of feedback was how differently the font size was perceived: some reported the font size being annoyingly small, and others felt it was suitable and had no problems reading it. What I found as the most surprising aspect of both the reading styles and font sizes, was how neither seemed connected with the age of the participants.

While the arts student understood the structure quite fast, the other participants reported some troubles in finding the correct reading order, even though all of the participants showed the correct reading order when asked to.

The participants didn't notice the definition of the neutron star, since it was placed in a less prominent upper-right part of the poster, and while reading the poster expressed a need for an overview statement on what a neutron star is. Equally they reported confusion in regard to the bar chart on top of the poster – thinking of it as an element of decor at first.

The lensing section received the most diverging opinions. The expert and amateur astronomer participants deemed it as unclear, needing a legend or explanation, while the novices grasped it immediately and thought it was clear and interesting.

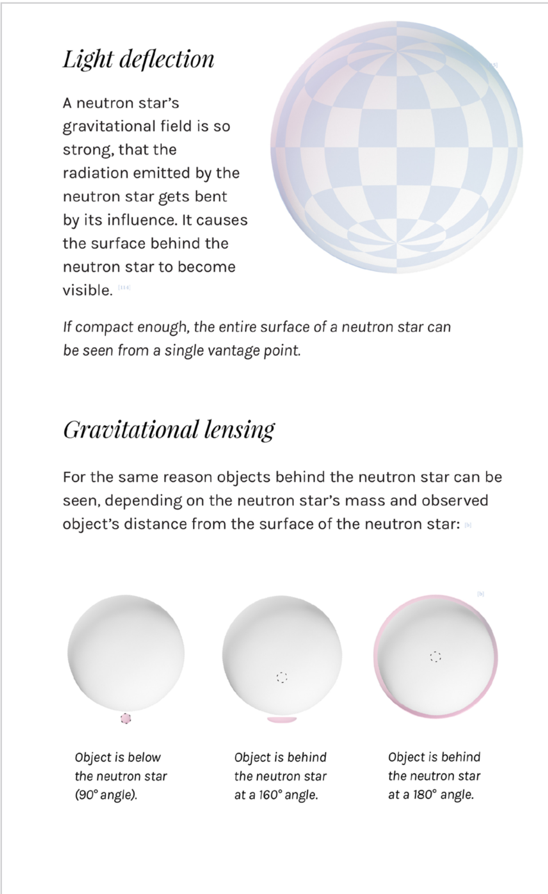


Figure 33: Gravitational lensing and light deflection section of the poster, as it was in the evaluation session.

Adapted from Kraus, "Light Deflection Near Neutron Stars," 66-81.

Across the board participants reported **enjoying** both reading the poster and interacting with it and felt **satisfied** by the level of knowledge offered by it. However, despite the amateur and expert astronomer reporting joyfulness in the exploration of the poster, one of the novices reported feeling overwhelmed by the amount of text.

The QR codes got very little exposure. The amateur scanned the pulsar sound and liked the extra dimension that brought to the poster but didn't feel they had time or enough interest to see the other digital content. About the 3D models the same participant said they have seen animated pulsar models in a course quite recently:

> *"I have seen such things that's why I wasn't so interested in it."*

The expert astronomer felt they didn't have time to spend on these digital features during the evaluation session. A novice participant on the other hand scanned the QR code leading to a guess quiz but hadn't filled it out as they felt it was pointless, since the answers were obtainable from the poster and felt limited with time:

> *"I wanted to try these out, but I didn't want to make the testing too long."*

Surprisingly all of the participants continuously **complimented** the idea of these QR codes with extra content, despite not interacting with them even remotely as much as I had hoped.

Apart from the expert astronomer the rest of the participants appreciated the comparisons used in the poster to clarify topics such as the density of the neutron star:

> *"I liked that you had comparisons in there, to make it easier to understand what it actually is, because numbers are just nothing - just numbers."*

All involved answered that they have become more **interested** on the topic of neutron stars after interacting with the poster.

4 REFLECTION

The evaluation phase offers ground for further improving the poster, as well as insights into how the target audience perceived such an approach to the topic of neutron stars. In the following sections I reflect upon these **findings**, critically assess the **methods** used, and conclude with a **discussion** on which aspects of the approach work well, which do not and what future steps should be taken.

Findings

This section reviews the results of the evaluation in order to answer the research question stated at the beginning:

> *What kind of value can a user-centric information design approach bring to adult novices interested in neutron stars?*

It was interesting to see Holšánová's appeal to think about the character of the reader when planning the structure coming into play so strongly.[62] Indeed, the approach for people patiently reading structures linearly versus readers that explore multiple entry points should be either different or carefully attempted to accommodate both reading styles. This issue is especially relevant in the case of a poster, where the entire content is visible at once. The approach I took for the poster accommodated both reading styles to a certain degree. Both kinds of readers reported enjoying the reading, however I found that for the linear readers a single **entry point** needs to be made more prominent to avoid confusion regardless if the poster is structured linearly or not. For non-linear readers, the **chunks** of information that depend on each other need to be even more prominently connected and clearly separated from chunks that can be read independently. Even though improvements needed to be made after the feedback and evaluation sessions, bringing this twofold idea of structure to the design accommodates both types of readers and can help readers orientate and stay focused on the content instead of structure.

Thinking about personas from the beginning brought the idea of layering the content in a way that to accommodate both the **novice** reader with no astronomy fundamentals, as well as an **amateur** who has never delved deeper into the topic of neutron stars, but has a sound understanding of the bigger picture. The former needs understanding of how stars evolve, while the latter is more interested in the place of the neutron stars within that evolution and in extra information regarding the time of stages in the life of stars.

An interesting finding was that the *Life of stars* continuously proved as the most interesting part of the poster. The expert astronomer expressed interest in using it for teaching purposes and asserting that they haven't encountered it in this form with all the adjacent information and clarity. When studying the topic, the moment when I formed the mental model of how stars evolve, was the moment when all the disconnected pieces of information fell into place in form of an aha moment. I discovered that any article I found on neutron stars or any other similarly specific astronomical phenomenon failed to provide this bigger picture, into which the phenomenon can be placed. In this sense this serves to Shneiderman's idea of **overview first**[63], and shows how important it is to offer underlying structure and context before details. When showing the diagram to people I continuously encountered the 'aha moment'. People had never before holistically understood the evolution of stars until that moment, when the bits and pieces of knowledge they have already gathered fell into place.

The novice and amateur appreciated the **claims** at the start of the poster which were supposed to spark interest in the topic. One novice reported those claims felt friendly and interesting, supporting Kosara's idea of offering claims as attention grabbers, instead of spoiling all surprises further down the reading path by giving the gist away at the beginning with the inverted pyramid structure[64]. The combination of the two approaches proved as an appropriate decision for the infographic poster at hand.

64 Kosara, "An Argument Structure for Data Stories,".

On asking the participants of the evaluation sessions what kind of value the poster brings in comparison to Wikipedia – the latter having hyperlinks to delve deeper into any topic, the participants responded with a similar sentiment:

A novice participant's Wikipedia experience is that *"you might click on the neutron star link but then there's like on and on and on and on paragraphs of scientific, physics, maths [sic] formulas... I'm no physicist, most of that stuff I'm definitely skipping."* Contrasting that with the poster they stated that the poster gives a good overview as a starting point to delve deeper if interested.

Likewise, the expert commented that on Wikipedia *"The depth of information on certain topics varies a lot."* And that *"you really have to read carefully and dig for that correct information, that is very simply said here... [pointing at the poster]"*. The astronomer concluded with:

"For example, for a student that hears about this for the first time, this is completely adequate."

Understanding the **level of knowledge** of the reader and forming the structure, textual content, and visuals accordingly proved as essential. Albeit there is much to be improved in the poster, the participants reported being more interested in the topic after interacting with the poster, and all reported the session being fun and interesting. The amateur and novices continuously reported feeling they had learned plenty.

Methods

Taking a critical approach to the methods used one can notice the pitfall of using ad-hoc personas: contrary to the data-driven personas, ad-hoc personas are based on designer's guesses, biases and assumptions. In order to avoid selecting unusual evaluation participants based on those biases and guesses which would yield flawed results, Adlin and Pruit suggest to "*stick to generic attributes of your personas (such as age and skill level)*."[65] To mitigate this risk the recruiting profiles for the participants in the evaluation were based on age and level of expertise, with the addition of the participants needing to have an interest in astronomy. There also persists the, so called, *WEIRD* problem of only selecting the western, educated, industrialized, rich, and democratic participants[66], which is a common pitfall in any kind of academic research and needs to be acknowledged here as well.

65 Pruitt and Adlin, *The Persona Lifecycle*, 155.

For the evaluation to yield reliable results a bigger participant sample size would be required, as well as another session after the poster has been updated according to the current evaluation session.

The choice of the medium of a poster, despite being made on the basis of paper outperforming screen in regard to student preferences, would need to be critically evaluated and compared to other paper or screen media. Alternatives could be an astronomy zine, a collection of printed booklets, e-book or website.

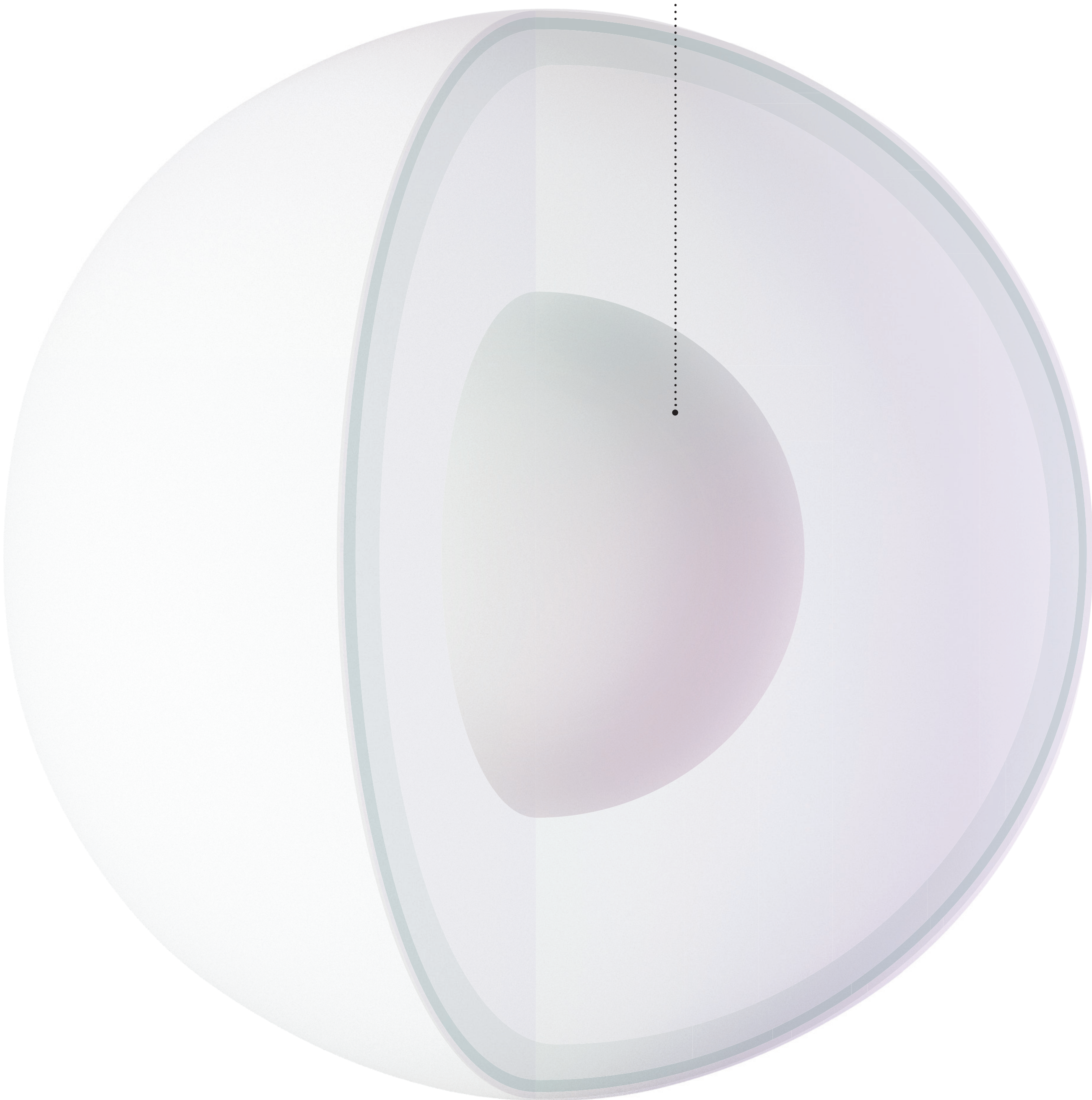
Discussion and future work

The aspects of the information design approach that worked well were the mixture of different approaches to structure, tailored to the task at hand: from both the designer and reader's perspective. Accommodating the different reader styles turned out more important than different age groups.

The benefit of the extra digital content is unclear since it didn't play an important role in the evaluation. It would be interesting to see, whether readers without time constraints of an evaluation session would indeed scan the content or not. As a means to explore that, counters can be set up to see how many times the QR codes have been scanned if the poster was hung in public or private spaces. Instead of finding the optimal software and ways of bringing the interactive content to the poster, the time could be better spent improving the visuals on the poster itself.

To evaluate the benefits of the information design approach an empirical study would be needed on what level of insight people receive from interaction with information graphics and whether this approach supports better **knowledge retention**.

As far as the project itself is concerned, another testing session would be needed to ensure the changes made accommodate the target readers. Expanding the neutron stars poster into a series of posters, each dealing with other astronomical phenomena would be my desired continuation, which would give me the opportunity to test the findings with slightly different content.



5 CONCLUSION

In summary, this thesis identified a gap in available material on neutron stars in the spectrum between the expert material and overly simplified factoids. It addressed the overlooked audience of an interested educated adult without professional astronomical background to find what kind of a value would a user-centric information design approach bring to them via designing an infographics poster on the topic. For this, the thesis offers an overview of information design literature from the perspective of structure and visuals. After touching upon the extensive study of neutron stars and the structure of the narrative, the thesis focuses on the development of ad-hoc personas. The personas influenced the design choices made about the structure, textual and visual content produced. Various augmented reality technologies were reviewed and selected to expand the affordances of a paper poster with digital content. The approaches were tested with multiple feedback sessions as well as with structured evaluation sessions, where participants, fitting the personas defined at the beginning, reported their experience of the poster. The results were connected to the research question stated at the beginning, while findings methods and design approaches were critically reflected upon.

The careful approach to structure proved valuable when accommodating for different reading styles, while the careful attention to the textual content ensured the consistency of the content depth. Others undergoing the communication of similarly complex phenomena, be it astronomical or not, can learn from the theoretical background, the described approach and the evaluation, to avoid the pitfalls and improve confidence in their design decisions. This thesis opens up questions for future studies to empirically verify the benefit of Information design approach in regard to learning and knowledge retention.

Figure 34: Final version of the infographics poster.

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APPENDIX

- Poster reproduction 50 × 70 cm (original size: 100 × 70 cm)
- Poster bibliography
- Evaluation session questionaire

Poster Bibliography

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Aalto University
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and Architecture

Neutron stars

Definition: *A neutron star is the **collapsed core** of a star much larger than our Sun, that ended its life by exploding in a **supernova**.[1] It is the densest form of matter.[2]*

*Take a **guess test** about neutron stars.* →

Discovery

In 1967 astronomers at the University of Cambridge discovered unusual **radio pulses**.[5] The pulses were more precise than any clock on Earth: they seemed unnatural.[6]

An example of pulses astronomers were receiving.[7]

They considered whether they had discovered extraterrestrial intelligence and even named the source of the pulses LGM-1 (Little Green Men 1).[8] What they have in fact discovered was the **first neutron star**.

*Listen to **a neutron star**.*[9] →

Amount

Neutron stars are not common. Our Galaxy is estimated to have about 200,000 million stars,[10] out of which a **few 100 million** are neutron stars.[11]

At present, there are over 2,000 discovered neutron stars,[12] the closest one being **400 light years** away.[13]

DEFINITION

*A **light-year** is a unit of length in astronomy. It measures the distance light travels in a year:*[14]

$1ly \approx 9.5 \times 10^{12} km$

Size

Neutron stars measure about **20km in diameter** which is about the size of Helsinki.[15]

A 1.4 solar mass neutron star superimposed over Helsinki. Its diameter equals the distance from Suomenlinna island to Vantaa Airport.

Mass

They are small and incredibly dense: containing 1.4 to 3 times the mass of **our Sun**.[16]

Imagine an area the size of Helsinki on this tiny Earth containing the mass of the Sun.

EARTH SUN

DEFINITION

***Solar mass** is a standard unit of mass in astronomy. It uses the mass of our Sun to express mass of other objects:*[17]

$M_{SUN} \approx 2 \times 10^{30} kg$

*See **3D models** of Sun and Earth to scale.* →

Density

Neutron stars contain the densest material that can be directly observed.[18] Their density and composition exceeds that of an atomic nucleus.[19]

We can compare it to condensing the biggest airplane in Finnair fleet - an Airbus A350-900[20] into the size of one grain of sand.[21] [22]

A sugar cube amount of neutron star material would have a mass over 10^{12}kg.[23] That equals the estimated mass of Mount Everest.[24]

Life of stars

To understand how neutron stars form let's first put them into the **context** of the life cycle of stars.

illustrations not to scale

Interstellar cloud

The life of stars starts with a **cloud of gas** also called a stellar nursery.[25]

Its density is 10^{17} times lower than the air on Earth.[26] [27]

MASS $< \sim 10^{6} M_{SUN}$ [28]
DIAMETER $\sim 10^{14}$ km [29]
TEMPERATURE ~ 10 K [30]
TIME* $\sim 10^{6}$ years [31]

*until next stage

Fragment

The interstellar cloud starts **collapsing**, forming many clumps of gas.

A lot of heat is released when fragments become denser and **denser**.[32]

MASS $< \sim 10^{2} M_{SUN}$ [33]
DIAMETER $\approx 10^{12}$ km [34]
TEMPERATURE $\sim 10^{2}$ K [35]
TIME $\sim 10^{4}$ years [36]

Protostar[37]

The fragments further **compress** to form protostars.[38]

MASS $> 0.08 M_{SUN}$ [39]
DIAMETER $\approx 10^{8}$ km [40]
TEMPERATURE $\approx 10^{5}$ K [41]
TIME $< \approx 10^{7}$ years [42]

Brown dwarf

If a protostar does not gather enough mass, nuclear fusion **cannot start** in its core: it contracts to become a brown dwarf.[43]

MASS $< 10^{-1} M_{SUN}$ [44]
DIAMETER $\sim 10^{4}$ km [45]
TEMPERATURE $\sim 10^{3}$ K [46]
TIME ∞ **(it is a failed star)** [47]

Main-sequence star

If the star gathers enough mass it starts **fusing hydrogen** in its core. This phase is where stars spend most of their time. How they evolve depends on their mass:[48]

Low- and mid-mass star

MASS $< 8 M_{SUN}$ [49]
DIAMETER $\sim 10^{5}$ km [50]
TEMPERATURE $< \sim 10^{4}$ K [51]
TIME $< \sim 10^{12}$ years [52]

High-mass star

MASS $> 8 M_{SUN}$ [53]
DIAMETER $\sim 10^{6}$ km [54]
TEMPERATURE $> \sim 10^{4}$ K [55]
TIME $\sim 10^{6}$ years [56]

Red giant

The low-mass star uses up the hydrogen in its core. It starts fusing heavier elements and **swells up**.

MASS 0.3 - 8 M_{SUN} [57] [58]
DIAMETER $\sim 10^{7}$ km [59]
TEMPERATURE (*surface*) $\sim 10^{3}$ K [60]
TIME $< \sim 10^{6}$ years [61]

Red supergiant

The high-mass star exhausts the hydrogen in its core, forming heavier elements. It **swells up** even **more** than a red giant.

MASS $> 8 M_{SUN}$ [62]
DIAMETER $< 10^{9}$ km [63] [64]
TEMPERATURE (*surface*) $\sim 10^{3}$ K [65]
TIME $\sim 10^{6}$ years [66]

Planetary nebula

The star **sheds** its outer layers forming a nebula of gas.[67]

MASS $\sim 0.1 M_{SUN}$ [68]
DIAMETER $\approx 10^{12}$ km [69]
TEMPERATURE $\sim 10^{4}$ K [70]
TIME $\sim 10^{4}$ years [71]

Supernova

The star collapses and sends out a **shockwave**, that expels the outer layers of the star.[72]

SPEED (*of expansion*) $\sim 10^{3}$ km/s [73]
TEMPERATURE (*of expelled gass*) $\sim 10^{6}$ K [74]
TIME (*of explosion*) ~ **minutes** [75]
TIME (*until fading*) $\sim 10^{4}$ years [76]

White dwarf

The core that remains is a white dwarf: 97% stars will **end up** like this.[77] The faintest white dwarfs imply the universe's age.[78]

MASS $< \sim 1.4 M_{SUN}$ [79]
DIAMETER $\sim 10^{4}$ km [80] [81]
TEMPERATURE (*core*) $\sim 10^{7}$ K [82]
TIME $\sim 10^{9}$ years [83]

Black dwarf

The white dwarf will become a black dwarf when it **cools down**.[84] There is no example of one yet: the universe isn't old enough.[85]

MASS $< \sim 1.4 M_{SUN}$
DIAMETER $\sim 10^{4}$ km [86]
TEMPERATURE ≈ 0 K [87]
TIME ∞ **(it is a dead star)** [88]

Neutron star

If the **core survives**, a neutron star was born.

MASS 1.4 - 3 M_{SUN} [89]
DIAMETER ~ 10 km [90]
TEMPERATURE $\sim 10^{9}$ K [91]
TIME ∞ **(it is a dead star)** [92]

Black hole

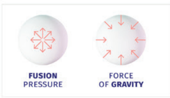
If the **core collapses** a black hole was born. Nothing can escape its gravitational pull.[93]

MASS $> 3 M_{SUN}$ [94]
DIAMETER ~ 30 - 600 km [95]
TEMPERATURE $\sim 10^{-8}$ K [96]
TIME ∞

Formation

Main-sequence phase

In a main-sequence star **nuclear fusion**[97] converts hydrogen into helium.[98] The energy released causes stars to shine,[99] and prevents them from collapsing under their own **gravity**.[100]

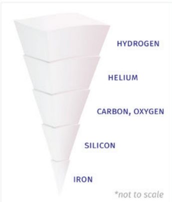


The two opposing forces keeping the main-sequence star in balance.[101]

Giant phase

When the hydrogen in the star's core gets used up, the star enters the red giant phase: heavier elements start to form, **layering up** the core:

Helium fuses into carbon, which fuses into oxygen. In supergiants the fusion continues with silicon and **finally iron**.[102]

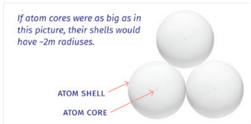


Layered structure of a red supergiant.[103]

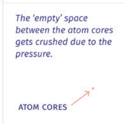
Collapse

Iron **cannot fuse** anymore, which ruins the balance between fusion pressure and gravity.[104] Electrons and protons of the star's core collapse into neutrons.[105]

Since atoms are mostly 'empty' space,[106] the **density** of the material is immense: the star's core becomes as dense as an atomic nucleus.[107]



Atoms before collapse.



Atoms after collapse.

Supernova

Neutrons can't be condensed further: this stops the collapse and sends a **shock wave** through the star's outer layers, expelling them in a supernova blast as luminous as billions of stars combined.[108]

The **core** that remains after the blast is a neutron star. However, if the star's mass is high enough to crush even neutrons, the core continues to collapse, forming a black hole.[109] [110]

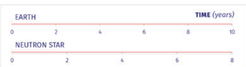
Gravity

Great mass in a small radius results in an immense gravitional force. At $10^{14} cm/s^2$ a neutron star's gravity is 100,000 million times stronger than Earth's:[111] if you weigh 70 kg on Earth, you'd weigh 700 megatonnes on a neutron star.[112]

This causes effects such as time dilation, light deflection and gravitational lensing.

Time dilation

Gravity causes time to **slow down**. In ten years, only eight would've passed on a neutron star.[113]

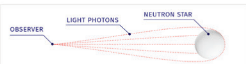


Comparison of time passing on a neutron star and on Earth.

Light deflection

The strong gravitational field bends the radiation emitted by the star. It causes the **surface behind** the neutron star to become visible.[114]

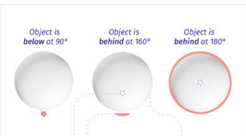
First person view of light deflection. Each checquer shows 30° of the surface.[115]



Side view of light deflection.[116]

Gravitational lensing

Objects **behind** the neutron star can be seen. How they appear depends on the distance from the surface and mass of the neutron star.[117]

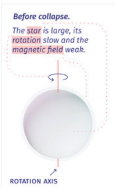


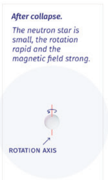
Location and projection of an object in regard to a neutron star.[118]

Rotation

Regular stars can take weeks to rotate once. Neutron stars however can rotate **extremely fast**: up to 700 times per second.[119] A kitchen blender rotates about 500 times per second.[120]

The reason the same as when ice skaters draw in their arms and legs to rotate faster:[121]



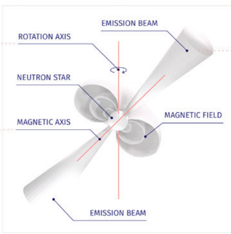


Conservation of angular momentum.[122]

There is one special type of a neutron star that rotates the fastest: a pulsar.

Pulsars

Most neutron are pulsars. Their magnetic fields shape their radiation into powerful **emission beams**.



A model of a special type of a neutron star: a pulsar.[123]

The magnetic and rotation axes are often not aligned: that causes the beams **sweep around** as the star rotates.[124] We can only see pulsars when their beam points towards Earth.[125]

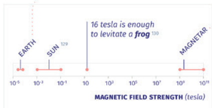
*See an animated **rotating pulsar**.* →

Magnetic field

One special type of a neutron star is the most magnetic object in the universe - a magnetar.[126]

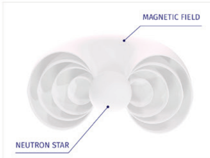
Magnetars

A magnetar's surface magnetic field ranges between 10^{9} and 10^{11} tesla.[127] At Earth's surface it is only a few millionths of a tesla.[128]



Logarithmic scale of magnetic field strength.

Magnetars are rare: we've only observed 26 so far.[131] However, if one passed Earth at a 200,000 km (about half the distance to the Moon), it would **pull** small metallic objects such as pens off Earth while **killing** human kind.[132]



A model of a special type of a neutron star: a magnetar.

The magnetic field **slows down** the rotation. This shortens the lifespan of magnetars since the rotation what is powering the magnetic field in the first place.[133]

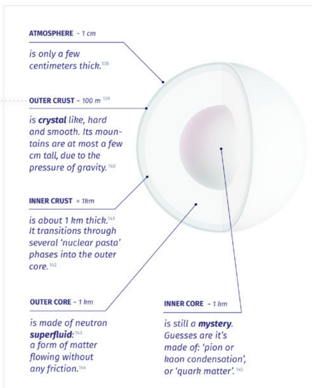
Flares

The crust of neutron stars is under intense strain due to the magnetic field, rotation and gravity. When it slips and breaks, a powerful **magnetic flare** is released.[134]

A flare from our Sun releases $\sim 10^{31}$ ergs of energy[135] which equals billions of hydrogen bombs.[136] A flare from a magnetar, however, releases $\sim 10^{45}$ ergs which is a million million times more.[137]

Structure

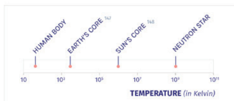
Neutron stars are composed of exotic states of matter. The composition of its core remains a mystery:



Structure of a neutron star.

Temperature

Neutron stars we can observe are **extremely hot**. Young ones can reach temperatures up to $\sim 10^{9}$K.[146]



Logarithmic scale of temperature.

Due to their extremes, neutron stars give us an opportunity to test theories we cannot test in any lab.[149] They might hold the keys to understanding spacetime or matter's fundamental properties.[150]

*See **sources**.* →

Made by **Marija Erjavec** in April 2018 at Aalto University, sources above.

Hello there,

Thank you very much for helping me out. I am **Marija Erjavec**, a Visual Communication Design student at Aalto ARTS. As part of my thesis project I am making a poster about neutron stars, which I am asking you to test today.

I will not disclose any of your personal information – your participation is anonymous. Your anonymized answers will be used as part of my thesis project and to improve the poster.

I will not be using any recordings from our session for any other purpose than to privately listen to them and refresh my memory on how the session went. If I ever wish to use them for any other purpose, I will first ask you for permission.

If this all sounds good, please sign below:

Demographics

Initials

____

Age

____

Highest completed level of education

____

Field of study/profession

____

Level of knowledge about astronomy

- ○ Novice (I don’t know much about astronomy.)
- ○ Amateur (I am interested in astronomy and know quite a bit.)
- ○ Expert (I am a professional astronomer.)

Native language

____

Poster evaluation

It was easy to find the correct reading order of the poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It was easy to understand the textual content of the poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
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It was easy to understand the visual content of the poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It was easy to understand the interactive content of the poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It was easy to use the interactive content of the poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It was easy to understand the neutron star phenomena using the poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It was easy to find information on the poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

The poster is clear:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

I enjoyed reading the poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

Interacting with the poster was pleasant:

- ◯ Strongly agree
- ◯ Agree
- ◯ Neutral
- ◯ Disagree
- ◯ Strongly disagree

The level of knowledge offered by the poster is satisfying:

- ◯ Strongly agree
- ◯ Agree
- ◯ Neutral
- ◯ Disagree
- ◯ Strongly disagree

The exploration of the poster was joyful:

- ◯ Strongly agree
- ◯ Agree
- ◯ Neutral
- ◯ Disagree
- ◯ Strongly disagree

The exploration of the poster was visually pleasing:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

I feared the topic of neutron stars beforehand.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

I overcame the fear of neutron stars after interacting with the poster (only applies if previous answer was ‘agree’ or ‘strongly agree’):

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

I became more interested in neutron stars because of this poster:

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree