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Knowing More than You Think

A study on misconceptions on the accumulation of atmospheric CO_2, and what it means to understand accumulation

Master's thesis for the Master programme Learning and Leadership

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Department of Communication and Learning in Science
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Abstract

Despite global agreements to limit the effects of anthropogenic climate change, emissions of CO_2 continue to rise as societies globally have yet to make the necessary readjustments to turn the trend. It has been suggested by some researchers of public climate science literacy that one reason for public complacency about climate change could be lacking understanding of the relationship between emissions, uptake, and total amount of CO_2 in the atmosphere. Research has shown lay people have difficulties applying fundamental physical principles when performing tasks on CO_2 accumulation by, for example, providing answers implying that the level of atmospheric CO_2 can stabilise even while the rate of emissions of CO_2 exceeds the rate of uptake. This type of misconception, failing to grasp the *stock and flow* (SF) nature of a dynamic system, has been termed *stock and flow failure* (SF failure). Several perspectives have been used by researchers to understand and suggest interventions to counteract SF failure, where one recently suggested perspective aims to elaborate what it means to "understand" SF dynamics. From this perspective, understanding accumulation of atmospheric CO_2 involves several forms of knowledge, and to successfully perform different tasks demands different forms of knowledge.

In order to further investigate using this perspective to explain the frequency of SF failure, a survey was conducted on engineering students (N=131) at Chalmers University of Technology, Gothenburg. The survey was designed to quantitatively study to what extent people possess the knowledge of the concepts and procedures required to successfully perform tasks on accumulation of atmospheric CO_2, but lack the demanded knowledge of when to apply these concepts and tools. Also, misconceptions regarding processes through which CO_2 is removed from the atmosphere were investigated, as well as possible correlations between misconceptions concerning CO_2 accumulation and opinion on emission reduction.

The results of the study show that people perform differently on a variety of tasks considered to demand the same knowledge of concepts and procedures, which could be explained by difficulty of knowing when to apply these concepts and procedures varying across the range of tasks. This substantiates a suggestion made in previous research, that high rates of SF failure in the CO_2 context could be heavily influenced by inability to invoke and apply the required knowledge, rather than simply not knowing. Also, novel results are presented showing major misconceptions concerning removal of CO_2 from the atmosphere, where subjects heavily underestimate uptake of CO_2 by the ocean, and believe notable amounts of CO_2 leaves the atmosphere into space or decomposes. Further, no clear correlations between opinion on emission reduction and SF failure was found. Implications for practise and future research are discussed.

Keywords: Accumulation of CO_2, Climate Change, Climate Science Literacy, Public Opinion, SF failure, Uptake, Misconceptions

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Contents

List of Abbreviations

- CK - Conceptual Knowledge
- CSL - Climate Science Literacy
- CTH - Chalmers University of Technology
- DAC - Direct Air Capture
- GC - Graphical Criteria
- GHG - Greenhouse Gases
- IPCC - The Intergovernmental Panel on Climate Change
- MIT - Massachusetts Institute of Technology
- PK - Procedural Knowledge
- Q - Question
- SBS - Sterman & Booth-Sweeney
- SF - Stock-and-Flow
- SK - Situational knowledge
- T - Task

1

Introduction

In this chapter, a short overview of the research context is presented, followed by research aims, delimitations, and the thesis layout.

1.1 Research Context

On the 12th of December 2015 in Paris, 195 countries adopted a universal legally binding agreement to make efforts to limit the global mean temperature increase, or "global warming", to *"well below 2°C above pre-industrial levels"*. The agreement, commonly known as the Paris Agreement, also states that efforts should be made *"to aim to limit the increase to 1,5°C, since this would significantly reduce risks and the impact of climate change"*[5].

The global mean temperature is on the rise due to increased amounts of greenhouse gases (GHG) in the atmosphere, enhancing the so called *"greenhouse-effect"*, where increased amounts of radiation is reflected back towards the surface of the earth, thus lowering the net amount of heat leaving the planet. It is uncertain how high levels of GHG can be allowed for before their contribution to global warming surpasses a chosen climate target, such as the 1,5° C increase limit of the Paris agreement[8]. Even when determining the current temperature increase since pre-industrial levels, the margin of error is fairly large (as concluded in the 2018 report from the Intergovernmental Panel on Climate Change, IPCC, the temperature increase to date lies within the range of 0,8° C to 1,2° C). With the current increase in emissions, global mean temperature rise is estimated to reach 1,5° C above pre-industrial levels somewhere between the year 2030 and 2052[10].

While there are several important GHG, the greatest contribution to long lived anthropogenic temperature increase comes from emissions of carbon dioxide (CO_2) to the atmosphere (mainly through burning of fossil fuels, such as oil and coal)[17]. Contrary to the addition of CO_2 to the atmosphere through emissions, CO_2 is also removed from the atmosphere through "uptake" to vegetation and the ocean[10]. The change in level of atmospheric CO_2 over a time period is the cumulative difference in emission and uptake, and for as long as emissions exceed uptake the level of atmospheric CO_2 will continue to increase. In order to stabilise the level of atmospheric CO_2, so called "net zero emissions" must be achieved (i.e. emissions must be equal to uptake).

Public understanding of systems governing climate change is studied in the Climate Science Literacy (CSL) field. One aspect of this field is studying people's perception of the relationship between emissions, uptake and total amount of atmospheric CO_2, which could be important in understanding public complacency about global warming, some researchers suggest[23][4][3], a correlation that has yet to be substantiated. What has been shown, however, is that even well educated people face difficulties solving tasks on accumulation of atmospheric CO_2. A majority have been shown to fail to apply fundamental physical principles to tasks on CO_2 accumulation, violating conservation of mass[23][15][4][3][25]. This has come with displays of various forms of erroneous reasoning, such as arguing that the amount of atmospheric CO_2 will stabilize for as long as the difference between emissions and uptake stays constant, or focusing on unrelated facts and opinions about climate change.

Several perspectives have been used to study the causes of these results, in order to design and improve interventions. In the current study, a quantitative method was used to further investigate one perspective where "understanding how" the accumulation of atmospheric CO_2 works is divided into different forms of knowledge. The theory of knowledge selected for this study includes *conceptual* (knowing *what*, concepts, principles etc.), *procedural* (knowing *how*, how to use principles to perform calculations etc.) and *situational knowledge* (knowing *when*, when to apply conceptual and procedural knowledge, and when not to)[11].

1.2 Aims

The aim of this study was to contribute to the Climate Science Literacy (CSL) field by providing more information about how people understand atmospheric CO_2 accumulation. This was done by studying people's performance completing tasks on accumulation of atmospheric CO_2 in order to investigate whether or not people can possess the conceptual and procedural knowledge demanded by these tasks, but lack the demanded knowledge of when to apply concepts and procedures correctly. In addition to this, misconceptions concerning processes through which CO_2 is removed from the atmosphere were studied, as well as possible correlations between opinion on emission reduction and understanding the relationship between emissions, uptake and amount of atmospheric CO_2.

1.3 Research Questions

To support the aim of the study, the following main research questions were formulated:

1. *Can failure to successfully perform tasks on accumulation of atmospheric CO_2 be attributed to lacking knowledge of when to apply the required concepts and procedures?*
2. *When studying people's perception of how CO_2 is removed from the atmosphere, what misconceptions can be found and to what extent do these occur?*

3. *Is there a connection between understanding the relationship between emissions, uptake and amount of atmospheric CO_2, and opinion on reducing emissions of CO_2?*

1.4 Delimitations

- The perspective on SF failure using different forms of knowledge was only studied with regards to accumulation of atmospheric CO_2. Task performance concerning systems that can be described with SF dynamics were not studied in general.
- Establishing a new theory on forms of knowledge was not one of the aims of this study, instead, a suitable theory was selected from existing ones and interpreted for use in the current context.
- Finding a connection between understanding the relationship between emissions, uptake and amount of atmospheric CO_2, and further engagement (beyond opinion on emission reduction) was an aim of this study.
- The focus of this study was on forms of knowledge. Ways of reasoning and heuristics were discussed in their relation to forms of knowledge, but were not studied in detail.
- Due to the vast amount of data collected, and limited resources (mainly project time and supervisor time) the data analysis was limited to be descriptive. Further analysis of the data collected has been left to future research.

1.5 Thesis Layout

The layout for the remaining chapters of this thesis is as follows:

2 Background
In this chapter, an overview of previous research on people's understanding of accumulation of atmospheric CO_2 is presented, while the description of the misconceptions that are to be investigated are elaborated. The theory of knowledge used in this study is also described in more detail.

3 Method
In this chapter, the methods used for data collection and analysis are presented.

4 Results & Analysis
In this chapter, the results of the study are presented and analysed in preparation for an in depth discussion in the following Chapter, 5 Discussion.

5 Discussion
In this chapter, the results and the methods used are discussed, as well as implications for climate science communication and future research.

6 Conclusions
In this brief chapter, a few main conclusions drawn in the previous Chapter, 5 Discussion, are summarised.

Appendix A
This appendix contains a list of graphical criteria for the graphical tasks, as well as the matrix used to relate the criteria to the different elements of knowledge.

Appendix B
This appendix contains additional figures and tables related to results from the survey.

2

Background

In this chapter, an overview of previous research on people's understanding of accumulation of atmospheric CO_2 is presented, while the description of the misconceptions that are to be investigated are elaborated. The theory of knowledge used in this study is also described in more detail.

2.1 Public Misconceptions on Accumulation of Atmospheric CO_2

In the following subsection, two important concepts, Stock-and-Flow dynamics and Stock-and-Flow failure, are described. Next, existing literature on public understanding of the Stock-and-Flow nature of CO_2-accumulation has been reviewed. Finally, forms of removal of CO_2 from the atmosphere are described briefly, along with some misconceptions concerning processes through which CO_2 can be removed from the atmosphere noticed in previous research.

2.1.1 Stock-and-Flow Dynamics and Stock-and-Flow Failure

A fundamental and important part of understanding dynamic systems is understanding the relationship between *stocks* and *flows*, where flows add to or subtract from a stock[2]. Stock-and-Flow dynamics (SF-dynamics) can be found in many every day examples, such as:

- Money in a bank account (stock) and income/expenses (flows).
- Water in a sink or bathtub (stock) and inflow through the tap/outflow through the drain (flows).
- Population (stock) and birth rates/death rates (flows).

A schematic description of SF-dynamics can be seen in Figure 2.1.

Several studies have shown lay people have difficulties applying SF-dynamics to an array of dynamic systems, such as people entering and leaving a store[2], a food resource being consumed and replenishing[14], the water level of a bathtub and the amount of money in a bank account[22], and CO_2-accumulation[23][15][4][3]. Erroneous reasoning about such systems, where conservation of mass is violated, has been termed Stock-and-Flow failure (SF-failure).

Figure 2.1: Schematic representation of Stock-and-Flow (SF) dynamics, with one stock, one inflow, and one outflow.

2.1.2 Stock-and-Flow Failure in the CO_2 Context

Several studies have investigated public understanding of the relationship between emissions, uptake and amount of atmospheric CO_2, i.e. the SF nature of the system. (e.g. [23][15][4][3]) In one article (Sterman & Booth-Sweeney, 2007)[23] titled *"Understanding public complacency about climate change: adults' mental models of climate change violate conservation of matter"*, the authors presented the results of a study where MIT-students (Massachusetts Institute of Technology) were asked to perform tasks on the relationship between emissions, uptake and accumulation. In one of the tasks, a reference graph was shown where the amount of CO_2 is stabilised from year 2050 to year 2100 at a slightly higher level compared to year 2000. The tasks included descriptive information, suitable for policymakers or well informed laypeople that was quoted or paraphrased from the *Summary for Policymakers* in the IPCC's Third Assessment Report[9]. The description provided cues hinting to the relationship between the emissions, uptake, and level of atmospheric CO_2 by describing how CO_2 is added to the total amount in the atmosphere through emissions, and how natural processes remove CO_2 from the atmosphere. Subjects were asked to draw trajectories for emissions and uptake for the rest of the century, in a way that is consistent with the reference graph, meaning trajectories for emissions and uptake must coincide during year 2050 to 2100. Figures similar to those used in (Sterman & Booth-Sweeney, 2007)[23], that were used as material in the current study, are shown in Figure 2.2 and Figure 2.3. This type of task will henceforth be referenced to as the Sterman & Booth-Sweeney-task (SBS-task).

In another task, similar to the SBS-task including the same descriptive information, a reference graph shows the total amount of atmospheric CO_2 gradually decreasing from year 2000 to 2100, where it stabilises. Using this graph as a reference, subjects in a different sample group were asked to draw trajectories for emissions and uptake in a figure similar to Figure 2.3. A summary of the results of both tasks showed that 84% of subjects drew trajectories for emissions and uptake in a way that was not consistent with the reference graphs. In 63% of the responses, emissions were drawn to exceed uptake, and the authors point out that the responses where emissions exceed uptake even when the amount is supposed to stabilise is *"analogous to arguing a bathtub filled faster than it drains will never overflow"* and suggest that

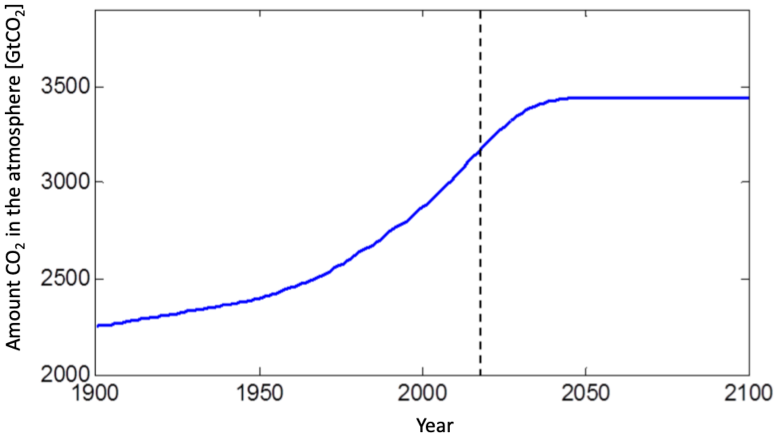


Figure 2.2: Reference graph showing the total amount of atmospheric CO_2 over time, stabilising around the year 2050. Similar to the graph used by (Sterman & Booth-Sweeney, 2007)[23].

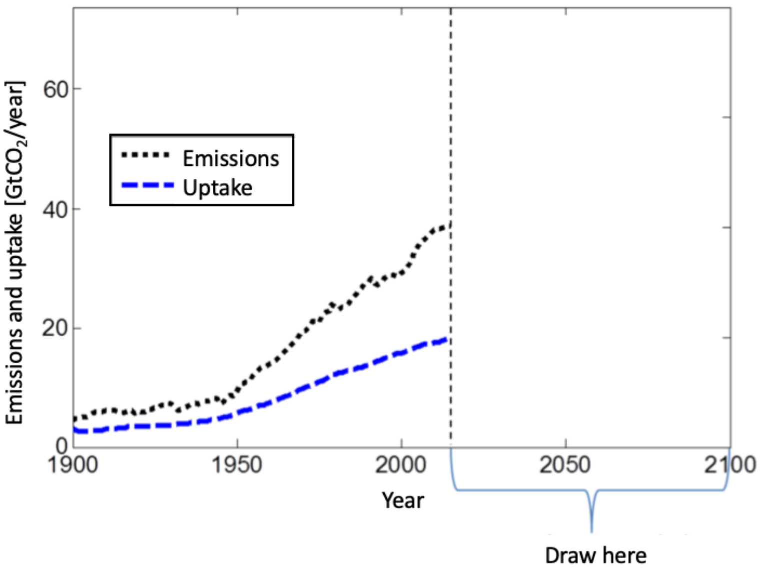


Figure 2.3: Trajectories for emissions and uptake over time, with the rest of the century from present time left for the subject to complete. Similar to the graph used by (Sterman & Booth-Sweeney, 2007)[23]. **Note**: In the original graph, the trajectory for uptake is not drawn, instead, the level of uptake at present time is marked.

these beliefs *"support wait-and-see policies"*, i.e. supports policies where action to prevent climate change are postponed until the effects of climate change is more noticeable. The same suggestion was made by (Sterman 2008)[21] in a 2008 article in Science, and others have also suggested similar connections between SF-failure and low support for emission-regulating policies[4][3]. There has, however, not been shown there is a correlation between SF-failure and low policy support. In one study, (Sterner et al., 2018)[25] showed that being able to apply SF-dynamics in the CO_2-accumulation context was not a requirement for supporting stringent policies on emission reduction[25].

In the same study, (Sterner et al., 2018)[25] used a questionnaire divided into three parts in order to assess people's understanding of accumulation of atmospheric CO_2. The first part consisted of a similar task (T1) to that of the SBS-task, where subjects selected one out of four figures for future trajectories of emissions and uptake. In short, these four figures depicted scenarios where 1) Emissions and uptake continue to rise with a stabilised difference between the trajectories 2) Emissions and uptake stabilise, at different levels, slightly above current levels 3) Emissions and uptake coincide and decline together (correct)[1] and 4) Uptake exceeds emissions. For this question, only 21% successfully selected the correct alternative[25].

The second part of the questionnaire was divided into three versions, one of which consisted of another multiple choice question (T2A) where subjects selected one out of four alternative statements, each describing a relationship between emissions and uptake, where the task once again was to select the alternative that must be true in order for the total amount to stabilise. The implications of the four alternative statements mirrored the four alternative figures in the first task. In this task, 54% of the subjects selected the correct answer, a significantly higher rate of success compared to T1. Different success rate has been noticed in other research as well. In one study[6], higher success rates were also shown on tasks using a verbal format compared to a graphical format, and the authors suggest interventions could be more effective using more verbal information. However, (Sterner et al., 2018)[25] argue for using a different perspective, where the difficulty of successfully completing tasks on accumulation of CO_2 depends on the knowledge demanded by the task. Using a theory of knowledge[1], the authors argue that people may have the *declarative* and *procedural* knowledge needed to complete tasks on stocks and flows, but fail to invoke the knowledge demanded by the task due to lacking *conditional* knowledge. From this perspective, different task formats varies the knowledge demanded by the task. In section 2.2, a similar theory of forms of knowledge, including *conceptual*, *procedural* and *situational* knowledge, has been reviewed.

2.1.3 Removal of Atmospheric CO_2

In the present situation, there are two forms of removal of CO_2 from the atmosphere; uptake to vegetation and uptake to the ocean. In short, uptake to vegetation oc-

[1]The reason emissions and uptake decline after coinciding is that excess uptake to the ocean decreases as emissions of CO_2 to the atmosphere decreases [9].

curs through the process of photosynthesis, while uptake to the ocean occurs due to CO_2 dissolving in the ocean, to thereafter react with H_2O to form carbonic acid (H_2CO_4)[10]. Uptake by artificial means, such as Direct Air Capture (DAC), currently exists only as smaller scale research or pilot projects[13] and removes comparatively insignificant amounts of CO_2 from the atmosphere.

Although uptake to oceans and vegetation are both significant forms of uptake, both heavily affecting the level of atmospheric CO_2, in one interview study only 7 out of the 10 participating interviewees mentioned vegetation and 3 mentioned the ocean when asked to describe what is important for the amount of CO_2 in the atmosphere [24]. In addition, 2 interviewees displayed a misconception that CO_2 leaves the atmosphere into space[26]. This misconception, as well as other potential misconceptions on removal of atmospheric CO_2, has been investigated using methods presented in the next Chapter, 3 Method.

2.2 Epistemological Perspective

There are several theories describing how knowledge used in performing tasks can be categorised. In their 2018 study, Sterner et al. used a theory of knowledge by (Biggs 2003)[1] where knowledge is described to be divided into *"declarative (knowing what), procedural (knowing how), and conditional (knowing when) knowledge."* Since the purpose of this study is to assess whether or not performing tasks on accumulation of atmospheric CO_2 includes use of knowledge that can be categorised in some way, and not to confirm the use of a specific theory of knowledge, a similar, yet in some aspects different theory was used, compared to the one used by (Sterner et al. 2018). The theory selected, based on (de Jong Ferguson-Hessler, 1996)[11] involves two dimensions, *types* and *qualities* of knowledge. For this study, using only types of knowledge was deemed sufficient for the project aim. The types of knowledge includes *conceptual*, *procedural*, *situational*, and *strategic* knowledge, described in more detail below.

- **Conceptual:** static knowledge. Conceptual knowledge includes principles, formulas and facts that apply within a certain domain. For example: being able to declare Newton's second law of physics, $F = m * a$.
- **Procedural:** valid manipulations or actions. Can be domain specific or more general. Procedural knowledge is used to transform a task from one state to the next. For example: being able to use Newton's second law of physics to calculate the force required to accelerate a car weighing $1500kg$ by $5m/s^2$.
- **Situational:** being familiar with tasks as they typically appear. Situational knowledge is used to add information to the information provided by the task, as well as discerning what information is relevant for solving the task. Situational knowledge is realising in what situations to apply conceptual and procedural knowledge, and in what situation not to. For example: being familiar with tasks on aerodynamics and therefore realising that a car in motion is subjected to air resistance even though it's not mention in the problem description. Also, being familiar with tasks how vehicles are powered, and

therefore realising that the type of fuel mentioned in the task description does not influence the force needed to accelerate a car.

- **Strategic:** knowledge of meta cognitive nature about how one can structure the problem solving process in order to reach a solution. It is applicable to a wide variety of problems and generally not domain specific. For example: using Polya's four-step plan[18] for solving a problem on a car accelerating, where the four steps are 1) understanding the problem 2) designing a plan, 3) carrying out the plan, and 4) looking back.

In the coming chapters, a distinction was made made between different *manifestations of knowledge*. The terms that have been chosen are *possessed*, *applied* and *displayed* knowledge. To make it clear in what sense these terms are used, definitions are presented below. These definitions are not based on any established theories and should not be treated as such.[2]

- **Possessed** knowledge is the conceptual, procedural and situational knowledge considered to be all the knowledge an individual has available for use when performing a task.
- **Applied** is possessed knowledge that has, in one way or another, been used performing the task.
- **Displayed** knowledge is representations of the applied knowledge made available for interpreters in drawn and written answers.

A simple schematic representation of the distinction between possessed, applied and displayed knowledge used in this study can be seen in Figure 2.4.

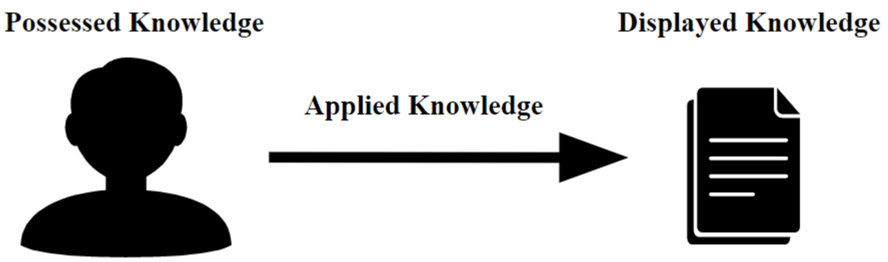


Figure 2.4: Schematic representation of the distinction between the three terms *possessed*, *applied* and *displayed* forms of knowledge, used in this study.

[2]Attempts were made to find suitable theories describing different manifestations of knowledge. Search words used (Google Scholar search engine): "Displayed knowledge", "Explicit and tacit knowledge", "Demonstrated knowledge", "Manifestations of knowledge", "Knowledge application", "Knowledge application theory", "Identify knowledge", "Identifiable knowledge", "Knowledge Assessment", "Definition Knowledge", "Knowledge in use".

3
Method

In this chapter, the methods used for data collection and analysis are presented.

3.1 Study Overview

This section presents an overview of the study, while in the following sections the methodology used in the different major parts of the study is described in more detail. The study process, illustrated in Figure 3.1, included four parts: survey preparations, questionnaire design, questionnaire execution, and data analysis.

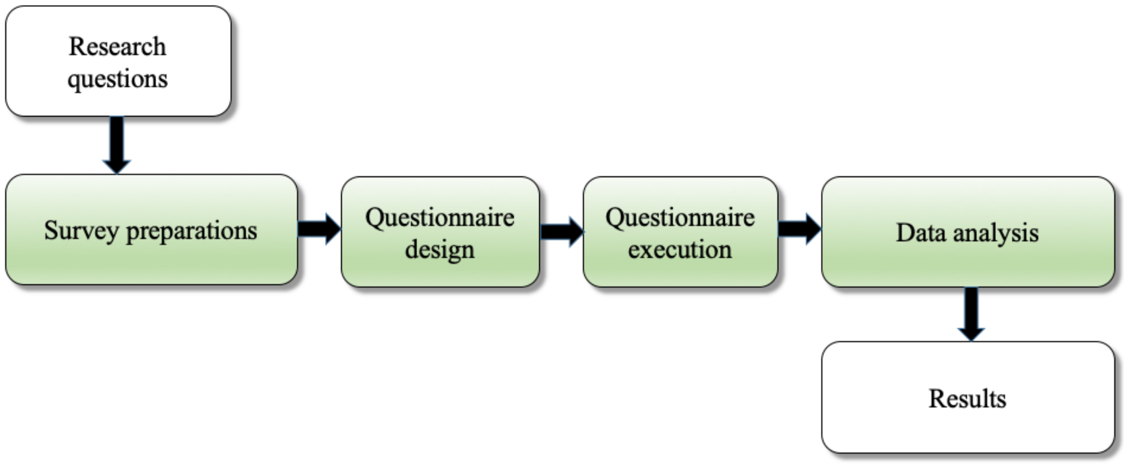


Figure 3.1: Simplified overview of the study process. Once initial research questions were chosen, the survey preparations began, which lead to designing a questionnaire and executing it. Final results were then produced by analysing the questionnaire data.

Survey preparations included studying literature on theories of forms of knowledge, studying literature on previous research on SF-failure, and selecting a method for data collection. A previous questionnaire by Erik Sterner (supervisor) and his colleagues was also studied, along with responses to it.

3.1.1 Data Collection Method - a Questionnaire

Questionnaires have been extensively used in research on public understanding of SF-dynamics, in both the CO_2-accumulation context as well as other contexts (e.g.

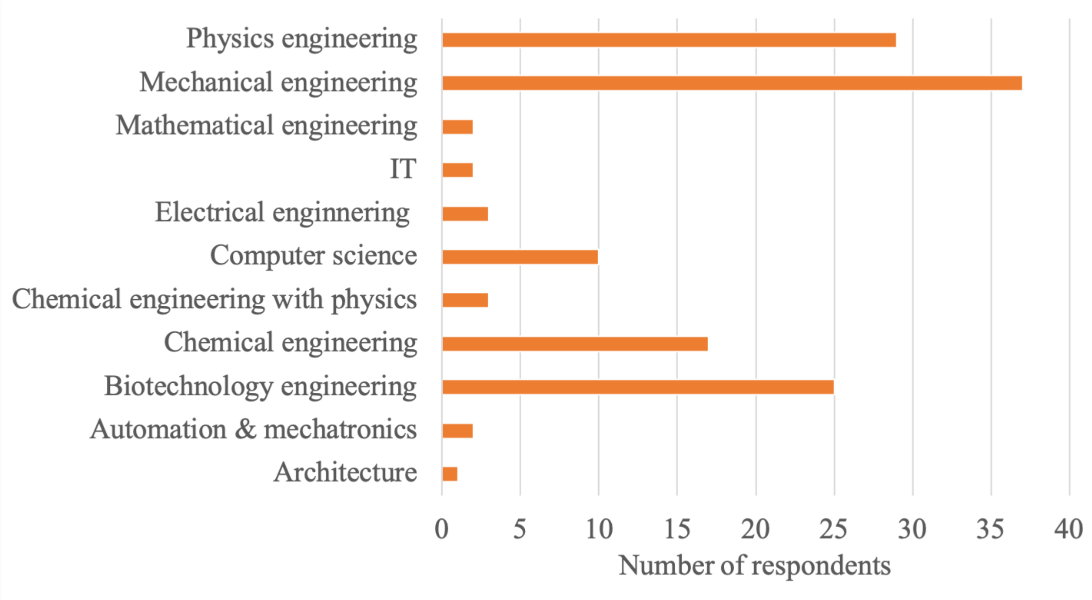


Figure 3.2: Distribution of students participating in the questionnaire, from different study programs at Chalmers University of Technology, Gothenburg.

[23][25][15][4][3]). Therefore, using the same format for this study may improve the possibility to make comparisons with previous research. Using a questionnaire also allowed for greater quantities of data to be collected within the time frame of the study (compared to e.g. collecting data through interviews), which benefited the quantitative method used in this study. A questionnaire can also easily be designed to include a variety of task formats, including multiple choice, drawing figures, written explanations, and marking scales. It also ensures each participant is presented with the exact same descriptions and questions, which may be more difficult with a more dynamic method, such as interviews.

3.1.2 Participants

The study took place at Chalmers University of Technology (CTH), Gothenburg, where a variety of engineering students (N=131) participated in the questionnaire. Students from all programs and years at CTH were allowed to participate, although only a number of programs were notified of the study taking place in advance. The distribution of students from different programs is shown in Figure 3.2. Of the 131 participants, 42 where women, 86 men, 2 other, and 1 participant who did not disclose their gender. Most students (128) studied at bachelor level, and few (3) at a master's level. The average age was 21 years, where the youngest participant was 18 years old, and the oldest 29. Throughout the report, the terms "participant", "respondent", and "subject" are all used to refer to the students participating in the survey.

3.2 Questionnaire Design

The questionnaire was in part designed using tasks similar to tasks used in previous research (e.g. SBS-task), with varying degree of alteration, and in part with new tasks created specifically for this study. Not all data collected by the questionnaire is presented as results, nor used in the discussion that follows, as the extensiveness of the data collected allowed for a large variety of analyses for which the resources (mainly time and supervisor time) of this study were not sufficient. The full questionnaire, however, is described in this chapter as the questionnaire itself and the data collected may be suggested for future research, for further analysis of the data and using the questionnaire as a template.

3.2.1 Questionnaire Overview

The questionnaire consisted of seven different parts, each explained in detail below. Each part consisted of multiple tasks and/or questions, where tasks demand some degree of problem solving, while the questions collect data on demographics, or the respondents' opinions, reflections and perceptions. It was assumed that most students at Chalmers University of Technology have Swedish as their first language. Therefore, the questionnaire was designed in Swedish to reduce misunderstandings due to language difficulties. There were two different versions of the questionnaire, version A and B, with 50% of the participants taking version A and 50% version B. The two versions were distributed randomly, meaning no difference was made between participants taking version A or B. The only difference between the two versions was the descriptive text of the main task in Part 2, which is described in more detail in Section 3.2.4. Also, Part 6 included a copy of the task in Part 2, added in order to investigate difference in performance before and after attempting Parts 3-5.

Each description of the different parts below begins with an overview of the tasks and/or questions for that part. The notations for tasks and questions are "TX.Yz" and "QX.Yz" respectively, where "X" refers to the part number, "Y" to the consecutive order in which it appears in that part, and "z" to a sub-part of that task/question, noted with a letter. For instance, Part 3 consists of one task and one question, which have the notations T3.1 and Q3.2. The question in consecutive order five, in Part 5, consists of six sub-parts, which have the notations Q5.5a, Q5.5b, etc.

3.2.2 Questionnaire Introduction

The front page of the questionnaire had an introductory text. It explained the context of the survey, that the participants would stay anonymous, and how they were to answer the questionnaire. They were instructed not look ahead but to look at the questions in the order they appear, and once they had written an answer and moved on to the next questions, they were asked not to go back and change their answer later. Participants were also encouraged to give their honest thoughts and reflections when answering, not what they thought the questions expected them to answer, or trying to make answers "politically correct". While the questionnaire was written in Swedish, participants were informed answers in Swedish and English were both accepted.

3.2.3 Part 1: Background

Overview

- Q1.1: Asked for the respondent's gender
- Q1.2: Asked for the respondent's age
- Q1.3: Asked for the respondent's current university program
- Q1.4: Asked which year of the study program the respondent currently studied
- Q1.5: Asked which program the respondent studied in high school
- Q1.6: Asked if the respondent had attended any courses with focus on environmental sciences (and which)
- Q1.7: Asked if the respondent had been or was part of any environmental organisation
- Q1.8: Asked if the respondent thinks emissions from use of fossil fuels should be reduced. (Yes/No)
- Q1.9a: Asked by how much the respondent thinks emissions from use of fossil fuels should be reduced until 2030
- Q1.9b: Asked by how much the respondent thinks emissions from use of fossil fuels should be reduced until 2050

The purpose of Part 1 was mainly to gather data about the sample's demographics. It included nine questions asking background questions, e.g. gender, age, study program, former experience in environmental science etc. The last two questions asked about the participants opinion rather than demographics. Q1.8 asked, translated from Swedish: "do you believe humanity should reduce emissions of CO_2 [from use of](due to an error, "from use of" was excluded in the questionnaire) fossil fuels?". Respondents could mark two options, "Yes" or "No". The last question (Q1.9a-b) asked the participant by how much emissions should be reduced (in %) until 2030 and 2050 respectively, if they had answered "Yes" on the previous question.

3.2.4 Part 2: Emissions and Uptake for a Future Scenario

Overview

- T2.1: The respondent was asked to draw trajectories for emissions and uptake, based on a reference graph showing total amount of atmospheric CO_2 stabilising
- Q2.2: Asked the respondent to describe the reasoning behind their response to T2.1

Part 2 consisted of one task (T2.1) and one question (Q2.2), where the question asked for the respondents reasoning behind solving the task. T2.1 was similar to the main tasks in Sterman and Booth-Sweeney's, and Sterner's, research [23][25], where emissions and uptake had to be drawn (see Figure 3.4), given a future scenario for the amount of atmospheric CO_2 (See Figure 3.3). The task began with a descriptive text and a graph showing estimated historic emissions and uptake, i.e. the first part of Figure 3.4, from 1900-2019[1]. The descriptive text came in two different versions, A and B. The description in version A included information necessary for understanding the task, and redundant information, whereas version B only included the necessary information. The necessary information explained what emissions and uptake are, and that the amount of atmospheric CO_2 has increased. The redundant information included information about global warming, that humanity causes the emissions and specific values not required to solve the task. Version A was more similar to Sterman and Booth-Sweeney's main task [23] in that it included relevant information for policymakers beyond what was needed for solving the task, whereas version B did not. The purpose of version B was to test if the absence of redundant information reduces the frequency of SF failure.

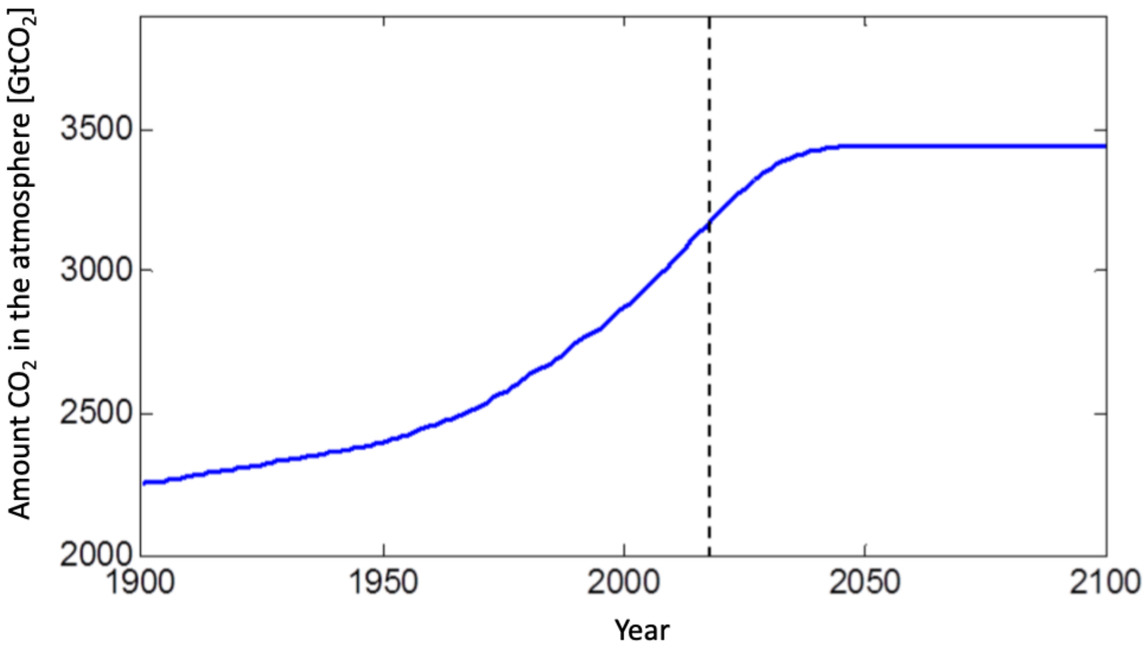


Figure 3.3: Graph showing the historic amount of atmospheric CO_2 from 1900-2019* followed by a future scenario where the amount stabilises around 2050, roughly 10% higher than the current level.
*The original graph, used to construct the current graph, spanned from 1900-2015, but was presented as 1900-2019 in the questionnaire as not to make respondents think about what happened between the years 2015-2019.

[1]The graph actually spanned from 1900-2015 but was presented as 1900-2019 in the questionnaire, as not to make respondents think about what happened between 2015-2019

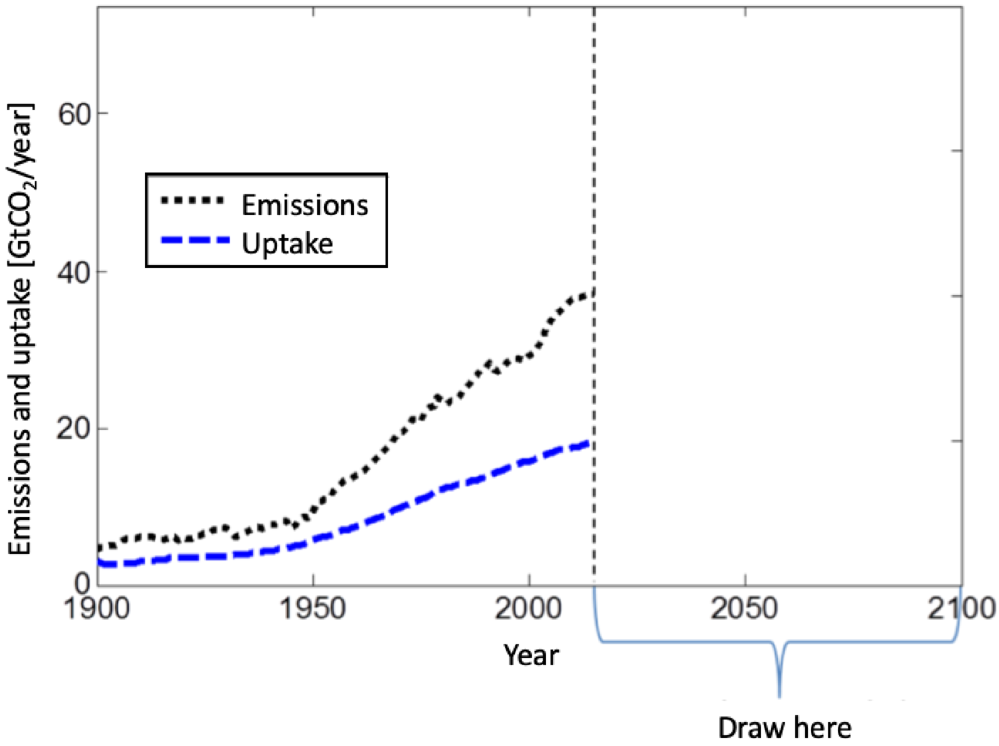


Figure 3.4: Graph showing estimated historic CO_2 emissions and uptake from 1900-2019*, with space for respondents to draw emissions and uptake given the future scenario, shown i Figure 3.3, from 2019-2100.
*The original graph, used to construct the current graph, spanned from 1900-2015, but was presented as 1900-2019 in the questionnaire as not to make respondents think about what happened between the years 2015-2019.

3.2.5 Part 3: Amount of CO_2 for a Hypothetical Scenario

Overview

- T3.1: The respondent was asked to draw a trajectory for the amount of atmospheric CO_2 based on a reference graph showing trajectories for emissions and uptake, in a hypothetical scenario
- Q3.2: Asked the respondent to describe their reasoning behind their response to T3.1

Part 3 consisted of a task (T3.1) and a question (Q3.2), where the question asked for the respondents reasoning behind solving the task. T3.1 asked the respondent to draw the amount of atmospheric CO_2 given an initial value and a hypothetical scenario for emissions and uptake, displayed through Figure 3.5. The scenario was not meant to be realistic, but to allow for simple calculations. First, the graph showing the scenario was shown, followed by a task description and an empty coordinate system (except for the initial value marked) where the respondent was asked to draw a trajectory for the amount of atmospheric CO_2 over time. See Figure 3.6.

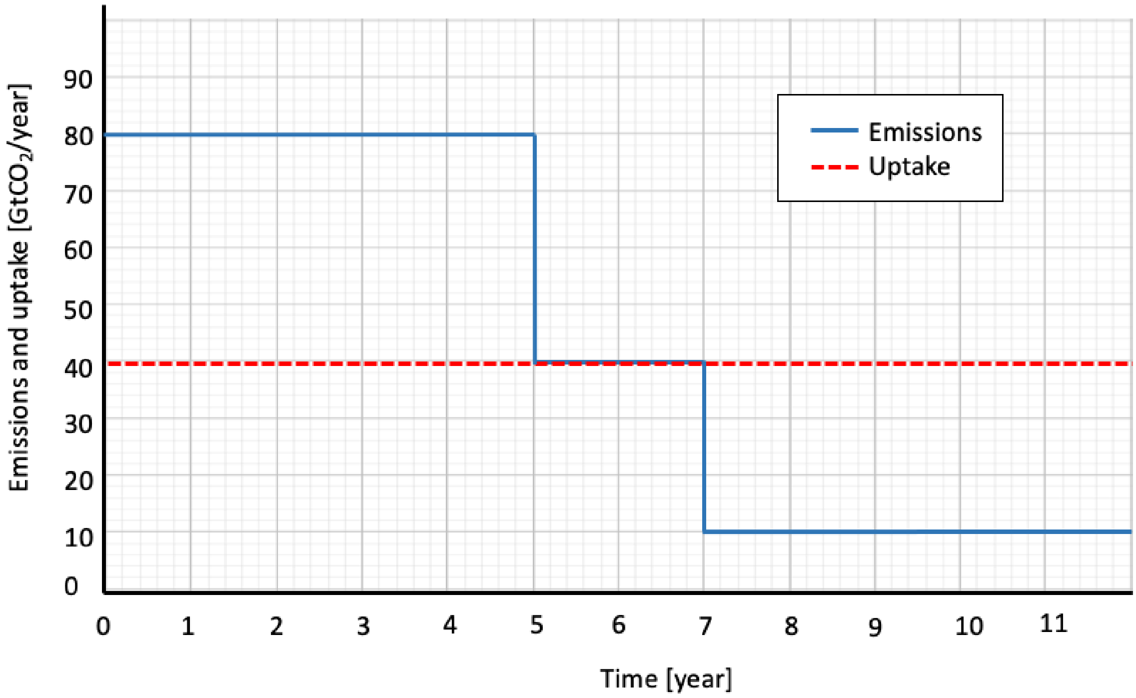


Figure 3.5: Hypothetical scenario for emissions and uptake of atmospheric CO_2. The scenario was not meant to be realistic, but was instead made to allow for simple calculations.

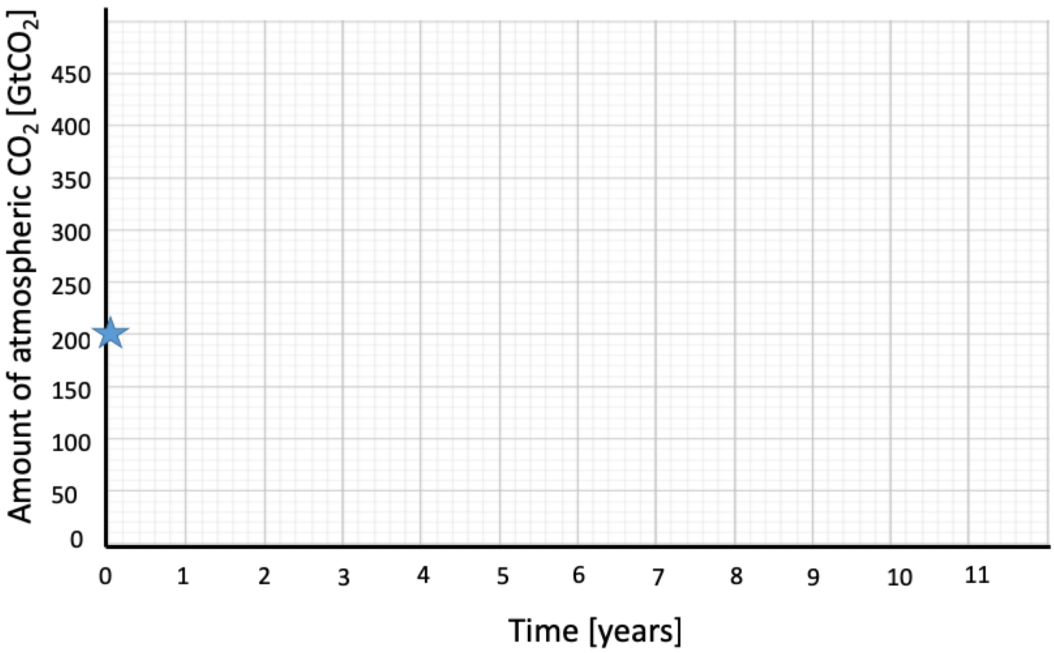


Figure 3.6: Empty coordinate system for respondents to give an answer to task T3.1 in. The blue star marks the initial value, 200 $GtCO_2$, at time 0.

3.2.6 Part 4: Emissions and Uptake for a Hypothetical Scenario

Overview

- T4.1-4.4: The respondent was presented with a graph showing trajectories for emissions and uptake in a hypothetical scenario, and was asked to complete four tasks by marking different points in time
- Q4.5: Asked the respondent to describe their reasoning behind their response to T4.1-4.4

Part 4 consisted of four tasks (T4.1-4.4) in multiple choice format, followed by an open-ended question (Q4.5) asking for the respondents reasoning behind solving the task. First, a graph showing a hypothetical scenario for emissions and uptake was shown, Figure 3.7, where different points in time was marked, A-K. The respondent was then asked to answer by choosing one of the alternatives A-K, or "I don't know", for each of the following events:

- **T4.1:** When is the amount of CO_2 in the atmosphere the largest?
- **T4.2:** When does the amount of CO_2 in the atmosphere increase the most?
- **T4.3:** When is there no change in the amount of CO_2 in the atmosphere?
- **T4.4:** When does the amount of CO_2 in the atmosphere decrease the most?

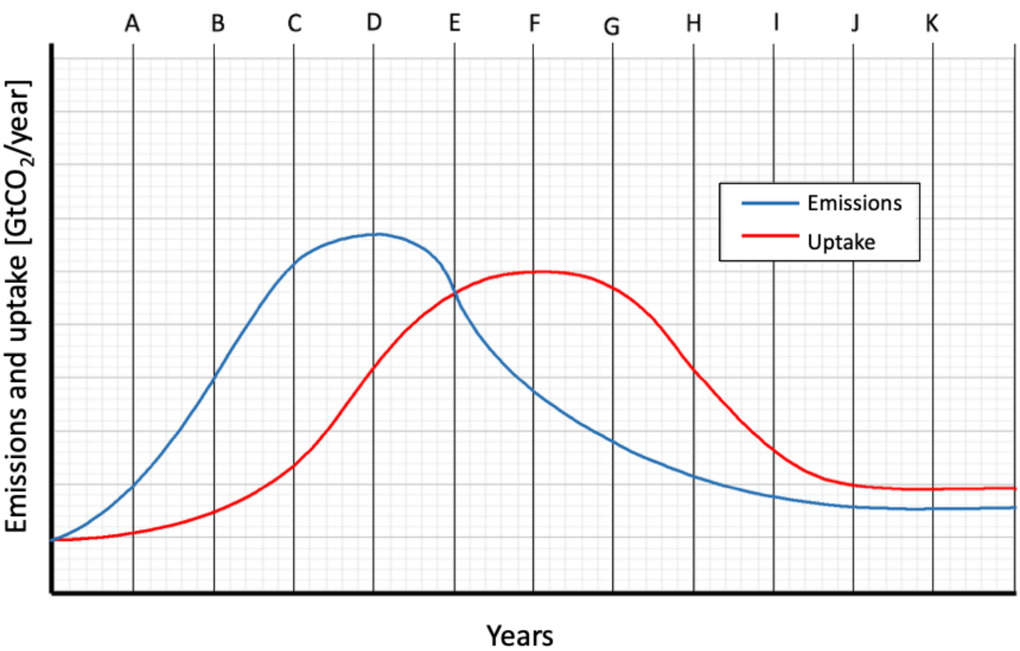


Figure 3.7: Graph showing a hypothetical scenario for emissions and uptake. The letters at the top mark different alternatives which respondents were asked to choose between when answering T4.1-4.4.

3.2.7 Part 5: Mixed Questions

Overview

- T5.1: The respondent was asked to give a mathematical expression for the relationship between emissions, uptake, and the amount of atmospheric CO_2.
- Q5.2: Asked the respondent to describe their reasoning behind their response to T5.1.
- T5.3: The respondent was asked to choose mathematical expressions that can be used to describe the relationship between emissions, uptake, and the amount of atmospheric CO_2, from a list.
- T5.4: The respondent was asked which of four examples listed can be used as a metaphor for atmospheric CO_2 stabilising.
- Q5.5a-e: The respondent was asked to mark the level of significance for different processes through which CO_2 can be removed.

Part 5 consisted of three tasks (T5.1, T5.3, and T5.4) and two questions (Q5.2 and Q5.5a-e), where the first three, in chronological order, were related to giving a mathematical expression for accumulation, and the last two were independent.

T5.1: Open question where the respondent was asked to describe the relationship between the amount of atmospheric CO_2, emissions, and uptake, using a mathematical expression. They were also asked to explain characters and abbreviations used in the expression.

Q5.2: Open question asking the respondent to explain how they arrived at the mathematical expression in T5.1.

T5.3: Multiple choice question where the respondent was asked to mark all mathematical expressions that could be used to describe the amount of atmospheric CO_2. This meant the respondents only had to check options instead of constructing expressions of their own, as they were asked to in T5.1. The last option was an open field were the respondent could write down an answer of their own, for instance if they did not find their expression from T5.1 in the list of expressions. The options were:

- $M = E$
- $M = E - U$
- $M = E - U + M_0$
- $M = (E - U)t + M_0$
- $M' = E - U$
- $M' = (E - U)t$
- $M = \int_{t_0}^{t} E - U d\tau$
- $M = \int_{t_0}^{t} E - U d\tau + M_0$
- $M = M_0^{(E-U)t}$
- *Other* :

where M was the amount of atmospheric CO_2, E emissions, U uptake, M_0 initial amount of atmospheric CO_2, t time, and t_0 initial time. Lastly, it is noteworthy to mention that T5.3 was on a separate page than T5.1, to reduce the risk of respondents accidentally seeing the listed expressions and being helped with creating their own.

T5.4: Multiple choice task asking the respondent to mark all examples listed that can be used as a metaphor for atmospheric CO_2 stabilising. The examples were:

- A company's annual profit is determined by annual incomes and expenditures. For the annual profit to stabilise over several years, the difference between annual incomes and expenditures most stay equal every year.
- A leaking bathtub is filled with water from a tap. For the water level to stabilise, the amount of water that runs into the bathtub per minute has do be the same as the amount leaking out per minute.
- For the oceans to stop getting polluted with plastic, measures must be taken to reduce the amount of plastic that ends up in nature, and the plastic that is already there must be collected.
- If a person eats too much saturated fat their cholesterol level in the blood increases. Physical activity and food with less saturated fat leads the cholesterol level to drop back to a stable original state.

Q5.5a-f: Rating question where the respondent was asked to rate how significant different ways of CO_2 removal currently are. The answer was given by putting a mark on a line, where the the two extremes were: Does not contribute - Very significant. Respondents could also circle the two extremes. The different ways of CO_2 removal were:

- Q5.5a: Capturing by means of technology
- Q5.5b: Leaving into space
- Q5.5c: Taken up by vegetation
- Q5.5d: Naturally decomposes
- Q5.5e: Dissolving into the oceans
- Q5.5f: Other (the option to add an option)

3.2.8 Part 6: Part 2, Again

Overview

- T6.1: The respondent was asked to draw trajectories for emissions and uptake, based on a reference graph showing total amount of atmospheric CO_2 stabilising
- Q6.2: Asked the respondent to describe how their reasoning differed responding to T6.1, compared to their reasoning behind their response to T2.1

T6.1 was essentially the same as T2.1, but without most of the descriptive text and the reference graph showing the future scenario. There was no difference between versions A and B for T6.1. The open question, Q6.2, asked the respondent how their reasoning differed when solving task T6.1, compared to the first time they completed the task in Part 2.

3.2.9 Part 7: Concluding Questions

Overview

- Q7.1: Asked the respondent what part of the questionnaire they thought was difficult
- Q7.2: Asked the respondent what, if any, they learn by conducting the questionnaire

Part 7 consisted of two open questions (Q7.1 and Q7.2). The first one asked what had been difficult throughout the questionnaire, and the second asked if they had learnt something by completing the questionnaire.

3.3 Questionnaire Execution

The questionnaire was held a total of four times, twice on the 2nd of April and twice on the 10th of April (2019). To find participants, several classes were informed during lecture breaks. Focus was on recruiting bachelor students from chemical and mechanical engineering, and related programs, to do the questionnaire[2]. The students were informed about time and place for the survey, and that they would get a free baguette and soft drink if they participated in the survey by taking a questionnaire on understanding climate science.

The first time the questionnaire was held was during lunch time (2nd of April) in the lecture hall where mechanical engineering students had had their lecture previously. The expectations were that more students would attend the questionnaire if the questionnaire was held in the same lecture hall as the students had just finished a lecture in. Some students were in a hurry but still wanted do participate, while others had break time before the questionnaire was supposed to start. To get as many participants as possible, everyone who wanted to start beforehand was allowed to do so. This meant that the participants could not be informed all at once, but instead individual students, or groups of students, were informed when they came to get food and a questionnaire. The information they received was: the questionnaire is conducted individually, look at the questions in the order they appear, and don't go back and change your answer once you have moved on to the next question.

The second time was the same day as the first but in the afternoon. This time had not been planned but was a spontaneous event. The questionnaire, again with free food and drink, was given out after the last lecture of the day for bachelor students in physics engineering. This time, all the students received the information at once, the same information as the first time the questionnaire was held. The third and

[2]Originally, the purpose for focusing on students from chemical and mechanical engineering was to make the study more relevant for us, the authors Joakim Ferring David Reckermann, in case our background in those two programs could be useful in some way when analysing the data.

fourth time (10th of April), the questionnaire was held under similar circumstances as the first and second. The main difference was that students from chemical and biotechnology engineering had been informed of the event beforehand.

The time available for students to complete the questionnaire was at least one hour for for each time it was held. Some students finished the questionnaire in about 20 minutes, whereas some finished in about 45 minutes. It seemed as though some students made serious attempts at performing well on the questionnaire, while others did not. Another observation was that the students often sat next to what appeared to be friends. Occasionally, a few participants exchanged a few words, and it is possible that they could have helped each other to some degree, even though they were told not to.

3.4 Data Analysis

The purpose of this analysis was to test, using a quantitative method, whether or not people can possess the conceptual and procedural knowledge demanded by tasks on accumulation of atmospheric CO_2, but lack the knowledge of when to apply concepts and procedures correctly. In the following subsections, two alternative approaches that were considered are briefly described; a positive approach, and a negative approach, followed by a description of the data analysis process. Other analyses, on data concerning processes through which CO_2 is removed from the atmosphere, and public opinion on emission reduction, consisted mainly of simple averages and distributions, and will not be presented in this chapter.

3.4.1 Choosing an Approach

Two alternative approaches were considered for the data analysis, a *positive* approach, or a *negative* approach. A method using the positive approach attempts to identify knowledge possessed by the subject by analysing the knowledge displayed in the responses. In other words, using this approach, it must be shown the subject possesses a form of knowledge through identifying that the knowledge has successfully been applied when performing the task. A method using the negative approach, however, attempts to identify features in the responses that contradict that demanded knowledge has been applied correctly when performing the task. The negative approach therefore does not rely on showing what knowledge the subject possesses by identifying displayed knowledge in the responses, but instead relies on analysing the knowledge demanded by the tasks and establishing criteria to determine whether the subject responded in a way that contradicts successful application of the demanded knowledge or not. The negative approach was chosen after the positive approach proved to be difficult to use due to the varied nature of the tasks, making the possibility to identify displayed forms of knowledge (with some level of certainty) depend heavily on the task format, rendering comparison between tasks difficult.

3.4.2 Elements of Knowledge

To solve a graphical task (i.e. T2.1, T3.1, T4.1-4.4, or T6-1), certain conceptual (CK) and procedural (PK) knowledge need to be invoked, using situational knowledge (SK). CK and PK useful for solving the task, and relevant for the context of atmospheric CO_2 in general, have been defined as elements of CK and PK. Elements of knowledge, without specifically referring to CK or PK, refers to both elements of CK and PK. Elements of CK and PK for the graphical tasks were determined by identifying what knowledge respondents had used in the questionnaire, with assistance of a content expert, i.e. an expert of the field (Environmental Sciences. Content expert: Erik Sterner, researcher at Space, Earth and Environment at Chalmers University of Technology, and supervisor for this thesis project). Consulting a content expert was done in order to improve the analysis of the steps needed in order to solve each task[28].

In total, three elements of CK and six elements of PK of interest were identified, listed below. The CK were formulated as statements about accumulation of atmospheric CO_2, all being aspects of the principle of accumulation applied to the atmospheric CO_2 context. The PK were formulated as abilities, more or less specific to the atmospheric CO_2-accumulation context.

List of elements of CK and PK

- CK1: Emissions and uptake must be the same when the amount is unchanging (and the amount is unchanging when emissions and uptake are the same).
- CK2: The rate of change of the amount is the difference between emissions and uptake.
- CK3: A change in total amount over time is the cumulative difference between emissions and uptake.
- PK1: How to interpret a reference graph in order to acquire values of M at different points in time and over intervals of time.
- PK2: How to transform a mental representation of correct (according to the criteria for the CK and PK) knowledge to a graphical representation.
- PK3: How to use a representation of general SF-dynamics to produce the case specific value M' = 0 from the dependency E = U, or vice versa.
- PK4: How to use a representation of general SF-dynamics to produce an inequality M' > 0 or M' < 0 from E > U or E < U, or vice versa.
- PK5: How to use a representation of general SF-dynamics to produce a case specific value of E, U, M and/or M' at some point in time using given or chosen values for the other variables E, U, M or M' (for example E = 60 $GtCO_2$/year and U = 20 $GtCO_2$/year, so M' = 40 $GtCO_2$/year) where M' $\neq$0.
- PK6: How to produce approximate continuous values of E, U, M and/or M' over a time interval where M' $\neq$0.

There are a few important comments to make on this method and the list of elements of CK and PK above. First, it should be made clear that any elements of CK or PK absent in a response does not necessarily mean the subject does not possess the CK or PK. Second, all elements of knowledge were considered for all tasks with one exception; tasks T4.1-4.4 does not include constructing any graphical representations, hence PK2 could not be considered for these tasks. Third, for each task, all elements of CK and PK were not necessarily required to be considered explicitly in order to complete the task in a satisfactory way. It is possible, for example, that T3.1 may be solved in a satisfactory way applying only CK1 and CK2 of the conceptual elements of knowledge, while never explicitly considering CK3. However, considering and successfully applying CK3 could also have been central to the subjects performance on the task. In other words, for some CK or PK, for some tasks, if a response does not contradict that the element of knowledge has been applied, it does not necessarily imply that the element of knowledge has been applied.

3.4.3 Criteria and Matrix for Assessment

The negative approach chosen for the data analysis meant that respondents' answers were assessed based on whether or not they contradicted that the successful use of the elements of CK and PK assigned to the task. Using T2.1 as an example, if a response showed emissions exceeding uptake during the period where the amount is stable in the reference figure, the answer contradicted successful use of CK1. For tasks T2.1, T3.1, and T6.1, graphical criteria were created to to determine which elements of CK and PK each response contradicted. The criteria are listed in Appendix A. T4.1-4.4 are multiple choice questions, hence the corresponding criteria rely on the alternatives chosen in the response. The criteria for T4.1-4.4 are displayed in Figure A.1 in the appendices. A matrix was created as a tool for assessment, connecting the criteria of the graphical tasks to the elements of knowledge. In other words, the matrix stated which criteria a response needed to pass to not contradict successful use of elements of CK or PK. Figure 3.8 shows a simplified version of the matrix. For a more detailed version, see Figure A.1 in the appendices. Once the assessment of the graphical tasks was completed, the obtained data, including data from other tasks and questions, was compiled into tables, figures and numbers used for analysis.

	Elements of knowledge
GC, T2.1	GC for elements of knowledge
GC, T3.1	GC for elements of knowledge
-	Criteria for T4.1-4.4, for elements of knowledge
GC, T6.1	GC for elements of knowledge

Figure 3.8: Simplification of the matrix used for assessment of the graphical tasks. "GC" is an abbreviation of "graphical criteria". The left column contains the graphical criteria for the different tasks, except for T4.1-4.4 which were stated in the right column. The purpose of the matrix was to connect the graphical criteria to the elements of knowledge. See Figure A.1 in in the appendices for a more detailed version.

4

Results & Analysis

In this chapter, the results of the study are presented and analysed in preparation for an in depth discussion in the following Chapter, 5 Discussion.

This chapter is divided into three main sections. First, results regarding graphical responses are presented and analysed. The second section treats results regarding respondents' perception of processes through which CO_2 can be removed from the atmosphere. The last section presents results regarding respondents' opinions on emission reduction, in combination with graphical task performance and perception of removal processes of atmospheric CO_2. Throughout this chapter, the "graphical tasks" refer to T2.1, T3.1, T4.1-4.4, and T6.1. Additional figures and tables can be found in Appendix B, which have been excluded from this chapter in an attempt to make it concise. The purpose of Appendix B is to show results that are not necessarily used for answering the research questions, but that may be of interest for the interested reader.

4.1 Graphical Responses and Forms of Knowledge

We found that respondents performed with different success on different tasks. The graphical tasks were deemed to demand the same elements of conceptual and procedural knowledge, but respondents where able to apply this knowledge with varying success, as Figure 4.1 shows. The largest difference in performance was between T2.1 and T3.1. An average of 30% of respondents passed the criteria in T2.1, whereas the same number for T3.1 was 51%, meaning that they contradicted correct use of knowledge to a higher degree in the first task, T2.1.

Another interesting finding was that respondents had a higher success rate on T6.1 than T2.1, see Figure 4.1, which are the same task. This could be due to several reasons. It is possible that some respondents learned what knowledge was useful, and what was not, through the course of taking the questionnaire. The graphical tasks demand the same elements of conceptual and procedural knowledge, why some respondents could have noticed a pattern for the tasks. Another possibility is that the difference is due to the lack of a descriptive text and graph in T6.1. The text could trigger associations to climate change that redirects focus from the relationship between the amount of atmospheric CO_2, emissions, and uptake. This is further substantiated by comparing versions A and B of the questionnaire, as it

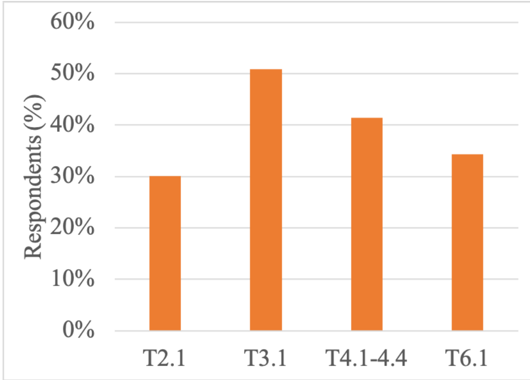


Figure 4.1: Comparison of respondents' answers that did not contradict the use of correct knowledge for the graphical tasks. The figure shows that respondents were able to pass criteria with varying success in the different tasks. The figure also shows an increase of answers that passed criteria from T2.1 to T6.1, which are the same task.

was found that respondents of version B passed more criteria for T2.1, see Figure 4.2. This means that more respondents successfully applied correct knowledge for the task without any redundant information in the task description. Assuming that respondents of both versions possessed the same conceptual and procedural knowledge, the difference of the redundant information may have caused the difference in performance. This is further discussed in the next Chapter, 5 Discussion.

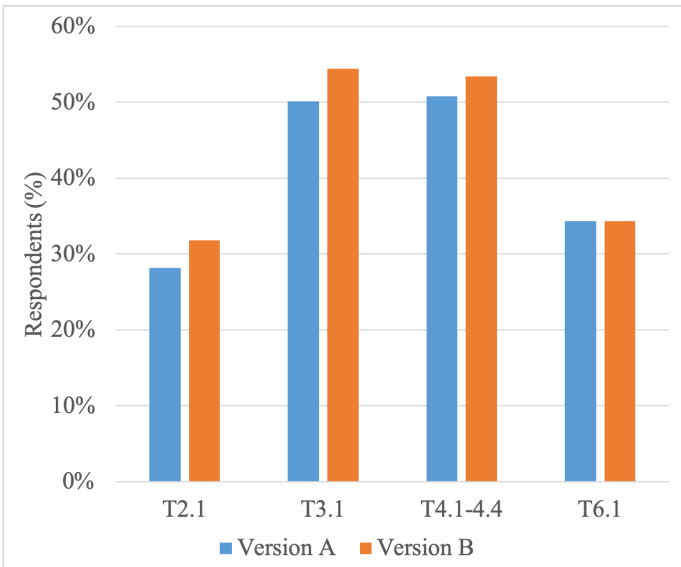


Figure 4.2: Comparison of respondents' performance on the graphical tasks for versions A and B of the questionnaire. The figure shows that respondents of version B passed more criteria for each of the graphical tasks, compared to respondents of version A. The difference in performance for T2.1 and T6.1, which are the same task, decreased to almost no difference at all.

Figure 4.2 also shows that the difference in performance stays almost the same until T6.1, where there is almost no difference at all between versions A and B.

Lastly, it is noteworthy to mention that there was one student who answered the correct answer where emissions and uptake decrease together after coinciding, for T2.1. For T6.1, there were a total of five students how gave the same correct answer.

4.2 Removal of Atmospheric CO_2

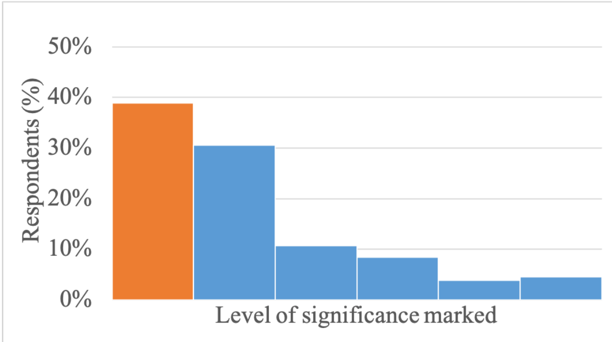
It was found that a majority of respondents displayed misconceptions about processes through which CO_2 can be removed from the atmosphere. Despite that CO_2 does not go into space or decompose[27], a majority of respondents marked that they have some level of significance, see Figure 4.3. It was also found that the significance of uptake to oceans may be considerably underestimated. Figure 4.4 shows that 10% of the respondents marked the ocean as not contributing to removal of atmospheric CO_2, and 20% marking the significance of uptake to the ocean as low, between 0 and 0,2 on the scale from 0 to 1. This can be compared to responses to question asking for the significance of vegetation, Q5.5c, where almost no one answered "does not contribute" nor between 0 and 0,2.

The results for removal of atmospheric CO_2 by means of technology is not presented here, but can be found in Figure B.4 in Appendix B. This is due to that the results are ambiguous, which may stem from ambiguity in the question asked in the questionnaire. In the description to the question, it says that they should mark the current significance, which can be interpreted to include the current potential for development. It may also be so that the respondents failed to consider "current" at all.

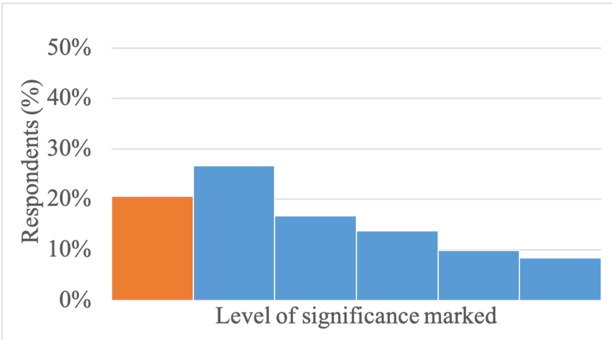
To see if there was any correlation between respondents perception of processes though which CO_2 can be removed from the atmosphere, and their performance on graphical tasks, Table 4.1 was created. It shows that the average perception of those that fulfilled all criteria for the graphical tasks varies considerable when compared to those who fulfilled none. Respondents who fulfilled all criteria estimated the significance of CO_2 going into space, or decomposing naturally, to be substantially lower then those who did not fulfil any. At the same time, they estimated the significance of uptake to vegetation and oceans to be higher. This implies that there could be some correlation between performance on the graphical tasks, and perception of process through which CO_2 can be removed from the atmosphere.

4.3 Emission Reductions from Use of Fossil Fuels

All 131 respondents answered that they thought humanity should reduce emissions from use of fossil fuel. The average stated emissions reduction until 2030 was 36%, and 69% until 2050, which can be compared to the IPCC's recommendation for



(a) CO_2 going into space.

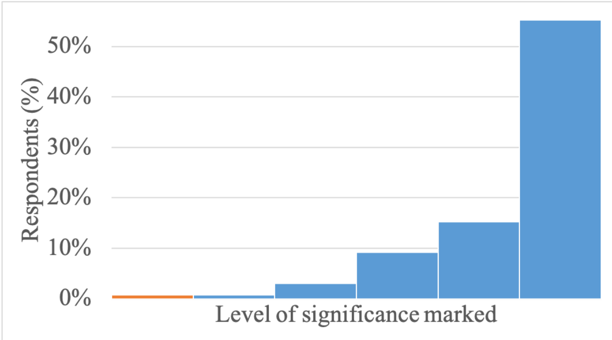


(b) CO_2 decomposing naturally

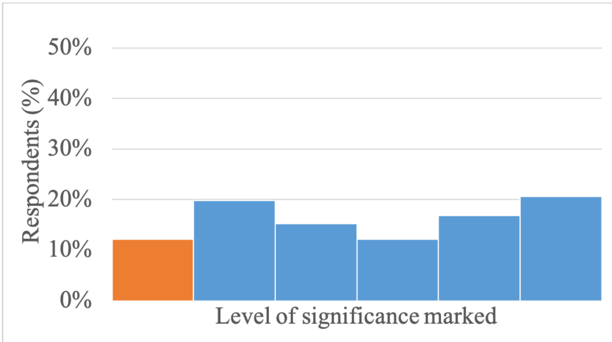
Figure 4.3: Respondents' perception of processes through which CO_2 can be removed. The orange bar represents answers marked "does not contribute". The blue bars are on a scale, where the further to the right side it is, the more significant the process through which CO_2 can be removed is.

emission reduction in order to limit the temperature increase to 1,5°C (100% linear reduction until 2040 for 95% confidence, or 100% linear reduction until 2055 for 66% confidence)[10] and the Swedish "Climate Law" (85% reduction of emissions, counted nationally, until 2045)[19]. Previous researchers have suggested that there may be a correlation between understanding accumulation of atmospheric CO_2, and policy support regarding reduction of emissions from fossil fuels[21]. To examine if there may have been any correlation between stated emissions reduction and task performance, two scatter plots were created, see Figure 4.5. Looking at the scatter plots, we could not identify any trend suggesting a correlation. In another attempt, a table was created with a different approach, see Table B.4 in the appendices. It also did not indicate any correlation.

Lastly, it was of interest to examine whether there was a correlation between respondents' perception of CO_2 removal, and stated emission reduction. This was, however, out of scope for this study, so it was not given much attention. To examine if such correlation may exist, a table was created, see Table B.5 in the appendices. We could not see any clear correlation and leave this task for future research.



(a) Uptake to vegetation.

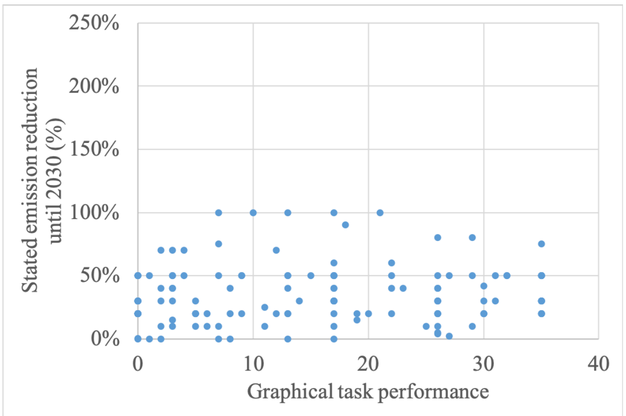


(b) Uptake to the ocean.

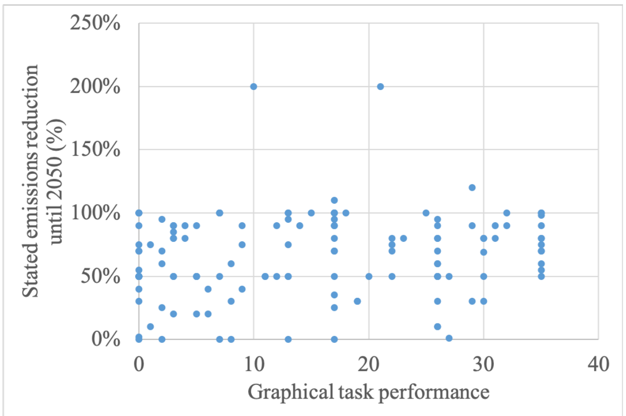
Figure 4.4: Respondents' perception of processes through which CO_2 can be removed. The orange bar represents answers market "does not contribute". The blue bars are on a scale, where the further to the right side it is, the more significant the process through which CO_2 can be removed is.

Table 4.1: Comparison between respondents who fulfilled all criteria for the graphical tasks, and those who fulfilled none. The table shows that the marked level of significance for different processes through which CO_2 can be removed from the atmosphere, varies between the different groups. The scale is from 0, does not contribute, to 1, very significant.

	Average marked level of significance for respondents who:	
	Fulfilled **all** criteria N=12	Fulfilled **no** criteria N=18
CO_2 going into space	0,07	0,25
Uptake to vegetation	0,93	0,88
CO_2 decomposing	0,12	0,39
Uptake to oceans	0,65	0,35



(a) Graphical task performance and stated emission reduction until 2030.



(b) Graphical task performance and stated emission reduction until 2050.

Figure 4.5: Scatter plots of respondents' stated emission reduction until 2030 and 2050, and their performance on the graphical tasks. 0 graphical task performance means that no criteria for the graphical tasks were fulfilled, and 35 means all were fulfilled. The figures do not indicate any obvious correlation between stated emission reduction and graphical task performance.

5 Discussion

In this chapter, the results and the methods used are discussed, as well as implications for climate science communication and future research.

In the following sections, we will discuss the results and the method used in this study. Implications for practise and suggestions for future research have also been discussed. This was done for each research question separately. Lastly, the questionnaire used for this study is discussed further in a separate section.

5.1 Forms of Knowledge and Accumulation of Atmospheric CO_2

In this section, the discussion is centred around the first research question, which is repeated below for convenience.

- *If people's performance vary when completing a range of tasks on accumulation of atmospheric CO_2 demanding similar knowledge of concepts and procedures, can this variation be attributed to the difference in difficulty to know when these concepts and procedures should be applied?*

Subjects in this study were more successful performing some tasks compared to other tasks, even though these tasks were deemed to asses the same knowledge of concepts and procedures. It therefore appears as if for some, it is not concepts or procedures available to the individual that is the issue, but rather knowing that these concepts and procedures should be used, as previous research has suggested [25]. The validity of these results, however, depends on the method used. We must therefore discuss strengths with and possible flaws in the method. Below, we discuss the data collection method, followed by a discussion on the data analysis, before discussing implications for future research and practise.

5.1.1 Discussion on the Data Collection

We chose a questionnaire for the data collection for this study, mainly to be able to compare the results of this study with results in previous research. However, there are a few things to consider concerning this method.

The four graphical tasks used to assess people's knowledge of concepts and procedures were ordered (with all respondents performing the tasks in the same order) which could affect differences in performance for the sample. For example, there is a possibility that the performance on T3.1, which was the highest of all tasks, could have been lower if T3.1 would have been the first task. A randomised order of the tasks could have been used to reduce possible influences by order on the results.

One reason that may speak for that the order does not matter is the low difference in performance for the pre-post-test. A low increase in performance is shown when comparing performance on T2.1 and T6.1. Similar low increase in performance has been noticed on task performance in this context before, when a pre-post-test has been used[25]. This could indicate that respondents may not transfer knowledge used in one task to another to any higher extent. If we consider the opposite, a higher performance may have been shown in T6.1 compared to T2.1.

This is, however, just one hypothesis on the pre-post-test. It is also possible that respondents performed T2.1 with the perception that they did understand what the task asked of them and performed it accordingly. When performing the other tasks, that perception was not challenged. When reaching T6.1, the perception of what task T2.1 asked for had not changed, and therefore the perceived solution to the task had not changed either. In other words, it is not necessarily so that they did not learn how their solution was incorrect, but rather that they did not re-evaluate what the task asked of them. This may indicate that the low difference in performance on T2.1 and T6.1 is not strong evidence that the order had low influence on the results.

Another aspect that should be considered is the length of the questionnaire, and that no further incentives (apart from the lunch that was given out together with the questionnaire) were used to reduce a possible tendency to lose focus or attempting to complete the questionnaire as fast as possible. It is possible this influenced performance throughout the questionnaire. This, and other aspects, are discussed further in section 5.4, where a more holistic perspective on the questionnaire is taken.

5.1.2 Discussion on the Data Analysis

When considering the relationship between the data analysis method used and the results, it is important to note that the theoretical basis on knowledge used in this study is not claimed to provide an exact image of reality. In other words, when using the theory on forms of knowledge in this study we do not claim that knowledge in reality consists of the different types of knowledge defined, in any other sense than that this categorisation can be used in an attempt to describe task performance. This is done based on the premise that elaborating "understanding" into different forms of knowledge may be a useful perspective, as suggested by previous research[25], a perspective that this study aimed to, in a sense, evaluate. The theory used (de Jong & Ferguson-Hessler, 1996)[11] is not the only theory that could have been used for this aim, and methods using other theories could have provided a more accurate description of people's understanding of accumulation of atmospheric CO_2. Below, we discuss strengths and weaknesses with the method for data analysis and the theory used in this study. Doing this, we hope to facilitate designing suitable methods for possible future research in this field.

Theoretical Basis and Data Analysis Design

For this study, we chose not only a theory of forms of knowledge, but also made definitions on how knowledge can manifest in this context (possessed, applied and displayed knowledge) and chose an approach (negative or positive). These choices were altered more than once throughout the study, both before the data was collected and after. The entire process that lead up to these choices included extensive verbal discussions between us, the authors of this study, as well as discussions between us and our supervisor, co-supervisor and their colleagues. To retell this process and define all the premises behind the epistemological perspective used in this study was therefore considered too comprehensive for the Chapter 2 Background, in this report. Instead, in the current chapter, we discuss how some of the choices were made, in cases where they are important to note in relation to the method used and the results yielded. Choosing a theory describing different forms of knowledge, defining "possessed", "applied" and "displayed" knowledge, as well as choosing a negative approach, were all choices that were also made in close relation to the other. What follows will therefore attempt to be a holistic discussion on the theoretical basis on knowledge used.

One central question that appeared early in the study was: how can we, using our data, claim something about the respondents knowledge of accumulation of atmospheric CO_2? This question is based on the premise that the respondents knowledge of accumulation of atmospheric CO_2 may not necessarily be available for interpretation or is not interpretable in the responses. We therefore required definitions of how knowledge can manifest in a task performance context, in order to further define what it is we are claiming something about. No suitable established theory of how knowledge is manifested was found, which may be a weakness of the theoretical basis for this study. Instead, definitions of how knowledge can manifest in the current context, i.e. respondents performing tasks in a questionnaire, was made based on our, the authors, subjective view on what definitions were necessary in order to design the data analysis and describe the results.

With definitions for how knowledge can manifest in place, a way to make the claims about these manifestations was also required. For this, the positive and a negative approach was considered (see Chapter 3 Method). These two approaches considers different manifestations of the defined manifestations of knowledge, in that the positive approach considers *displayed* knowledge, while the negative approach considers *applied* knowledge. This choice of approach is therefore central to the method and to what results it yields, as it decides how knowledge is assessed but also *what* knowledge is assessed, per our definition of how it manifests. The results of this study needs to be viewed with this in mind, as a positive approach may have yielded a significantly different description of the frequency of elements of conceptual and procedural knowledge for the responses.

Even with the negative approach chosen, choices made on the elements of conceptual and procedural knowledge, and the criteria assigned to them, could heavily influence the performance rates. It has been up to us, the authors, together with our supervisor (whom acted as content expert[28]) to determine suitable elements of knowledge, as well as choosing criteria that allow for a comparison that did not favour performance on some tasks or elements over others. An important component of any description of the results concerning performance on the graphical tasks in this study, is that the tasks were *deemed* to assess the same knowledge of concepts and procedures, a component that is meant to inform the reader that the conclusions are based on assumptions made by subjective agents and should be treated as such. This information should also accompany the reader in the next section, where we discuss how the varying performance on the tasks may be explained by differences knowledge demanded that is categorised as situational or strategic knowledge.

5.1.3 Situational and Strategic Knowledge

Thus far, analysis of the situational and strategic knowledge demanded by the different tasks, used in the current study, has not been discussed. It is not the purpose of this study to in detail investigate the characteristic differences in the situational and strategic knowledge demanded by the tasks. However, performance on the tasks varied when assessing conceptual and procedural knowledge, which poses the question whether or not the varying performance "can be attributed to the difference in difficulty to know when these concepts and procedures should be applied", as the research question states. Difficulty to know when to apply concepts and procedures is, with the theoretical bases used in this study, dependent on situational and strategic knowledge demand. In this section, we will therefore present some considerations for the tasks, and discuss how the tasks used in this study may demand different situational and strategic knowledge.

Situational Knowledge Demand

First, to return to the definition of situational knowledge used in this study (see section 2.2): situational knowledge includes being able to supplement the information available in the task description with knowledge of concepts and procedures, and being able to separate relevant information from irrelevant information, i.e. which concepts and procedures that should, and should not, be applied[11]. Situational knowledge is defined as "knowledge about situations as they typically appear" in the source paper[11], and finding what information should be supplemented depends on the case at hand, which means the difficulty in invoking the conceptual and procedural knowledge demanded by the task depends on the situation in which they are to be applied. Similarly for sifting information, what concepts and procedures may seem relevant or irrelevant depends on the situation. The "cases" for each of the tasks used in this study are different, in that they provide different hints and hinders to supplementing information and sifting information correctly, and can therefore be said to demand different situational knowledge. To in detail, and exhaustively, define the differences in situational knowledge demanded by each task will not be attempted in this discussion, however, a few examples of how different tasks poses different cases are described below.

In previous research, it has been suggested that one reason that for varying difficulty of knowing when the principle of accumulation should be used could be that some tasks point towards the relationship between emissions, uptake and total amount of atmospheric CO_2 more clearly than others[25]. One major difference between T2.1 and T3.1 is how T3.1 more clearly directs the respondents attention towards the relationship between emissions, uptake and total amount by simplifying the graphical information. This is done by introducing constant differences between emissions and uptake, removing the historic values (other than the starting point for total amount) and using a time axis which cannot be related to a real calendar. In addition to this, task T3.1 asks the respondent to draw a trajectory for the total amount, based on uptake and emissions, which may direct the respondent towards considering what the relationship between emissions and uptake means for the change in total amount, more so than in T2.1 where they are asked to draw trajectories for emissions and uptake. Finding a resulting change in total amount from values on emissions and uptake may be more intuitive since there is only one rate of change for the total amount accounting for one value on emissions and one value on uptake. Knowing the rate of change in total amount, however, yields a unique difference between emissions and uptake, but cannot yield specific values on emissions nor uptake unless one of them are known.

Continuing on this, task T2.1 asks the respondent to draw trajectories for both emissions and uptake, while task T3.1 asks the respondent to draw one trajectory for total amount. For T3.1 the respondent only needs to produce one trajectory, and must therefore only consider everything that affects the appearance of that trajectory, while in T2.1, the respondent needs to consider two trajectories, and everything that affects the appearance of those trajectories, including how the appearance of the trajectories that are to be drawn influence each other.

The task description accompanying task T2.1, together with the realistic historic emissions and uptake, and the task to draw emissions and uptake for a future scenario starting at present time, could also distract the respondent by triggering associations to their expectations for the future concerning emissions of CO_2. For some responses that did not pass either graphical criteria, the responses to question Q2.2, asking for the reasoning behind the solution to T2.1, did not include any statements about the relationship between emissions, uptake and total amount, but instead included statements on, for example, human inability to adapt, deforestation, consumption, technology and population increase (an example of this can be seen in Figure B.3 in Appendix B). For these responses, the respondent appears to have failed to consider the reference graph at all. Instead, they appear to complete the trajectories for emissions and uptake based on their expectations of the future, which is irrelevant in order to complete the task. This type of reasoning, termed *phenomenological reasoning*[25], has been suggested as a challenge for subjects performing tasks on accumulation of atmospheric CO_2 in previous research, and may increase the frequency of SF failure.

In comparison to task T2.1, the format of task T3.1 and T4.1-4.4 does not invite to the use of phenomenological reasoning in the same extent. This lowers the demand for sifting irrelevant information, both from the task description itself and the irrelevant supplemented information invoked through associations. Comparing the results of the two versions of the questionnaire, A and B, also showed a difference in performance, where respondents on average performed marginally better (a difference of 2%) on the task T2.1 in version B, where less redundant information was provided in the task description, suggesting the redundant information may have increased the difficulty of sifting the information for relevant features and may have increased the irrelevant associations invoked. This may be further strengthened by comparing with previous research, where researchers found even lower performance on a task very similar to T2.1. For this task, the task description included even more redundant information[23].

Strategic Knowledge Demand

Strategic knowledge demand is more difficult to analyse for specific tasks, as it is of general nature (less domain specific). However, the frequency of phenomenological reasoning may also depend on lacking strategic knowledge. Strategic knowledge could, for example, be using a strategy such as Polya's four-step plan to solving a problem[18]. The first step in this strategy is "Understanding the problem", which includes asking one-self what value or information the problem description asks for. Respondents performing this step may be less likely to provide a response based on phenomenological reasoning. Task T2.1 could therefore also be said to demand not just more situational knowledge, but also more strategic knowledge, compared to T3.1 and T4.1-4.4.

5.1.4 Implications for Practise

For these suggestions, we will continue to use the perspective of dividing understanding accumulation of atmospheric CO_2 into conceptual, procedural, situational and strategic knowledge. This is because we wish to use two perspectives, based on the last two of those types of knowledge. Below, we begin by describing suggestions based on situational knowledge demand.

Situational knowledge

Not knowing what accumulation is and how to perform procedures may not be the issue for some who fail to acknowledge the SF nature of the relationship between emissions, uptake and amount of atmospheric CO_2. Instead, they may not realise that in this context the principle of accumulation is applicable. This could be attributed to lacking knowledge of the situations where the principle is applicable appears, i.e. lacking situational knowledge. From this perspective, we see two alternative approaches for interventions. The first is to acknowledge the difficulty of realising that the principle of accumulation is applicable to the relationship between emissions, uptake and amount of atmospheric CO_2, and circumvent this by making the SF dynamics of the system explicit, or easily accessible. The relationship between emissions, uptake and amount may require additional attention, compared to other context, due to rising levels of atmospheric CO_2 and climate change being a subject that is in general heavily politicised and emotionally associated. The immense information on e.g. temperature increase and other complex climate science, emission regulating policies and calls for behavioural change that meet people on an every day basis may cloud the fundamental dynamics of CO_2 accumulation when performing tasks. When the goal for climate change communication is informing on how accumulation of atmospheric CO_2 works, interventions may be more effecting when the information is accompanied by less superfluous information and statements that may trigger distracting associations.

The second alternative is providing the receivers of information with educational material that allows them to attempt and possibly fail to apply the principle of accumulation in the CO_2 accumulation context, but in different situations, in order to make them more familiar with these situations long term. Further research to evaluate the methods for the interventions suggested here may prove valuable for the climate change communication field.

Strategic Knowledge

The suggestions for practise described above were based on acknowledging that people may not possess the required situational knowledge. We now move on to a perspective based on possible lacking strategic knowledge. The issue is the same, in the sense that people may not realise that the principle of accumulation should be applied in the context. However, instead of circumventing the issue by presenting easily accessible situations or building familiarity with difficult situations, the frequency of failing to apply the principle of accumulation may be reduced by improving problem solving skills. This means interventions do not necessarily have to be centered around accumulation of atmospheric CO_2, nor climate change in general, but can be long term education in general problem solving strategies. This is rather a suggestion for institutions of educational in general, rather than specifically climate change communicators.

5.1.5 Implications for Future Research

Here, we will make a few more suggestions for future research concerning public understanding of accumulation of atmospheric CO_2.

For a first, we wish to remind the reader that this study was conducted with participants from a university of technology. In order to evaluate a broader validity of the results, using a more diverse sample may be of interest for future research in this field. The participants of this study can be assumed to be well versed in tasks demanding a level of education in mathematics that may not be representative of a larger population, such as Swedish citizens in general. Results from assessing people's understanding of the concepts and procedures needed to perform tasks on co_2 accumulation, and if they lack the knowledge of when to apply these concepts and procedures, may differ significantly from the results of this study if a more diverse sample is used.

We also suggest further of what characteristics in tasks result in higher situational knowledge demand. In this discussion, we have suggested that superfluous information that lead to phenomenological reasoning is one such characteristic. We have also suggested that the amount of information in the graphical format may influence situational knowledge demand, and that calculating emissions and uptake from total amount of atmospheric CO_2 may be more demanding compared to calculating total amount of atmospheric CO_2 from emissions and uptake. Other possible characteristics that may lead to higher situational knowledge demand and substantiating their importance is suggested.

5.2 Removal of CO_2

In this section, the discussion is centred around the second research question, which is repeated below for convenience.

- *When studying people's perception of how CO_2 is removed from the atmosphere, what misconceptions can be found and to what extent do these occur?*

The focus in the discussions for this section is on respondents' misconceptions regarding CO_2 leaving into space, CO_2 decomposing, and respondents' perceptions of uptake to vegetation and oceans. Also, a possible correlation between understanding CO_2 accumulation and understanding processes through which CO_2 can be removed from the atmosphere is discussed.

5.2.1 Misconceptions Regarding CO_2 Leaving into Space, and CO_2 decomposing

One question in the questionnaire was dedicated to answering our second research question. Responses to the question indicate that there are misconceptions among students, regarding processes through which CO_2 can be removed from the atmosphere, as had been suggested in previous[26]. CO_2 does not leave into space, but a majority of students responded that it does to some degree. The distribution of responses, however, is clearly skewed towards having a low significance of CO_2 leaving into space for the removal of atmospheric CO_2. It is possible that students to begin with did not think about the possibility of CO_2 leaving into space and were confronted with the idea for the first time. Because of uncertainty, they could have chosen to mark a low significance without thinking too much about whether it is possible or not. Simply having the alternative of marking CO_2 leaving into space could have influenced students to think that it in fact does, to some degree. The results do, however, show that there were students (30,6%) who marked CO_2 leaving into space at above 0,2 on a continuous scale from 0 to 1. We deem it implausible that student marked such a high degree of significance based only on that the alternative was shown. There is also nothing else in the questionnaire that would suggest this perception. It is difficult to determine to what extent having the alternative in the questionnaire influenced students' responses. Despite this uncertainty, we argue that responses show that a substantial number of students in our study had misconceptions regarding CO_2 leaving into space.

If we look at responses to how significant CO_2 decomposing naturally is for the removal of atmospheric CO_2, we see a similar distribution to that of leaving into space. There were, however, even less students who marked that it does not contribute. It would appear that misconceptions are more common and substantial for CO_2 decomposing, when compared to it leaving into space. It is, however, possible that students interpreted the option as another way of saying that it is taken up by plants. In questionnaire, the alternative was written as "naturally decompose/degrade". This could have lead students who thought that vegetation was of high significant, to also mark decompose at a high significance.

Giving respondents different alternatives to choose from, when trying to find out their perceptions regarding processes through which CO_2 can be removed from the atmosphere, could have influenced them to think that CO_2 leaving into space or decomposing was significant to some degree. An alternative way to formulate the question could be to ask where they think one ton of CO_2, that has left/been removed from the atmosphere, has gone to. It could be formulated so that they answer in either mass units or in percent. With this approach, they would have to create alternatives themselves, and we would get a better measure for how significant they think the alternatives are. Another option is to ask what they think has happened with one ton of atmospheric CO_2 after a long period of time, for instance after a hundred years. This way, people's perception of CO_2 residence time could also be further investigated, which may be of interest.

5.2.2 Uptake to Vegetation and the Ocean

Uptake to vegetation and uptake to the ocean are currently the main processes through which CO_2 is removed from the atmosphere, where the ocean is most significant for net removal of emissions from fossil fuels [9]. Responses from students in the survey show, however, that most thought uptake to vegetation was of high significance, whereas responses for uptake to the ocean varied substantially more. Almost no students (0,8%) thought that uptake to vegetation does not contribute to the removal of atmospheric CO_2, whereas almost one eighth (12,2%) of students thought that uptake to the ocean does not contribute. It would appear that the significance of uptake to the ocean was underestimated, when comparing responses for the two alternative processes through which CO_2 can be removed from the atmosphere. There could be several possible explanations for this. For instance, photosynthesis is commonly taught in schools and is a mandatory part of biology class in Swedish elementary school [20]. If we assume that students were taught the principle of photosynthesis it seems plausible that they would mark uptake to vegetation as significant to a high degree. The process of CO_2 dissolving in the ocean, and also the carbon cycle in general, may however more rarely be taught in detail.

Another possible explanation for uptake to the ocean being underestimated by students could be that the question in the questionnaire was interpreted to mean how significant current potential for uptake is, or completely miss/ignore that the current significance was asked for. If the amount of atmospheric CO_2 stabilises, uptake to the ocean will decrease, making it less significant for the removal of atmospheric CO_2 [9]. In comparison, uptake to vegetation has some potential to increase, by, for instance, expanding forests. Perhaps the difference in responses for uptake to vegetation and uptake to the ocean can be explained by a perception that there is little future potential for the ocean, but some to vegetation. We do not, however, think that this is the reason, since there were only five students who answered that emissions and uptake need to decrease together in the scenario where the amount of atmospheric CO_2 stabilises (T6.1).

5.2.3 Implications for Practise

In the questionnaire, the question about processes through which CO_2 can be removed from the atmosphere (Q5.5) came after a task with a description where it was mentioned that uptake is to vegetation and the ocean. Despite this, respondents showed misconceptions regarding removal of atmospheric CO_2, for instance that it leaves into space. To avoid misconceptions, we argue that it may not be enough to describe what uptake is, but that it also is important to emphasise what it is not. By saying that CO_2 can be removed from the atmosphere through uptake to vegetation and the ocean does not exclude the possibility that it can decompose, for instance. When communicating processes of CO_2 removal, we suggest that using an approach based on variation theory could prove useful [12]. Such an approach could improve understanding of both processes through which CO_2 is actually removed, namely to vegetation and the ocean, while at the same time dealing with misconceptions.

We found that the significance of uptake to the ocean was underestimated by respondents, and we speculate that part of the reason could be that the process through which CO_2 is dissolved in the ocean is not commonly known, especially when compared to photosynthesis. Instead of suggesting that only the process should be communicated more, in schools for instance, we think that education may prove more effective if done in a context with the carbon cycle and accumulation of atmospheric CO_2. This way, not only the details of uptake are taught, but it is done in a context where it is useful.

5.2.4 Implications for Future Research

In our study, only students at Chalmers University of Technology participated. They are generally well educated, young and interested in technology. Therefor they do not represent the public very well as a whole, neither in Sweden nor globally. A study including participants who better represent the general public could yield different results than those that we found, or validate them. A larger sample group could also reveal other misconceptions on processes through which atmospheric CO_2 can be removed. We noticed few responses that mentioned decreased emissions as a way to remove CO_2 from the atmosphere, which is the same as saying that CO_2 is removed by adding less. Respondents misunderstanding the question and more examples of misconceptions could be found and quantified with a larger sample group, we think.

As discussed previously, changing the question format could be beneficial. It would also be interesting to change the order in which it appears in the questionnaire. In the questionnaire used for our study, it came after a task where respondents were told that uptake is to vegetation and the ocean. Switching the order in which they appear could show different results. By first briefly mentioning what uptake is in a previous task could have primed respondents for the question about processes through which CO_2 can be removed from the atmosphere. Priming refers to the phenomenon where stimuli subconsciously influences one's response to a subsequent stimuli [16], for instance how a previous task description can influence later tasks. By placing the question regarding removal processes early in the questionnaire, this priming can be avoided to a higher degree and compared to responses from the current questionnaire. If the task with the description of uptake appears after the question about removal processes, however, respondents may instead be primed when solving the task. Therefore we recommend to consider both orders, depending on what the focus of the study is.

In our study, we found indications that there may be a correlation between understanding processes through which CO_2 can be removed from the atmosphere, and performance on the graphical tasks. We think that a correlation between understanding uptake and understanding CO_2 accumulation may exist, but that this has to be further studied in future research. It is possible to give an answer to the graphical tasks that does not contradict conservation of mass without fully understanding what uptake is and how it works, as long as uptake is perceived as the only process through which CO_2 is removed from the atmosphere. Knowing more about uptake and the carbon cycle, however, means knowing more about the context of CO_2 accumulation, thus making it easier to invoke useful knowledge for solving tasks, for instance the graphical tasks.

Another possible explanation for why respondents who performed better on the graphical tasks also seemed to have a better understanding of uptake, could be that they read the questions and task descriptions more thoroughly. As previously mentioned, uptake was described as being to vegetation and the ocean in a task earlier in the questionnaire, meaning that some respondents could have learned about it then, and remembered it when they answered the question about processes of CO_2 removal. Also, some respondents may have missed or ignored that the current significance for processes was asked for, and therefor answered differently then they otherwise would have. If a correlation can be found between understanding uptake and understanding atmospheric CO_2 accumulation, it would also be interesting to study whether there is a causation or not.

5.3 Opinion on Emission Reduction

In this section, the discussion is centred around the third research question, which is repeated below for convenience.

- *Is there a connection between understanding the relationship between emissions, uptake and amount of atmospheric CO_2, and opinion on reducing emissions of CO_2?*

5.3.1 No Correlation Found

In an attempt to find a correlation, we used performance on the graphical tasks as a measure for understanding the relationship between emissions, uptake, and amount of atmospheric CO_2. This means that in order to display a higher level of understanding of the relation, more of the graphical criteria had to be passed. Using this perspective, combined with a question where respondents were asked to state how much they thought emissions should reduce until 2030 and 2050 respectively, we could not find a correlation. The way we see it there are two general explanations for why we could not find a correlation: 1) the is non, and 2) the chosen approach did not result in showing correlation despite there being one.

Non Existing Correlation

A possible explanation for the option that there is no correlation is that even if people understand the relationship between emissions, uptake, and the amount of atmospheric CO_2, they could believe that technology will develop to significantly contribute to the removal of CO_2. If they believe this, it would explain why they think that emissions do not have to reduce substantially. Another explanation could be that respondents who understand the relation, and those that do not, on average have the same understanding of the consequences of increased levels of atmospheric CO_2. We have only looked for a connection between understanding CO_2 accumulation and opinion on emission reduction. We assume that most people probably do not care for how much CO_2 is in the atmosphere, but rather how it affects themselves, others, and their surrounding. Understanding CO_2 accumulation does not necessarily mean that they know how it affects the global mean temperature, or how the temperature affects the climate, or how the climate affects ecosystems, or how the climate and ecosystems affect humans. For instance, some might argue that it is acceptable that CO_2 stabilises in 2100, and therefor they state that emissions do not have to reduce drastically until 2030 and 2050.

Existing Correlation

It is possible that there was a correlation between understanding CO_2 accumulation, and opinion on emissions reduction from fossil fuels, but that we were not able to find it. As we have argued, not passing graphical criteria does not necessarily mean that one does not understand accumulation of atmospheric CO_2 in some sense, and there seem to be several reasons one could fail to perform well on these tasks. In our analysis, when comparing stated emission reduction with overall performance on graphical tasks, we have not accounted for this diversity of reasons. It may appear that some erroneous ways of reasoning or misconceptions, that cause low performance on tasks, are correlated to opinion on emission reduction and emission regulating policy support in general, but that in this aggregating analysis, these correlations are not visible.

5.3.2 Implications for Practise

Since we did not find a correlation between understanding CO_2 accumulation and opinion on emission reduction, but the might be one, it is difficult to argue for what this means for practise. We do, however, think that when communicating or teaching environmental science, one should not expect that the receiver of the information automatically thinks that emissions should reduce more drastically because of how CO_2 accumulates in the atmosphere.

5.3.3 Implications for Future Research

We could not find any correlation between understanding CO_2 accumulation and opinion on emission reduction, but we do not leave out the possibility that there is one. Therefor, we think that there is good potential for future research to study whether such correlation exists. We suggest an approach where different ways of reasoning behind incorrect and correct answers are examined more closely, and compared to opinion on reduction or some other measure of policy support. There is not only one reason for failing or succeeding to display understanding of CO_2 accumulation, why we argue that examining how people fail or succeed, and comparing it to opinion on emissions reduction, may possibly show a correlation.

In our attempt to find a correlation between understanding CO_2 accumulation and opinion on emission reduction, we only used graphical tasks to test understanding. It is possible, however, that people understand CO_2 but perform worse on tasks including graphs then they would on tasks without. One does not necessarily need to have a understanding of graphs in order to understand CO_2 accumulation[24]. Therefor, we suggest the use of tasks in different formats and with different ways of testing understanding, where some do not have a graphical element.

5.4 The Questionnaire as a Whole

In this section, the discussion is centred around the questionnaire as a whole. In addition to the results compiled from responses to the questionnaire, we suggest that the questionnaire itself can be seen as a result of this study.

5.4.1 Questionnaire Design

When we designed the questionnaire, we were not certain what approach was going to be used for analysing the data. A result of this uncertainty was that the questionnaire was longer than it needed to be, with many questions and corresponding responses that have not been analysed or presented. Because the questionnaire was so long, we had to plan for respondents to have time, and be motivated to take the questionnaire, in order to get responses. This was done by giving free food in locations where the participants could sit down with enough time to finish the questionnaire. If it had been shorter, other alternatives to get participants may have been possible, and it would not have been as large of a commitment for the participants. Also, answering a long questionnaire can be tiresome, making participants focus less on later questions and tasks. In hindsight, we think a shorter questionnaire would have been preferable, with hopes that more students would have participated, and spent more time and focus on a few selected tasks and questions.

Another factor to consider in the questionnaire, besides its length, is the order in which questions and tasks appear. There will always be some degree of priming, which means that choosing an order will most likely be a compromise. As discussed above, choosing a different order for the graphical tasks could prove to have a big impact on the results.

In the questionnaire, the question about opinion on reduction of emissions from fossil fuels (Q1.9) came just before the tasks where respondents were asked to draw emissions and uptake for a future scenario for the amount of atmospheric CO_2 (T2.1). It is possible that this could have primed participants to answer what they thought should happen, instead of focusing on the relationship between emissions, uptake, and the amount. If the question (Q1.9) would have been placed later in the questionnaire, however, respondents would have been primed from the tasks instead, perhaps making them answer that emissions should reduce more than they originally thought. A good enough compromise could be to have more distance between the question about opinion on emission reduction, and the first graphical task, by having other (on e.g. demographics) questions in between.

Of the graphical tasks there were two that were the same, except that the later one had little descriptive text (other than asking the participant to, once more, fill in the graph showing trajectories for emissions and uptake) and no reference graph (T2.1 and T6.1). Creating a pre-post-test for the chosen task posed a dilemma. If the second task would have had a full task description, it seemed likely that respondents would not have read to whole text again, since it is fairly long. Since the questionnaire was quite long, we also feared that the full text would make it feel even longer, thus making the respondent lose interest and motivation. If we had chosen to shorten the descriptive text to only include the most important information, this would have changed the characteristics of the task and possibly making finding a correct solution easier. We chose to refer back to the first time the task appeared in the questionnaire, if respondents wanted to see the full description again. We assume, however, that referring back to the earlier question could have influenced respondents to remember their previous answer and simply write it down again. A possible way to avoid this dilemma could be to use a different task for the pre-post-test, one with a brief descriptive text.

5.4.2 Future Use of the Questionnaire

The questionnaire used in our study has potential to be used for future research, for instance for suggestions previously made in this chapter. The questionnaire, as it was used in our study, is relatively long, but it does not have to be used in its entirety. For instance, in our study we did not use all the data, why we could have shortened the questionnaire to make it more concise. Depending on what is used for, parts can be taken away, added, or changed in order to fit the purpose of future studies.

We also suggest that parts of it can be used for testing people (e.g. students), or as inspiration for classes. The tasks are suitable for students at a technological university but may also be suitable for other university students, and some tasks may be suitable for secondary school education.

6
Conclusions

In this brief chapter, a few main conclusions drawn in the previous Chapter, 5 Discussion, are summarised.

Continuing on previous research, the study presented in this report set out to investigate public understanding of the relationship between emissions, uptake and total amount of atmospheric CO_2 and people's misconceptions concerning processes through which CO_2 is removed from the atmosphere. Public opinion on emission reduction was also studied, and was compared with task performance on accumulation of atmospheric CO_2. Based on the results of these investigations, we present the following main conclusions:

- It has been further substantiated that "understanding" accumulation of atmospheric CO_2 involves several types of knowledge. It was found that assessing people's performance on a range of tasks yielded varying results, even though the tasks were deemed to demand similar knowledge of concepts and procedures, indicating that lacking knowledge of when to utilise these concepts and procedures could heavily influence performance. For some, it appears irrelevant associations, such as opinion on politics, hinders people from applying correct knowledge of concepts and procedures to tasks on CO_2 accumulation. Climate change communication may thus prove more effective if information on limiting the level of atmospheric CO_2 highlights the relationship between emissions, uptake and atmospheric CO_2 or familiarises people to the context.
- Some heavily underestimate the uptake of atmospheric CO_2 to the ocean, and people also extensively show the misconceptions that notable amounts of atmospheric CO_2 decomposes or leaves the atmosphere into space. These misconceptions could increase the risk of SF failure in the CO_2 accumulation context, and is suggested for future research to investigate.
- No clear correlation between performance on SF tasks in the CO_2 accumulation context and opinion on emission reduction was found. We suggest further mapping of how people understand accumulation of atmospheric CO_2, in order to investigate possible correlations between policy support and some forms of erroneous reasoning or misconceptions that may cause SF failure.

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A

Appendix A: Method

This appendix contains a list of graphical criteria for the graphical tasks, as well as the matrix used to relate the criteria to the different elements of knowledge.

List of graphical criteria (GC)

- **T2.1**:
  If several trajectories for emissions and uptake has been drawn, the most prominent trajectories are chosen to determine if the GC have been fulfilled. If no such trajectories can be identified, the average of the trajectories (for emissions and uptake respectively) are used if the maximum distance between any two of them is 5 mm, else the answer is considered unusable.

  (Trajectories can be said to coincide if the difference between them is less than 2 mm in 90% of the interval, and less than 5 mm difference in the remaining %.)
  - **GC1:** Trajectories for emissions and uptake coincide, starting from a point in the interval 2030-2060 to a point in the interval 2075-2100.
  - **GC2:** GC1 is fulfilled and the difference between emissions and uptake decreases in the interval between 2019 and the first point where the trajectories coincide, by at least 20% of it's decrease in the first two thirds of this interval. During no more than 3 mm (in the x-axis direction) is U > E.
- **T3.1**:
  If several trajectories for total amount has been drawn, the most prominent trajectory is chosen to determine if the GC have been fulfilled. If no such trajectory can be identified, the average of the trajectories are used if the maximum distance between any two of them is 5 mm, else the answer is considered unusable.

  *In these GC, a segment of a trajectory is considered to be a "line"/"linear" if the trajectory is confined within a 3 mm interval, measured in the normal direction of a line drawn from the starting point to the end point of the segment.
  - **GC1:** From some point in the interval year 3.9 to 5.5 a stable (max 2 mm increase/decreease) line begins, that ends at some point in the interval year 6.1 to 7.5. (There are no other stable (M'=0) lines in the figure)

  - **GC2:** The trajectory for M is continously rising in the time interval year 0 to 3.9, rising or stable in the time interval 3.9 to 5.5, stable in the time interval 5.5 to 6.1, stable or decreasing in the time interval 6.1 to 7.5 and decreasing in the time interval 7.5 to 11.
  - **GC3:** a) The trajectory for amount starts from within 3 mm from the centrum of the star, and then increases linearly until the line ends at a point P1 in the two-dimensional interval [(4.8,380),(5.2,420)].
    and
    b) From P1, another line begins that ends at a point P2 in the interval year 6.8 to 7.2. (There are no other stable (M'=0) lines in the figure)
    and
    c) A new line then begins from P2, where the amount decreases linearly until a point P3 in the interval [(11.8, 230),(12,270)]. If a line has been drawn to year 10 and can be extended to a point P in the interval [(11.8, 230),(12,270)] it also fulfills GC2c).
- **T4.1-4.4:**
  No graphical criteria. See Figure A.1.
- **T6.1:**
  Same graphical criteria as T2.1.

	CK1:	CK2:	CK3:	PK1:	PK2:	PK3:	PK4:	PK5:	PK6:
T2.1 - GC1... - GC2...	GC1 fulfilled	GC2 fulfilled	GC2 fulfilled	GC1 fulfilled	GC2 fulfilled	GC1 fulfilled	GC2 fulfilled	GC2 fulfilled	GC2 fulfilled
T3.1 - GC1... - GC2... - GC3...	GC1 fulfilled	GC3 fulfilled	GC3 fulfilled	GC1 fulfilled	GC3 fulfilled	GC1 fulfilled	GC2 fulfilled	GC3 fulfilled	GC2 fulfilled
T4.1-4.4	Alternative E is selected in T4.3.	Alternative C is selected in T4.2. and alternative G is selected in T4. 4.	Alternative E is selected in T4.1.	At least two of the correct alternatives are selected.	-	Alternative E is selected in T4.3.	Alternative C is selected in T4.2. and alternative G is selected in T4. 4.	Alternative C is selected in T4.2, alternative G is selected in T4.4 and alternative E is selected in T4. 1.	Alternative C is selected in T4.2, alternative G is selected in T4.4 and alternative E is selected in T4. 1.
T6.1 Same as T2.1	GC1 fulfilled	GC2 fulfilled	GC2 fulfilled	GC1 fulfilled	GC2 fulfilled	GC1 fulfilled	GC2 fulfilled	GC2 fulfilled	GC2 fulfilled

Figure A.1: Matrix used to assess responses to the graphical tasks with graphical criteria (GC) for each task as rows, and the elements of knowledge (CK and PK) as columns. Elements of knowledge are described in Section 3.4, and GC in the list above. If a criteria for an element of knowledge was fulfilled, it meant that the respondent did not contradict that they used that element of knowledge correctly to solve the task. T4.1-4.4 was assessed by the respondent's chosen alternatives, since the task is a multiple choice question. For the same reason, PK2 could not be assessed in T4.1-4.4, since the task does not require a graphical response.

B

Appendix B: Results & Analysis

This appendix contains additional figures and tables related to results from the survey.

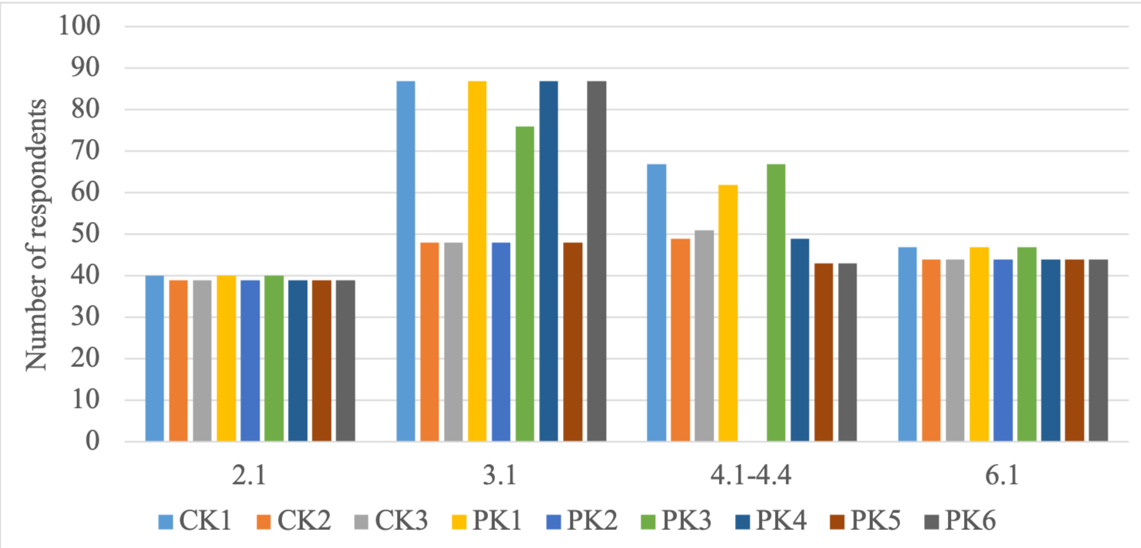
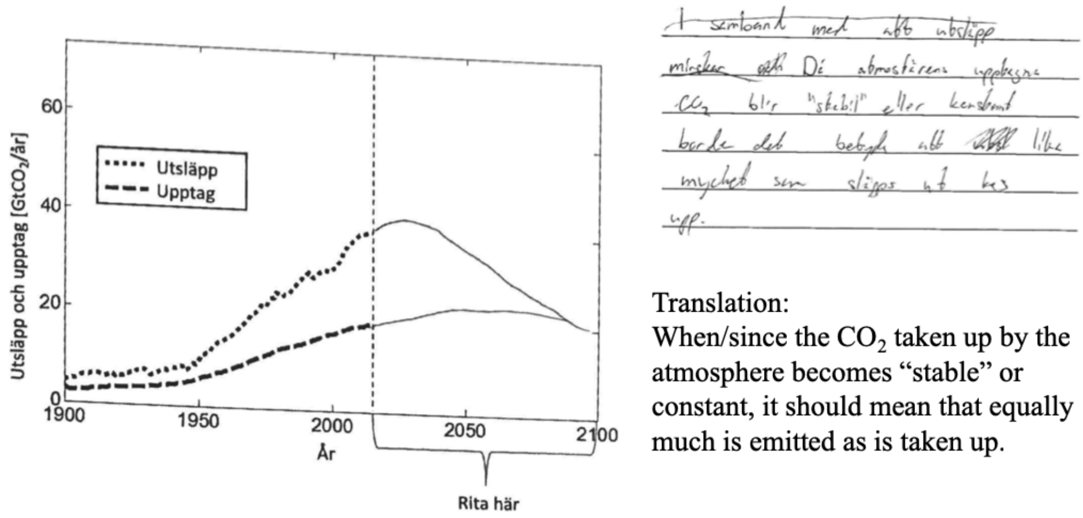


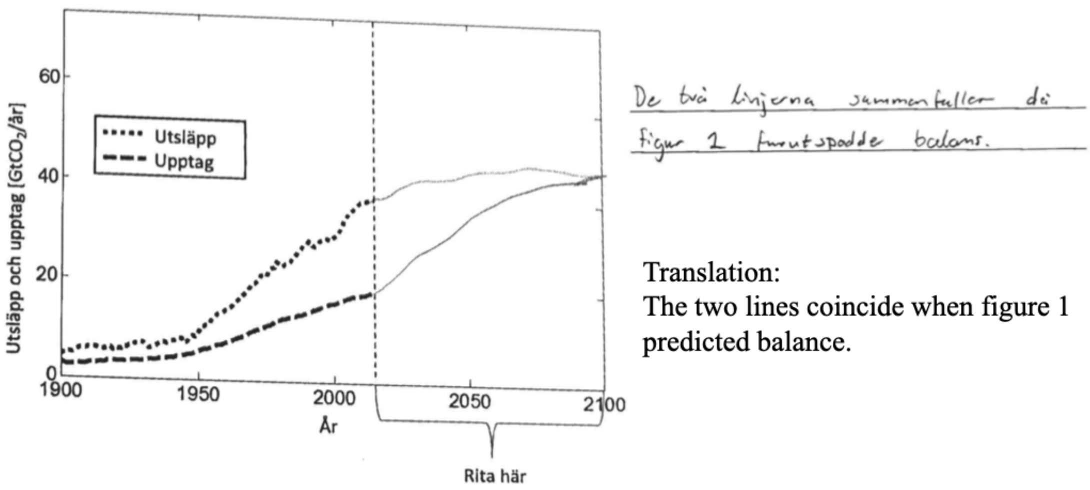
Figure B.1: Comparison of respondents' answers that did not contradict the use of correct conceptual (CK) or procedural knowledge (PK) for the graphical tasks. The figure shows that respondents were able to pass the criteria for CK and PK with varying success in the different tasks. The figure also shows an increase of answers that passed the criteria for CK or PK from T2.1 to T6.1, which are the same task.

Table B.1: Percentage of respondents that passed the graphical criteria (i.e. GC1 and GC2) for T2.1, T3.1, and T6.1. The table shows that respondents' performance varied with the different tasks. T2.1 and T6.1 are the same task, but the success rate of GC2 was 4,8% higher for T6.1.

	GC1	GC2	GC3
T2.1	30,5%	29,8%	-
T3.1	66,4%	66,4%	36,6%
T6.1	35,9%	33,6%	-

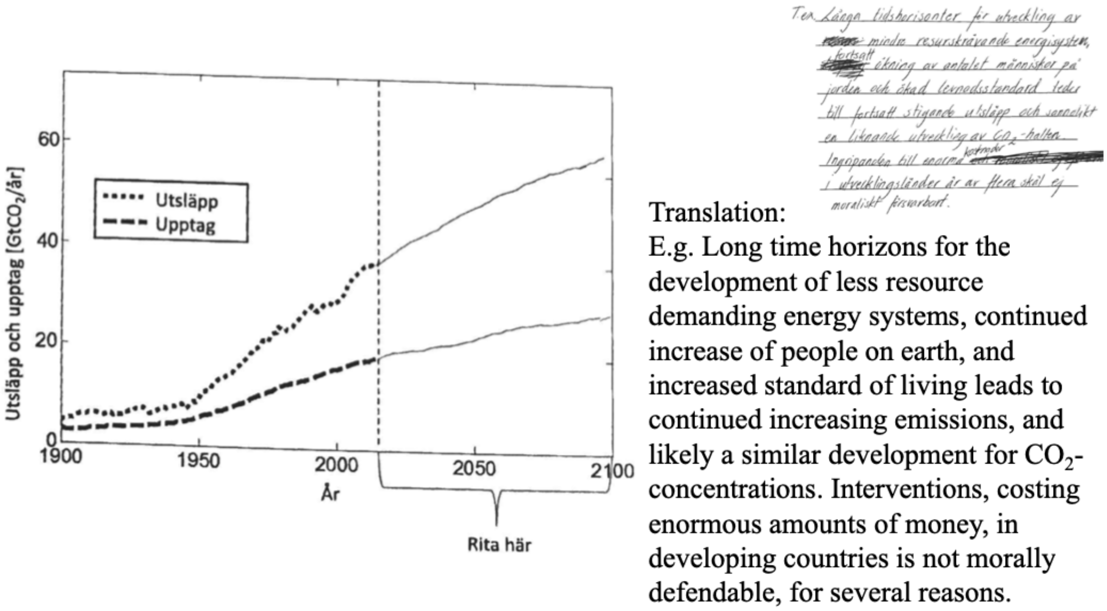


(a) Correct reasoning but incorrect graphical response.

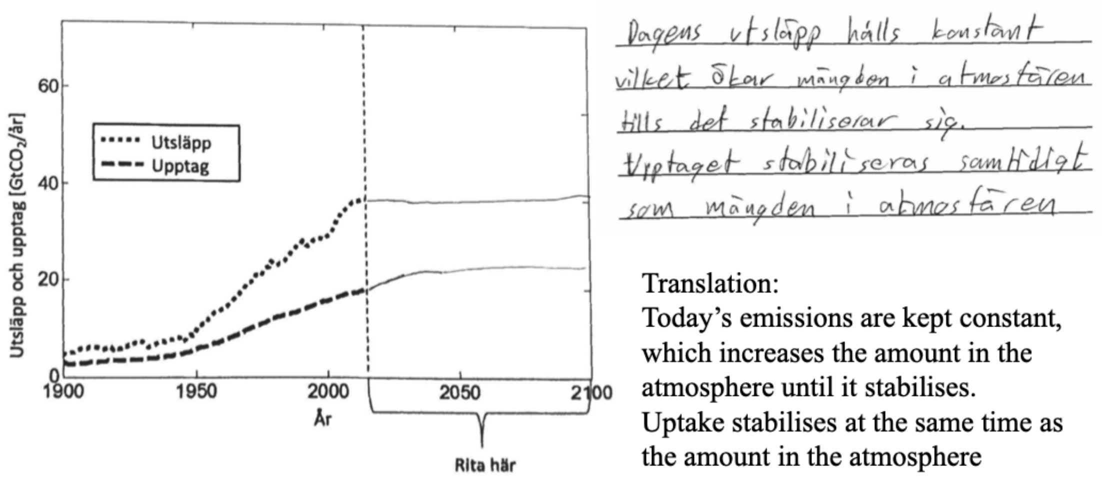


(b) Correct reasoning but incorrect graphical response.

Figure B.2: Examples of respondents' answers to T2.1 with the corresponding written explanation behind their reasoning. The written explanations can be interpreted to imply that emissions and uptake must be equal for the amount of atmospheric CO_2 to stabilise. However, drawn trajectories for emissions and uptake do not coincide until briefly before the year 2100, thus failing to pass the graphical criteria assigned to the task. Their drawn responses contradict correct use of knowledge, despite them displaying correct knowledge in the written responses. This strengthens the notion that failing to provide correct answers to tasks does not necessarily mean that respondents do not possess the conceptual and procedural knowledge demanded by the task.



(a) Focus on knowledge not related to the relationship between emissions, uptake, and amount of atmosheric CO_2.



(b) Incorrect relationship between emissions, uptake, and amount of atmospheric CO_2.

Figure B.3: Examples of respondents' answers to T2.1 with the corresponding written explanation. The examples show types of reasoning that do not include any use of correct knowledge related to solving the task successfully. It does not necessarily mean that the respondents do not possess correct knowledge for solving the task, but that they were not able ti invoke it. One reason could be that other knowledge was invoked and not dismissed, thus becoming an obstacle for focusing on knowledge useful for solving the task.

Table B.2: Percentage of respondents selecting the correct alternative in T4.1-4.4, respectively. The table shows that the rate of success varied depending on the event asked for in the task, since the graph and the format for the tasks was the same for T4.1-4.4. A trend can be seen where the rate of success gets higher with later tasks. This could imply two things: 1) respondents learned what knowledge was useful with every task, or 2) the later tasks demanded knowledge that more respondents had.

	T4.1	T4.2	T4.3	T4.4
Correct alternative selected	53,4%	54,2%	69,5%	78,6%

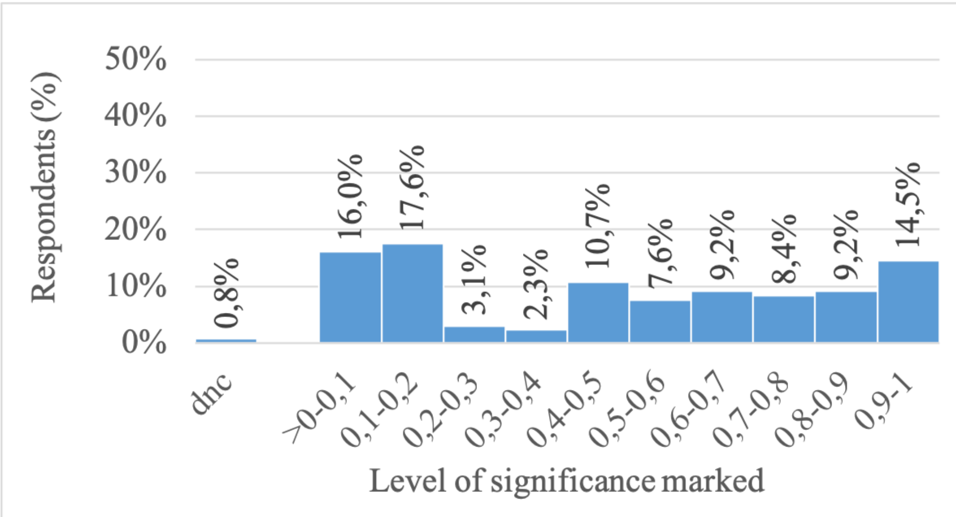


Figure B.4: Histogram over respondents' perception of how significant uptake by means of technology currently is for the removal of atmospheric CO_2. The scale ranges from 0 to 1, where 1 is very significant and 0 means that it does not contribute to the removal. Answers marked at 0 have a separate column marked "dnc", short for "does not contribute". The histogram shows that respondents' perception of technology's significance for uptake varies across the scale with no clear skew to either side, and no clear peak. It also shows that only 0,8% of the respondents marked that technology currently does not contribute.

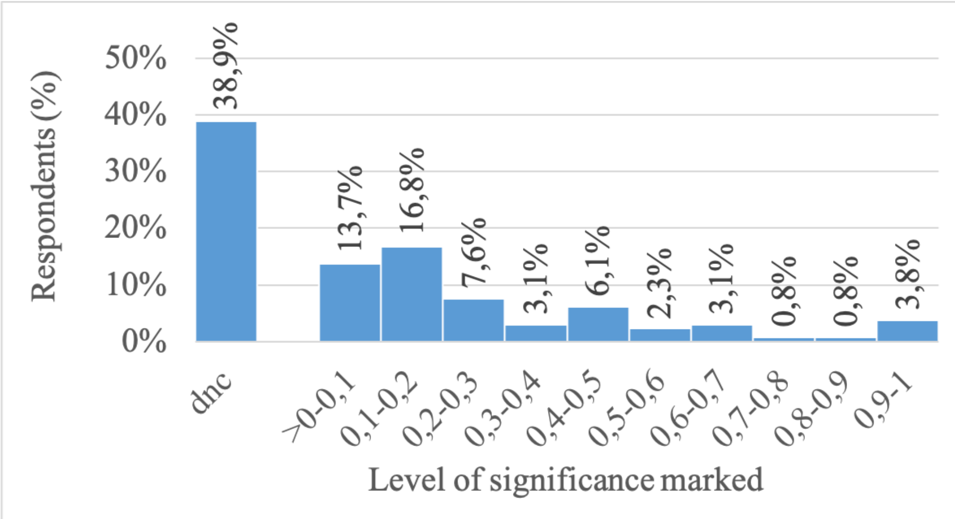


Figure B.5: Histogram of respondents' perception of how significant CO_2 going into space currently is for the removal of atmospheric CO_2. The scale goes from 0-1, where 1 is very significant and 0 means that it does not contribute to the removal. Answers marked at 0 have a separate column marked "dnc", short for "does not contribute". The histogram shows that a majority of respondents, 58,1%, think that CO_2 going into space contributes to the removal of atmospheric CO_2.

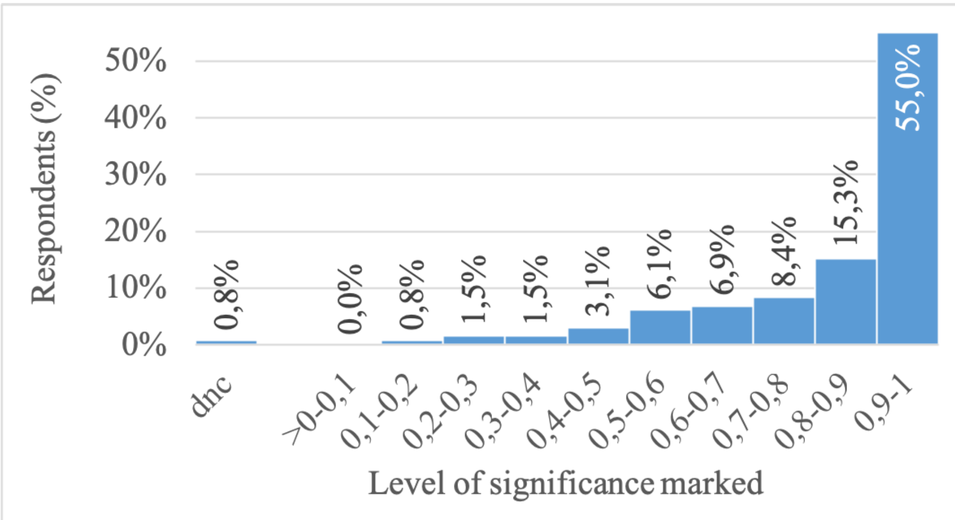


Figure B.6: Histogram over respondents' perception of how significant uptake by vegetation currently is for the removal of atmospheric CO_2. The scale goes from 0-1, where 1 is very significant and 0 means that it does not contribute to the removal. Answers marked at 0 have a separate column marked "dnc", short for "does not contribute". The histogram is heavily skewed to the right, implying that most respondents think that removal of atmospheric CO_2 by vegetation is significant to a high degree.

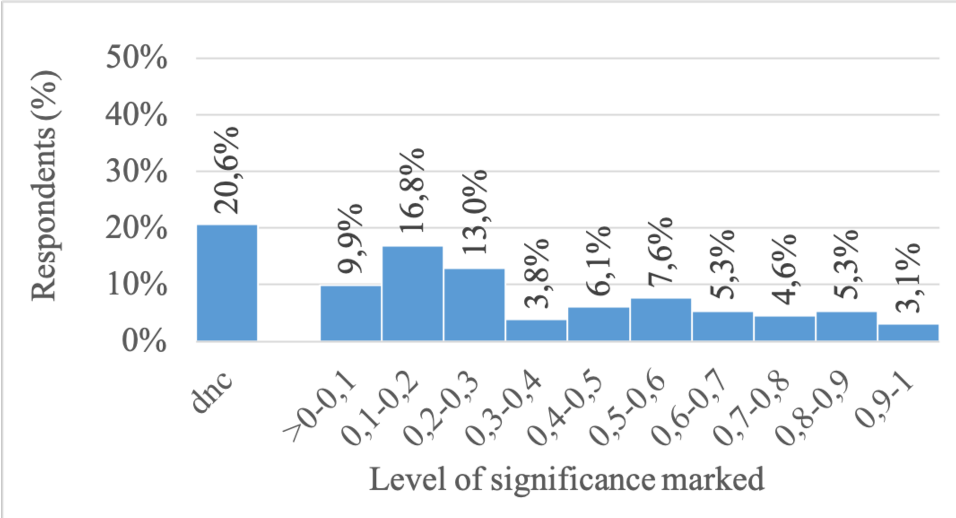


Figure B.7: Histogram over respondents' perception of how significant the natural decomposition of CO_2 currently is for the removal of atmospheric CO_2. The scale goes from 0-1, where 1 is very significant and 0 means that it does not contribute to the removal. Answers marked at 0 have a separate column marked "dnc", short for "does not contribute". CO_2 does not decompose naturally in the atmosphere but the histogram shows that most respondents (75,5%) marked that it has some level of significance for the removal of atmospheric CO_2.

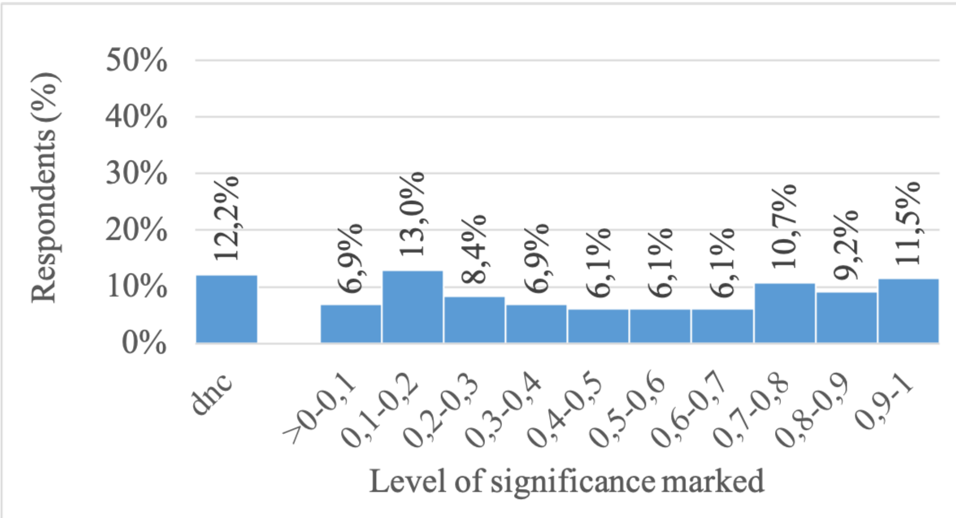


Figure B.8: Histogram over respondents' perception of how significant uptake from oceans currently is for the removal of atmospheric CO_2. The scale goes from 0-1, where 1 is very significant and 0 means that it does not contribute to the removal. Answers marked at 0 have a separate column marked "dnc", short for "does not contribute". The histogram shows that respondents' perception of the oceans' significance for uptake varies across the scale with no clear skew or peak.

Table B.3: Comparison between performance on the graphical tasks and marked level of significance for different processes through which CO_2 can be removed from the atmosphere. The table consists of four separate tables, one for each graphical task. The values in the centre column are averages of answers from Q5.5a-e, given by respondents who fulfilled all the graphical criteria for the respective graphical task. The right-hand column displays the same averages, but for respondents who did not fulfil any graphical criteria for the respective graphical task. The averages are on a scale from 0-1, where 0 means that the alternative does not contribute to the removal of atmospheric CO_2, and 1 that it is a very significant contributor.

T2.1	All criteria fulfilled N=39	No criteria fulfilled N=91
Q5.5a, technology	0,45	0,52
Q5.5b, space	0,14	0,19
Q5.5c, vegetation	0,89	0,83
Q5.5d, decomposition	0,27	0,32
Q5.5e, ocean	0,56	0,41

T3.1	All criteria fulfilled N=48	No criteria fulfilled N=44
Q5.5a, technology	0,50	0,51
Q5.5b, space	0,19	020
Q5.5c, vegetation	0,87	0,82
Q5.5d, decomposition	0,24	0,32
Q5.5e, ocean	0,54	0,41

T4.1-4.4	All criteria fulfilled N=56	No criteria fulfilled N=24
Q5.5a, technology	0,50	0,60
Q5.5b, space	0,14	0,22
Q5.5c, vegetation	0,89	0,83
Q5.5d, decomposition	0,25	0,37
Q5.5e, ocean	0,49	0,31

T6.1	All criteria fulfilled N=44	No criteria fulfilled N=84
Q5.5a, technology	0,42	0,54
Q5.5b, space	0,17	0,18
Q5.5c, vegetation	0,86	0,83
Q5.5d, decomposition	0,26	0,33
Q5.5e, ocean	0,46	0,45

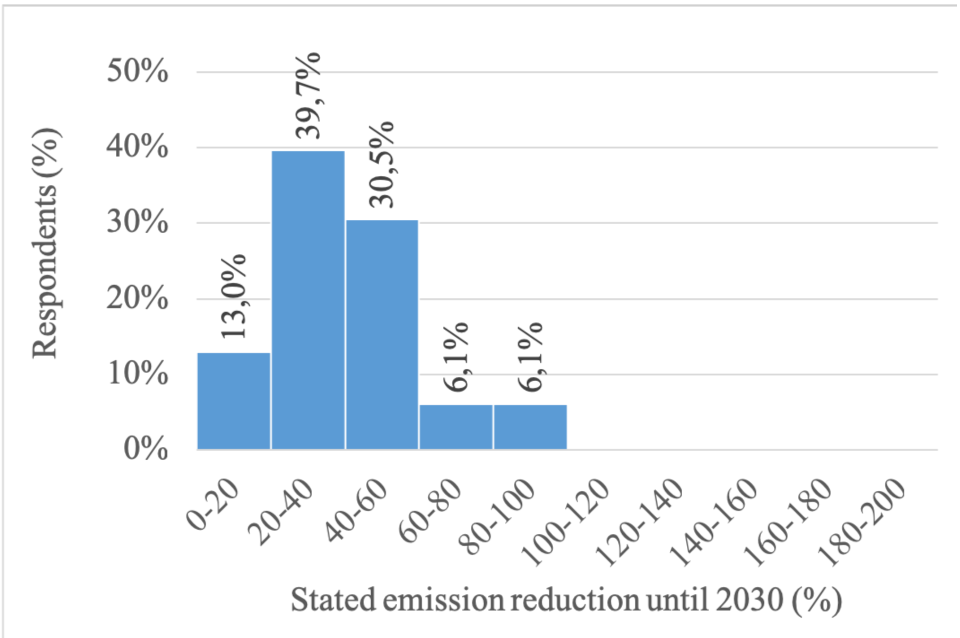


Figure B.9: Distribution of responses stating how much emissions should reduce by until year 2030.

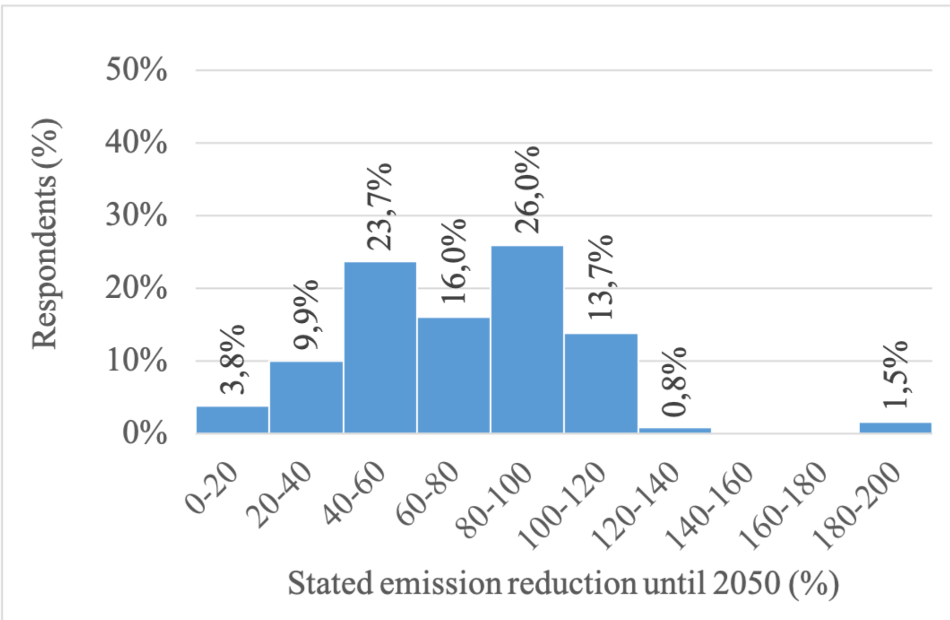


Figure B.10: Distribution of responses stating how much emissions should reduce by until year 2050.

Table B.4: Comparison between stated emission reduction and performance on the graphical tasks. The table displays averages of stated emission reduction, until year 2030 and 2050 respectively, for respondents who either fulfilled all of the criteria for a graphical task, or did not fulfil any. In all cases but one, the average stated emission reduction is slightly higher for respondents who fulfilled all of the criteria for a task. Comparing performance on T2.1 with stated emission reductions until 2030 is the exception where respondents who did not fulfil any criteria stated a higher average emission reduction.

	Average stated emission reduction until 2030		Average stated emission reduction until 2050	
	All criteria fulfilled	No criteria fulfilled	All criteria fulfilled	No criteria fulfilled
T2.1	33,5% (N=39)	36,6% (N=85)	70,5% (N=39)	68,1% (N=85)
T3.1	34,4% (N=47)	33,9% (N=78)	71.4% (N=47)	63,4% (N=78)
T4.1-4.4	37,1% (N=54)	31,8% (N=23)	72,2% (N=54)	62,7% (N=23)
T6.1	38,1% (N=44)	33,1% (N=84)	70,0% (N=44)	64,1% (N=84)

Table B.5: Comparison between stated emission reduction until 2030 and 2050, and marked level of significance for different processes through which CO_2 can be removed from the atmosphere (Q5.5a-e, a: technology, b: space, c: vegetation, d: decomposition, e:oceans). Responses were divided into two equally large groups for each process of CO_2 removal: one with responses marking lower than the median marked level of significance for an alternative, and one with responses marking higher. The average level of significance marked for each group is displayed in the table, along with the average stated reduction until 2030 and 2050 respectively. The table shows no clear correlations between marking well on ways of removal of atmospheric CO_2 and stated emission reduction for 2030 and 2050. One exception was that those who marked below the median on Q5.5a, i.e. those who put decomposition as less significant, stated higher emission reduction, compared to those who marked higher than the median. For both 2030 and 2050, the difference in emission reduction stated is larger than 10%.

	Respondents marking **lower** then the median marked level of signicifance			Respondents marking **higher** then the median marked level of significance		
	Average level of significance marked	Average stated reduction until 2030	Average stated reduction until 2050	Average level of significance marked	Average stated reduction until 2030	Average state reduction until 2050
Q5.5a	0,201	33,8%	65,0%	0,784	34,2%	67,2%
Q5.5b	0,010	36,3%	69,8%	0,331	33,3%	64,7%
Q5.5c	0,696	37,7%	69,4%	0,989	33,6%	68,3%
Q5.5d	0,071	40,6%	74,1%	0,551	30,5%	63,3%
Q5.5e	0,162	36,8%	68,9%	0,766	34,5%	68,7%