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Reflections on an Interdisciplinary Collaboration

To Inform Public Understanding of Climate Change, Mitigation, and Impacts

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Abstract

We describe two interdisciplinary projects in which natural scientists and engineers, as well as psychologists and other behavioral scientists, worked together to better communicate about climate change, including mitigation and impacts. One project focused on understanding and informing public perceptions of an emerging technology to capture and sequester carbon dioxide (CCS) from coal-fired power plants, as well as other low-carbon electricity generation technologies. A second project focused on public understanding about carbon dioxide's residence time in the atmosphere. In both projects, we applied the mental models approach, which aims to design effective communications by using insights from interdisciplinary teams of experts, and mental models elicited from intended audience members. In addition to summarizing our findings, we discuss the process of interdisciplinary collaboration that we pursued in framing and completing both projects. We conclude by describing what we think we have learned about the conditions that supported our ongoing interdisciplinary collaborations.

Keywords: Risk perception and communication, mental models, climate change, carbon capture and sequestration (CCS), CO_2 atmospheric residence time.

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INTRODUCTION

Real world problems in science, technology and public policy such as climate change typically cannot be addressed adequately from the perspective of any single discipline. Experts in the natural sciences, engineering, and social sciences are needed to identify how problems develop as well as the technological and behavior change needed to mitigate them. Climate scientists are needed to understand how the climate is likely to change. Engineers are needed to develop technologies to reduce future emissions of greenhouse gases. Psychologists and other behavioral social scientists are needed to understand the main drivers of human behavior, as well as how to design communications and interventions that tackle those drivers in a way that promotes needed behavior change. However, too often, experts from these different fields do not know how to talk with each other. They may not know how to work together, or even perceive the importance of doing so.

At least some natural scientists and engineers do not perceive a need to involve psychologists or other behavioral social scientists because they already feel (unwarranted) confidence about their intuitions of what drives human behavior. They may be subject to what has been referred to as "false consensus effects," such that they perceive their own behavior as typical for people in general -- even when it is not.[1] Indeed, they may fail to realize that they are no longer able to think or act like non-experts, at least where it pertains to problems in their own field of expertise.[2] Moreover, some natural scientists and engineers may not understand the extent to which the behavioral social sciences have developed an empirical evidence base to understand human behavior, its antecedents, consequences, as well as of interventions to change it. Indeed, we know some who hold the view that there is nothing in the social sciences that they couldn't invent themselves at a cocktail party on a weekend. When left to their own devices, many natural scientists and engineers may end up developing interventions that do not address the main drivers of people's behavior, or create communications that are too complex to be useful for non-experts.

At the same time, many psychologists and other behavioral scientists may not perceive a need for interdisciplinary collaborations either. They often prefer to limit their research to their labs, where they can carefully control conditions to identify when and why their theories do or do not hold. However, one criticism of such lab studies has been that the presented conditions are hypothetical and unrealistic – undermining their generalizability to real-world behavior.[3-4] When left to their own devices, psychologists and other behavioral scientists may end up developing interventions that overlook important technical solutions, and communications that oversimplify the problem at hand.

Yet, there is a growing literature on how to foster interdisciplinary collaborations that can overcome the insular focus of individual disciplines. In their PNAS Perspective, Bruine de Bruin and Fischhoff[5] identified four conditions that supported their interdisciplinary collaborations between psychologists and economists. These conditions involved (1) shared project goals that team members agree will be better achieved by relying on insights from both of the involved disciplines; (2) a shared methodology that combines best practices from the involved disciplines and outlines a clear strategy for empirically resolving disagreements; (3) shared effort and communication throughout the project, so that the end product reflects a true co-production; (4) shared benefits, such that the project produces outcomes that are relevant to each discipline but are better as a result of the contribution from both disciplines. These conditions echo those identified in research on effective medical research collaborations. [6-7]

Who we are

Granger is the Hamerschlag University Professor of Engineering, and served as the founding Head of Carnegie Mellon's Department of Engineering and Public Policy (EPP) for thirty-eight years. Department members include engineers, and natural scientists, as well as psychologists and other behavioral scientists, who work together on important policy problems where the technical details really matter. Granger has worked with interdisciplinary teams on a wide range of problems in science, technology and public policy,[8] focusing particularly on issues in energy, environment and climate change, and on the characterization and treatment of uncertainty.[9] Granger and Wändi have been working together for over 15 years.

Wändi currently holds a Leadership Chair in Behavioral Decision Making at the University of Leeds, where she directs the Centre for Decision Research. Her Center brings together researchers from different disciplines who aim to understand and inform how people make decisions about real-word issues such as health, finance, environmental risk, and climate change. If their research finds that people have difficulties in making those decisions, Wändi and her colleagues aim to develop communications and interventions to inform those decisions. Prior to moving to Leeds, Wändi was a member of the faculty at Carnegie Mellon University, where she still holds an appointment in the Department of Engineering and Public Policy.

Before she met Granger, Wändi's main interdisciplinary project had focused on developing a video intervention for reducing sexually transmitted infections in female adolescents.[10-11] The team, led by social psychologist Julie Downs, consisted of social scientists and medical doctors. In face-to-face interviews, female adolescents were able to repeat recommendations to remain abstinent or use condoms if sexually active, but seemed to find it difficult to take the initiative to talk about those strategies with their partners.[10] Young women who are less likely to communicate about sex with their sexual partners tend to be less likely to use condoms. [12] Among other things, our intervention therefore provided training on how to bring up abstinence and condom use with potential sexual partners.[10] A review of sex education programs by the US Dept. of Health and Human Services later recognized our intervention as one of the few that led to behavior change.[13]

Granger and Wändi first began to collaborate on a project that involved using the mental models approach to understand and inform public perceptions of low-carbon electricity generation technologies. Granger thought that if Wändi knew how to talk to teenagers about sexually transmitted infections then surely she could help him to talk to adults about carbon capture and deep geological sequestration (CCS). Wändi did not know what CCS was, but she said 'Count me in!' It helped that Granger offered to cover her time, and that MSc student Claire Palmgren (now at Kema), who had collaborated with Wändi on the sex education intervention, was also involved. The ensuing project was the start of an ongoing interdisciplinary collaboration that we describe here.

INTERDISCIPLINARY "MENTAL MODELS" APPROACH

Our projects have been grounded in the interdisciplinary "mental models" approach, which Granger originally designed in the 1990s, together with psychologist Baruch Fischhoff, economist Lester Lave, and several others at Carnegie Mellon University.[14] The approach recognizes that people may have a "mental model" or a set of beliefs about climate change and other topics, which may differ from those of domain experts. Research on science education[15] and health communications,[16] as well as cognitive anthropology and psychology[17-18] suggests that people will rely on their mental models when interpreting new information. For risk communications to be effective, they must therefore be developed on the basis of audience members' mental models. Rather than just repeating facts that recipients may already know, communications should address the limitations of audience members' mental models, while building on the beliefs they already have.

Each step in the mental models approach towards developing communications involves an interdisciplinary collaboration between domain experts (such as Granger) and social scientists (such as Wändi). Before developing communication content, the mental models approach first requires a comparison of the way in which domain experts frame the risk with the information and perceptions that people already have. This process involves domain experts who can provide a correct and balanced description from the scientific literature, and social scientists who can conduct interviews and surveys with members of the intended audience, to identify what they already know and still need to know if they are going to address effectively the risks they face. The next step of the mental models approach is to develop communication content that focuses on those pieces of advice that people need and want but seem to be missing, as well as identifying a few critical misunderstandings, all in wording they can understand. This communication development phase relies on iterative input from the domain expert, to ensure the accuracy of the information, and input from the social scientist, to test for understandability. The latter involves conducting think-aloud interviews in which members of the intended audience attempt to understand and use the presented information. Such participatory design processes – also referred to as formative evaluation – have been identified as critical for creating effective communications. [19] Testing the understanding of intended audience members can also be useful for resolving disagreements about what to present or how to present it. If budgets allow larger-scale evaluations, communications could be evaluated further in terms of their effect on recipients' understanding, by conducting pre-post tests, randomized experiments, and related social science research methods.[19]

We believe that the mental models approach towards developing communications has helped us meet the four conditions of interdisciplinary collaborations outlined above: (1) the shared goal is to study and inform public understanding of climate change and its impacts, that covers relevant advice that people want and need, in wording that they understand; (2) a shared methodology for developing these communications, with disagreements being resolved through tests with intended audience members; (3) shared effort and communication throughout the project, so that the end product reflects a true co-production; (4) shared benefits, such that the project produces insights that help domain experts and social scientists to better understand how non-expert audience think and learn about topics of interest.

Below, we describe two of our interdisciplinary projects, which were grounded in the mental models approach. The first focused on public perceptions of CCS and other low-carbon electricity generation technologies. The second focused on public understanding of how long CO_2 remains in the atmosphere. In addition to briefly summarizing the work, we discuss the process of interdisciplinary collaboration that we have pursued in framing and conducting these projects. We conclude by summarizing what we think we have learned about how to foster effective interdisciplinary collaborations.

Project 1: Public perceptions of low-carbon electricity generation technologies

<u>Background</u>

Electricity generation is the largest contributor to CO_2 emissions from the energy supply sector.[20] Almost all studies that explored how the world could stay below the Paris accord's target of 1.5 to 2° C involve negative emissions.[21] To reduce CO_2 emissions, the energy sector will need to rely on a portfolio of strategies that include energy efficiency, fuel switching, renewables such as wind and solar, nuclear power, as well as carbon capture and deep geological sequestration (CCS).[22] CCS is a technology that captures CO_2 before it is released by coal- or gas-fired power plants, and prevents it from going into the atmosphere by injecting it deep underground. Like most technologies, there are both benefits and risks associated with CCS. If people perceive the risks to outweigh the benefits, the resulting public opposition could prevent widespread implementation. We therefore started this project with our shared goal to understand and inform public understanding of CCS, and agreed on implementing our shared mental models methodology in a shared effort.

Initial findings

We started by conducting interviews and surveys to understand the beliefs people may form about CCS, when they learn about the technology. Our initial interviews and surveys found that few of our participants had heard of CCS.[23] After receiving information about the technology, they focused more on the risks than on the benefits. This finding is consistent with literature in the psychology of decision making, which suggests that people tend to pay more attention to negative attributes than to positive attributes of newly available options.[24] For CCS, this negative focus may have been exacerbated because the idea of putting CO_2 deep underground evoked negative associations with nuclear waste.[23] Negative affective responses to technologies tend to increase perceptions of risks and decrease perceptions of benefits.[25]

While our initial findings did not bode well for future acceptance of the technology, we also observed that many of our participants wanted to discuss CCS in comparison to other low-carbon technologies, such as wind and solar power.[23] Although our project goal had been to develop communications about CCS, this observation encouraged us to develop communications that also covered other feasible low-carbon alternatives. That decision was very much facilitated by the shared goal on which we had agreed in advance of the project: To communicate information that people still seemed to need -- and wanted. It was also facilitated by domain experts' view that CCS should be considered as part of a portfolio of low-carbon electricity generation technologies (Table 1).

<u>Developing communications</u>

With input from colleagues with expertise in different technologies, PhD student Lauren Fleishman Mayer (now at RAND) and Granger drafted comparative information about identical attributes, including risks, benefits and costs, for each of ten low-carbon technologies. [26] Subsequently, Wändi urged for making the texts easier to read. Readability can be improved by using shorter words, shorter sentences, and avoiding jargon, as assessed by the Flesch-Kincaid and other readability statistics.[19,27,]

Thus, our challenge was to find a balance between domain experts' complex terminology and social scientists' recommendations to simplify. Domain experts often have a tendency to use overly complex wording, but social scientists' recommendation is for outreach materials to be written at the 6^{th} -7^{th} grade level.[19] As many as 80-95% of people in OECD countries have the reading comprehension skills to understand text at that level.[28] In fact, readers at all levels tend to prefer simple text and understand it better.[29-30] It is possible to convey complex information in understandable words – and without undermining trust or the perceived quality of the communication.[30] Table 1 provides an example of how technical texts might be simplified, without harming the main message.

We simplified our communication content through iterative revisions, in which Wändi tended to push for simplifying the text and Granger to retain technical details – with Lauren often serving as our mediator. Lauren also helped us to decide by bringing us the results of one-on-one think-aloud interviews, in which she asked members of the public to read our materials out loud, and identify sections in need of improvement. Our interviewees helped us to better explain several complex topics, including how the intermittency of wind power limits the production of electricity 'because sometimes the wind is not blowing.'[26] Furthermore, interviewees also encouraged us to discuss specific attributes of low-carbon electricity generation technologies that domain experts had not explicitly addressed. For example, they wanted to know about the life span of specific technologies, which domain experts had implicitly incorporated in the technology costs. Here, too, decisions were facilitated by having a shared goal to address information that intended recipients wanted and needed, but seemed to be missing.

Example of simplifying a piece of text for lay understanding and readability:
Original text by IPCC[31] (Flesch-Kincaid reading level 17.9)
Carbon dioxide (CO_2) capture and storage (CCS) is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location, and long-term isolation from the atmosphere. This report considers CCS as an option in the portfolio of mitigation actions for stabilization of atmospheric greenhouse gas concentrations.
Source: IPCC[32]
Text simplified by iteration between Wändi and Granger (Flesch-Kincaid reading level 4.3)
CCS takes the CO_2 coming out of coal power plants and other industry, before it goes into the air. CCS then puts the CO_2 deep in the ground. Keeping CO_2 from going into the air can help to slow climate change. CCS can also be used with other ways to slow or stop climate change.

Table 1: Original and simplified text about CCS

Interviewees also noted that they found the amount of information overwhelming. We therefore prepared separate technology sheets that systematically covered the same set of attributes (e.g., how it works, CO_2 released, costs, and safety), deemed relevant by both experts and non-experts. In doing so, we built on evidence from social science that systematic presentation of attribute information facilitates side-by-side comparisons, [33] and especially makes less familiar attributes easier to evaluate. [34]

In addition to the technology sheets, Lauren produced a computer tool to help people construct feasible low-carbon electricity generation portfolios consisting of the technologies.[35-36] These materials were also all developed with input from domain experts to ensure accuracy, and from social science research with intended recipients to ensure usability and understanding. Interested readers can find the details in our published papers.[26, 35-36]

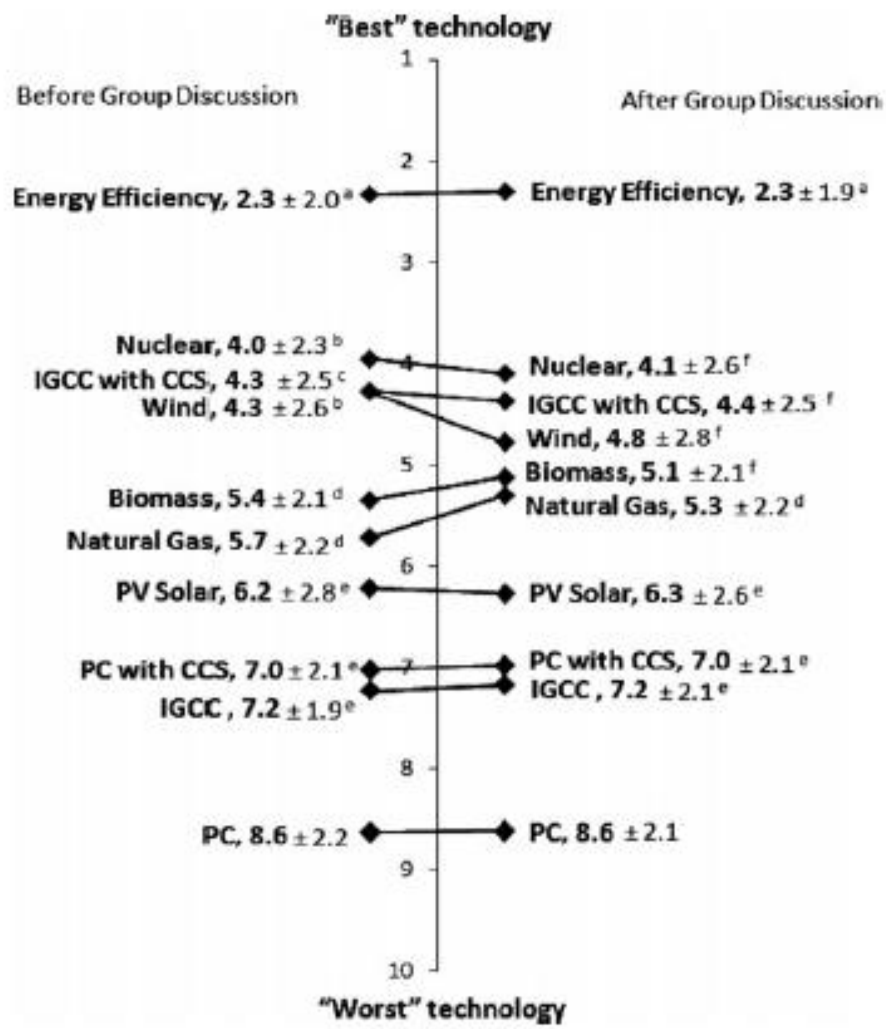

Figure 1: Participants' mean technology rankings ± standard deviation before group discussion (left) and after group discussion (right).[35]
Note: IGCC=Integrated Gasification Combined Cycle coal technology; PC=Pulverized coal technology; CCS=Carbon Capture and Sequestration; PV=Photovoltaic solar technology. Superscripted letters next to mean technology ranking indicate those technologies that ranked significantly worse at $p<0.01$, using a two-tailed Wilcoxon paired-rank test, where

a: all other technologies were ranked significantly worse
b: biomass, natural gas, PV, PC with CCS, IGCC and PC were ranked significantly worse
c: natural gas, PV, PC with CCS, IGCC and PC were ranked significantly worse
d: PC with CCS, IGCC and PC were ranked significantly worse
e: PC was ranked significantly worse
f: PV, PC with CCS, IGCC and PC were ranked significantly worse

Testing communications

In our first evaluation study, we asked Western Pennsylvania residents to imagine that they were members of a taskforce created by the Governor.[35] They were then given the task of choosing technologies to lower the carbon intensity of electricity generation in the state. They first worked individually, and then collectively, to rank the technologies, and feasible portfolios consisting of those technologies, in order of their preference. We found that our communication materials facilitated understanding, with recipients scoring significantly better than chance on true/false knowledge questions about CCS completed before entering group discussions.[35] Moreover, Figure 1 suggests that the two coal technologies (i.e., the newer Integrated Gasification Combined Cycle and the older Pulverized Coal) received significantly better ratings when combined with CCS rather than without, which was unaffected by group discussions.[35] That stability in preferences would be expected from informed participants. Similar findings were obtained in an evaluation study with the on-line computer tool, which allowed respondents to construct their own portfolios.[36]

The relative acceptance of some reliance on CCS, as found in these evaluation studies, contrasted with findings from our initial interviews. We believe that this difference occurred because our communication materials allowed participants to easily see that *all* technologies had risks and benefits. Indeed, when one technology is presented in isolation, people may focus more on its risks than its benefits. But when a range of technologies is presented, and people are given a specific policy goal, it may be easier to evaluate the level of risks and judge their acceptability. One potential lesson learned for communicators, then, is that proponents of a specific technology may want to communicate about that technology in light of its feasible alternatives. Not only does it provide the comparison information that people seem to prefer, it also facilitates better relative evaluations -- and maybe, just maybe, lead to increased acceptance of new technologies.

<u>Impact</u>

While we have not formally tracked the use of our research and communication efforts, there is evidence to suggest that our results have had impact. After our initial public perception studies of CCS, our approach and findings have been replicated in various other countries.[37,38,39] Our communications about low-carbon electricity-generation technologies have been adapted and validated for use in Germany and Switzerland.[40,41] They have been used in Carnegie Mellon University's Energy Week for thought leaders from industry, government, academia, and the non-profit sector. They have also been used in Carnegie Mellon University's Center for Energy Decision Making SUCCEED 5-day summer school for high school students wanting to learn about energy, the environment, and climate change. They have also been used in Carnegie Mellon University's associated continuing education courses for high school teachers, and developed into a lesson plan because these teachers wanted to use our materials in their classrooms.[42] Our communications about low-carbon electricity-generation technologies are publicly available online.[43]

Project 2: Public understanding of how long CO_2 stays in the atmosphere

Initial research

Beginning in the early 1990s, Granger began mental models research on public understanding of climate change, with behavioral social scientists Baruch Fischhoff and Ann Bostrom (now at the University of Washington) and others. [44,45] In initial interviews and surveys, they aimed to identify people's beliefs about climate change. Many participants seemed to be unaware that climate change was caused by the build-up of CO_2 in the atmosphere due to the burning of fossil fuels. Rather, people most commonly thought that the causes of climate change were stratospheric ozone depletion and general air pollution.[44] Perhaps as a result, participants found it difficult to distinguish effective mitigation strategies (such as energy conservation) from ineffective mitigation strategies (such as curtailing the space program or reducing use of nuclear power). The interviews also revealed confusion between "weather" (which refers to conditions of the atmosphere in a specific location over short periods of time, such as temperature and rain) and "climate" (which refers to average weather patterns in a specific location over periods of many years).

To address these potential misunderstandings, Granger and colleagues developed an extensive brochure[46] that, in keeping with the mental models approach, devoted special attention to those issues with which people seemed to struggle: the role of greenhouse gases and other factors affecting the earth's radiative balance, the difference between ozone depletion and climate change, the difference between weather and climate, and explanations of effective mitigation policies. Overall, the content provided a great deal of detail about climate science, the impacts of climate change, and strategies that could be used to reduce emissions of CO_2. To make the amount of information relatively less overwhelming, the brochure used a paper-based 'hypertext' format. That is, recipients could pull smaller brochures out from pockets in the main brochure, to read more about for example "If climate changes, what might happen?" or "What can be done about climate change?" The brochure was iteratively tested and revised on the basis of think-aloud interviews, with the goal of producing content that was both accurate (according to domain experts) and understandable (according to social scientists' think-aloud interviews).

Although the brochure was relatively elaborate, Granger now believes that informed discourse about climate change really requires understanding just three key facts:

1. Burning coal, oil and natural gas emits carbon dioxide (CO_2) to the atmosphere.
2. Carbon dioxide in the atmosphere traps heat and warms the planet which causes climate change.
3. Once CO_2 enters the atmosphere, much of it remains there for hundreds of years.

By now, the first two facts appear to be relatively well-known. Indeed, this was one of the findings when, seventeen years after the initial research on public perceptions of climate change described above, the team conducted the survey again.[47] However, as Granger gave more presentations about climate change and its impacts to diverse audiences, he became increasingly concerned that many people did not understand the third fact - that once CO_2 enters the atmosphere, much of it remains there for centuries. Figure 2 illustrates the long residence time of a pulse of CO_2 added to the atmosphere today. When Granger stressed this fact at a conference in Washington, one senior policy maker approached him after the talk to say "I did not know that. That was the single most important thing you told us today." Studies of public perceptions and discourse about climate change have also suggested that CO_2 is commonly treated as air pollution, which has a much shorter atmospheric residence time.[44, 48, 49]

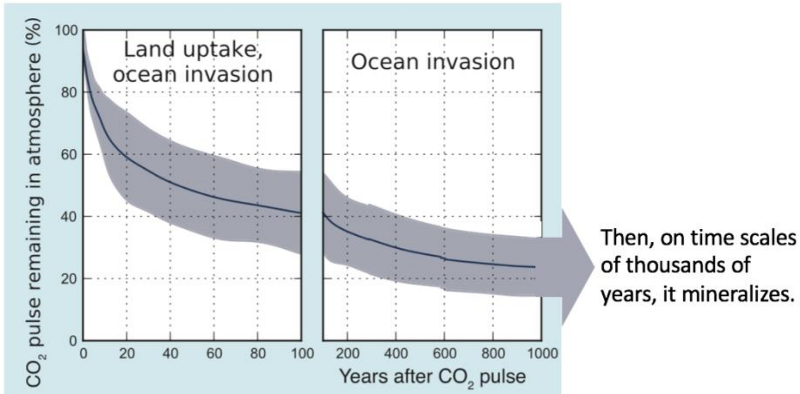

Figure 2: Figure, adapted from the report of Working Group 1 of the IPCC Fifth Assessment report[50], showing the fate of a pulse of CO_2 added to the atmosphere today.

<u>Ongoing research</u>

In order to understand how people thought about the atmospheric residence time of CO_2, Granger sought the social science expertise from Wändi and Ann, and recruited PhD student Rachel Dryden. Together, we agreed on a shared methodology for comparing people's perceptions of atmospheric residence times for carbon dioxide and for air pollution. Granger proposed the technical content we should explore, and Wändi and Ann suggested simplified wording. Rachel tested and refined the survey content, by conducting one-on-one think-aloud interviews in which participants read the materials out loud and highlighted content in need of improvement. In designing the wording of the study, we avoided technical terms such as "residence time." Rather, we posed the two questions, one about carbon dioxide and one about "common air pollution" using the wording shown in Figure 3. We defined common air pollution as being "like smog, oxides of sulfur and nitrogen, organic gases, and fine particles." The two questions were imbedded in a larger mail survey that explored a variety of other issues related to carbon dioxide, air pollution, electricity and climate change, which was completed by 116 respondents randomly selected across all zip codes in Allegheny County PA. In addition, Ann and her colleagues at the University of Washington included the same two questions in a national survey administered with the Mechanical Turk (Mturk) web survey system. There were 1,013 respondents from across the US who responded to that survey.

Wording of the CO2 question:

Imagine that the world's modern factories, transportation and power plants all stopped emitting **carbon dioxide** (CO_2) now. How long would it take for the amount of carbon dioxide (CO_2) in the air to fall back to what it was before those modern factories, transportation and power plants existed?

❑ Hours to days ❑ Weeks to months ❑ Years ❑ Decades ❑ Centuries ❑ Never

Wording of the air pollution question:

Imagine that the world's modern factories, transportation and power plants all stopped emitting **common air pollution** now. How long would it take for the amount of pollution in the air to fall back to what it was before those modern factories, transportation and power plants existed?

❑ Hours to days ❑ Weeks to months ❑ Years ❑ Decades ❑ Centuries ❑ Never

Figure 3: Wording of the two questions we posed to explore people's understanding of the atmospheric residence of CO_2 and common air pollution, defined as "like smog, oxides of sulfur and nitrogen, organic gases, and fine particles." [51]

Once the data were collected, Wändi and Ann guided Rachel through the statistical analyses, using standard social science methods that, despite years of co-authoring studies like this, still remain somewhat mysterious to Granger. Readers interested in the details of these analyses can find them in the paper we published in *Risk Analysis*.[51] Our main finding is that people do not know that carbon dioxide remains in the atmosphere *much* longer than conventional air pollution. Figure 4 shows that participants in our Pennsylvania (PA) mail survey and our online Mturk study mistakenly gave similar ratings for the atmospheric residence time of CO_2) and that of common air pollution. In both the PA and the Mturk sample, the distribution of ratings for the atmospheric residence time of CO_2 and common air pollution is essentially identical. Although our samples were not nationally representative, they suggest that people may grossly underestimated how long CO_2 emissions remain in the atmosphere.

We find these result deeply disturbing, because believing that the residence time of CO_2 is as short as that of common air pollution allows people to think: “I don’t know if this climate change stuff is real or not, but if it ever gets serious enough, we’ll just fix it by reducing emissions in the same way we have reduced air pollution in places like Pittsburgh and Los Angeles.” Of course, reducing emissions only after things get serious will not stop or reverse the warming.

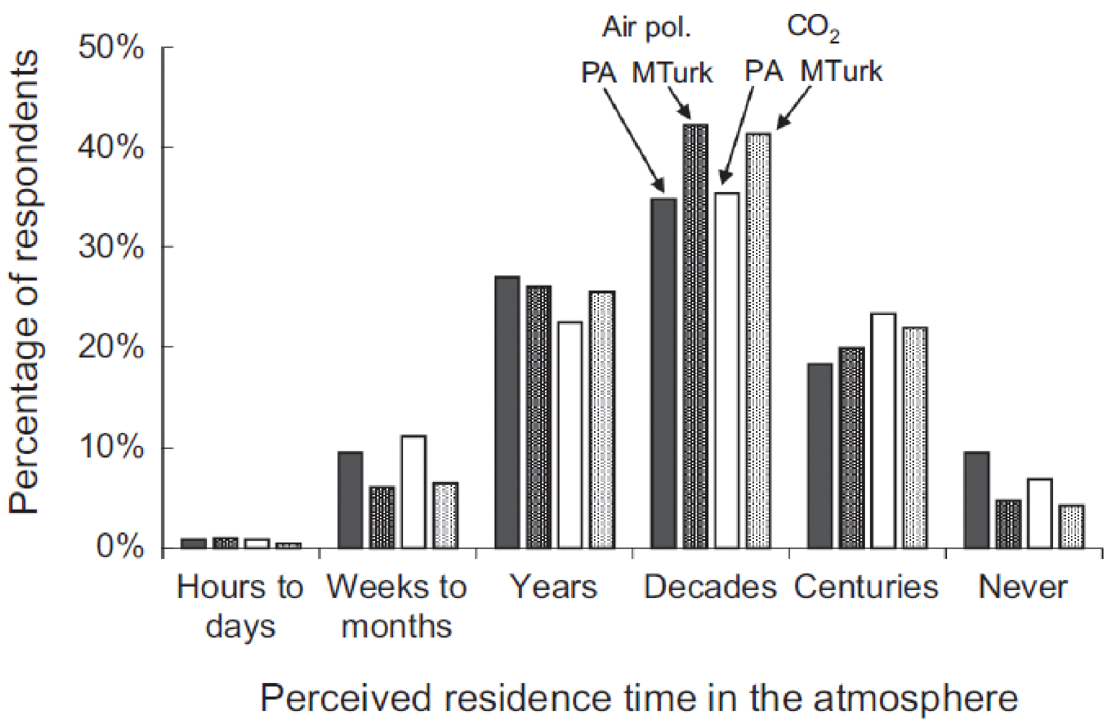

Figure 4: Histogram of responses to the parallel questions, “Imagine that the world’s modern factories, transportation and power plants all stopped emitting [**common air pollution/carbon dioxide**] today. How long would it take for the amount of [**common air pollution/carbon dioxide**] in the air to fall back to what it was before those modern factories, transportation and power plants existed?” For each time interval, the two dark bars on the left are results for air pollution, leftmost from the Allegheny County, Pennsylvania (PA) mail survey (N = 116), and the adjacent stippled dark bar is the analogous result for the MTurk study (N = 1,013). For each time interval, the two lighter bars on the right are results for CO_2, the left from the Allegheny County, PA mail survey, and the adjacent stippled light bar is the analogous result for the MTurk

study. The pattern and magnitude of average responses shows no statistically significant difference. [51]

For the balance of her PhD, Rachel is working with us on how to effectively communicate about residence time. She is also focusing on how to explain "climate attribution" or the idea that climate change does not so much *cause* extreme events as increase their probability of occurrence and their severity, and how people think about the relative efficacy of individual versus collective social action in reducing emissions.

<u>Impact</u>

Because our project on public understanding of CO_2 residence time is still ongoing, it is too early to determine its impact. Given that most people now understand the role of CO_2 from fossil fuels in causing climate change, our findings suggest that making people aware of the long residence time of CO_2 should now be the central focus of public communication about the science of climate change. However, most communications for the public about climate change either make no mention of residence time, or make only subtle mention in passing.

Social psychologist Leaf Van Boven and co-authors report that in the U.S. most Republicans believe that climate change is real, and caused by human action, but since Democrats have taken a strong stand with respect to climate policy they view climate as a political issue. [52] Their paper quotes one former member of Congress as noting "All I knew was that Al Gore was for it, and therefore I was against it." The obvious question is, if a proper understanding of residence time becomes widespread – that we can't just fix it in the future when climate change gets very bad – would that help to erode the political polarization?

WHAT WE THINK WE HAVE LEARNED

We have had an active interdisciplinary collaboration for over 15 years – which in and of itself suggests that we have learned how to work together. We have received external funding from the National Science Foundation and other agencies, co-supervised 5 graduate students, as well as written 7 peer-reviewed academic articles, 2 letters to editors, and 1 book chapter. As described above, the communication about low-carbon electricity-generation technologies is still in use in various outreach efforts through Carnegie Mellon University.

Below, we describe the conditions that we think fostered our interdisciplinary collaboration. Because our research goal was focused on public understanding of climate change, mitigation and impacts, it was not designed to test the effectiveness of interdisciplinary collaborations. The conditions we refer to below therefore reflect what we think we have learned, rather than scientific evidence we gathered about what makes collaborations effective. Nevertheless, the conditions we mention have previously been highlighted in the literature on interdisciplinary collaborations. We first echo the four conditions that Bruine de Bruin and Fischhoff[5] identified for fostering interdisciplinary collaborations between psychologists and economists. We also add four based on our own experience, and link those to research on interdisciplinary collaborations..

1. Shared research goal.

Our projects are motivated by a common goal that is agreed upon beforehand. We typically set out to understand and inform public perceptions of complex policy problems. We explicitly recognize the essential contribution of both disciplines towards achieving our shared goal, and that each of us has an important role to play. For example, we agree in advance that any communications we develop should have the specificity required by technical experts (like Granger), and the usability required by psychologists (like Wändi).

Having a shared goal helps us to overcome the challenge that our different fields typically aim to solve different problems, with Granger's field focused on the technical issues and Wändi's field focused on the psychology relevant to climate change mitigation. It expresses our commitment to integrate our mutual perspectives and make our work more useful, aiming for potential solutions that are both technically and psychologically sound.

2. Shared methodology.

We agree on a shared methodology, which combines those in which we are trained. We recognize that we have complementary strengths and insights, which are necessary for developing novel ideas. Granger brings expertise in natural science. Wändi brings social science and statistics expertise. We take the time to understand and value both, we learn how to integrate our different perspectives, and to communicate about our findings to wider interdisciplinary audiences. Where our two approaches diverge, we seek common ground.

Having a shared methodology also helps to resolve disagreements empirically. For example, we tend to resolve disagreements about how to word a survey question or a communication text by conducting read-aloud interviews with potential audience members, so as to elicit their understanding and preferences for different approaches.[19]

3. Shared effort.

On each project, we commit to collaborate from the start. We consult each other on every step, and take care to understand and address each other's concerns. The result is a true trans-disciplinary co-production. Treating the project as a shared effort also means that we actively help each other to understand the methods of our respective fields, including their strengths and limitations. In doing so, we also make each other aware of the relevant language and academic culture, which tend to differ between academic disciplines.[53]

According to research on interdisciplinary teams, taking the time to understand and value both of our fields, facilitates better communication and integration of perspectives.[53] We believe that it has also helped each of us to better communicate about our findings to wider interdisciplinary audiences beyond our own respective fields.

4. Shared benefits.

We both believe that our collaborations make our projects stronger than they would have been if we were working solely within our own discipline. Together, we are gaining more insight into understanding complex societal problems, which we would not have by relying solely on our own discipline.

Not all interdisciplinary teams will find it easy to share publication benefits, because of challenges in finding appropriate publication outlets. [54] In our case, it has helped that our respective fields have evolved in ways that have resulted in recognition and support in each for the work we have done together. Natural scientists have become increasingly interested in learning how to communicate their expertise more effectively. The psychology of decision-making has progressed beyond lab studies, towards developing communications and interventions that inform real-world decisions. Recent years have seen the rise of a variety of excellent, well refereed, interdisciplinary journals, such as *Risk Analysis*, that are respected by both of our fields.

5. Interpersonal connection.

Interdisciplinary research is not for everyone, but whether a collaboration is within or across disciplines, we have found that projects progress more smoothly if people get along well.

Even seemingly small gestures may promote team cohesion, as illustrated by the following example. Wändi *really* likes purple. When she was at Carnegie Mellon she even had a purple desk. For the talk that we gave on this paper at the National Academy of Sciences' "Science of Science Communication" Colloquium, Granger proposed to include purple in our color scheme. When Wändi talked the slide headings were purple, and when Granger talked his headings were green, which goes well with purple. For a bit of fun, Wändi selected her favorite purple outfit, and Granger bought a green shirt, so we could each dress in line with our color scheme.

According to research on interdisciplinary teams, positive interpersonal connections promote trust and easy sharing of information, which ultimately benefit productivity.[7] It has been suggested that such interpersonal connections may be fostered through social team activities beyond research meetings, though in our case social exchanges happen mostly as part of our research meetings.[7]

6. Excellent students.

We have been able to draw and co-supervise excellent graduate students, including Claire Palmgren, Lauren Fleishman-Mayer, Rachel Dryden, and many others. In working with the two of us, those students have managed to master the essentials of both of our disciplines, and to negotiate a balance between the two. According to the literature on interdisciplinary teams, graduate students are often keeping interdisciplinary projects together, in part because they are less committed to singular disciplines and more motivated to do what is needed to obtain societal benefits.[55]

7. Adequate funding.

In recent years, the U.S. National Science Foundation has been supporting interdisciplinary research and we have been fortunate to write successful proposals. For the work on public perceptions of CCS, we also persuaded the Electric Power Research Institute (EPRI) that an interdisciplinary approach was needed. While finding funding for interdisciplinary work sometimes requires some inventive "packaging" (e.g., to recast the specific applied interests we have in terms of the often more theoretical priorities of funding programs) we have generally found it possible. Securing support for PhD students to work between us has been especially important.

8. Supportive environment.

These days, while most universities talk a good line about interdisciplinary research and education, the number in which that rhetoric has been matched by supportive reality, is relatively low. Many traditional academic departments tend to still be confused by us. However, both of us have worked hard to lead the development of new groundbreaking academic units, with the support of our respective institutions (EPP at Carnegie Mellon and CDR at Leeds). We are both fortunate to work at universities that promote and cherish our interdisciplinary collaborations. Our advice to others who want to do similar interdisciplinary work is to choose their institution with care.

We hope that our experiences and insights will inspire new interdisciplinary collaborations, as they are essential to addressing applied problems. We also believe that interdisciplinary collaborations are crucial for developing individual disciplines, by testing theories in new contexts. We have found these interdisciplinary projects to be personally and intellectually gratifying.

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